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THÈSE DE DOCTORAT

DE L'UNIVERSITÉ PSL

Préparée à MINES ParisTech

Technological Innovation and Adaptation to Climate Change

Innovation Technologique et Adaptation au Changement Climatique

Soutenue par

Simon TOUBOUL

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Technological Innovation and Adaptation to Climate Change

Simon TOUBOUL

December 2021

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CONTENTS

| | |
|--|----|
| Introduction..... | 16 |
| 1 Invention and Global Diffusion of Technologies for Climate Change Adaptation: A Patent Analysis | 25 |
| 1.1 Introduction | 27 |
| 1.2 The Role of Technologies for Climate Change Adaptation..... | 31 |
| 1.3 Invention of Technologies for Climate Change Adaptation | 39 |
| 1.4 International Technology Transfer | 46 |
| 1.5 Patenting Activity in Relation to Climate Hazards | 54 |
| 1.6 Conclusion | 62 |
| 2 Can Technology Reduce the Impact of Tropical Storms? | 67 |
| 2.1 Introduction | 69 |
| 2.2 Data | 72 |
| 2.3 Descriptive Statistics | 80 |
| 2.4 Estimation Strategies | 83 |
| 2.5 Results..... | 85 |
| 2.6 Conclusion | 89 |
| 3 Innovation in Adaptation Technologies in Response to Extreme Climate Events: Evidence from Patent Data..... | 92 |
| 3.1 Introduction | 94 |

| | | |
|-----|---|-----|
| 3.2 | Measuring Innovation and Exposure to Climate Extremes | 101 |
| 3.3 | Descriptive Statistics | 109 |
| 3.4 | Methodology..... | 112 |
| 3.5 | Results..... | 117 |
| 3.6 | Conclusion | 125 |
| 4 | Impact of Extreme Weather Events on Adaptation Patents Owners Behavior: a Firm Level Analysis..... | 130 |
| 4.1 | Introduction | 132 |
| 4.2 | Data Issues | 135 |
| 4.3 | Sample Restriction | 136 |
| 4.4 | Descriptive Statistics..... | 138 |
| 4.5 | Empirical Strategy..... | 139 |
| 4.6 | Results..... | 142 |
| 4.7 | Conclusion | 148 |
| 4.8 | Limitations and Areas for Further Improvements | 149 |
| | Conclusion | 152 |
| | Appendix | 161 |
| | References | 222 |

List of Tables

| | |
|--|-----|
| Table 1. Technology Fields of Y02A Patents Included in the Study | 36 |
| Table 2. Average Annual Growth of Innovation in Different Fields, as Measured by High-Value Patents, 1995–2015 | 41 |
| Table 3. Top 10 Inventor Countries in Climate Change Adaptation Technologies, 2010–15 | 44 |
| Table 4. Average Number of Patent Offices Where Internationally Patented Inventions Are Filed, by Technology Type, 2010–15 | 48 |
| Table 5. Distribution between Country Income Groups of Patented Inventions of Technologies for Climate Change Adaptation, 2010–15 (in percent) | 50 |
| Table 6. Flow of FDI Deals in Climate Change Adaptation Technologies between Country Income Groups, 2010–15 (in percent) | 53 |
| Table 7. Definitions and Data Sources of the Five Hazard Indicators | 56 |
| Table 8. List of Selected Storm Adaptation Technologies | 74 |
| Table 9. Storm Impact and Technology Availability by Country (1990-2015) | 81 |
| Table 10. Summary Statistics for the Analysis of Technology Efficiency | 82 |
| Table 11. Effect of Technologies on Storm-Induced Fatalities..... | 85 |
| Table 12. Effect of Technologies on Storm Induced Damages to Assets | 87 |
| Table 13. Weather Event Indicators Building | 108 |
| Table 14. Patents and Weather Events Global Statistics | 109 |
| Table 15. Descriptive Statistics on Regression Sample | 110 |
| Table 16. Long-term Cumulative Effect of Extreme Weather Events on the Invention of Adaptation Technologies..... | 119 |

| | |
|--|-----|
| Table 17. Long-term Cumulative Effect of Extreme Weather Events on the Imports of Adaptation Technologies..... | 122 |
| Table 18. Share of Adaptation Technologies Invented by Identified Firms (1995-2015) | 136 |
| Table 19. Number of Patent Offices Where Firms Filed at Least One Adaptation Patent, by Inventor Country (1995-2015) | 137 |
| Table 20. Descriptive Statistics on Regression Sample | 138 |

List of Figures

| | |
|---|-----|
| Figure 1. Climate Adaptation Innovation, as Measured by High-Value Patents, 1995–2015 | 40 |
| Figure 2. Innovation in Climate Related Technologies and All Technologies, 1995-2015 | 42 |
| Figure 3. Global Average Technology Transfer Rates, 2010–15 | 47 |
| Figure 4. Trends in Climate Adaptation Technology Transfer as a Share of All Adaptation Technology Inventions, 1995–2015..... | 49 |
| Figure 5. Transfer Rates of Climate Change Adaptation Technology, by Field, 2010–15 | 49 |
| Figure 6. Number of FDI related Deals , 2000-2015 | 52 |
| Figure 7. Relationship between Adaptation Technology Invention and Climate Hazards in High- and Middle-Income Countries, 2010–15..... | 57 |
| Figure 8. Relationship between Climate Hazards and Adaptation Technology Inventions (as a Share of All Technology) in High- and Middle-Income Countries, 2010–15 | 58 |
| Figure 9. Relationship between Climate Hazards and Imports of Climate Change Adaptation Technologies in High- and Middle-Income Countries, 2010–15..... | 59 |
| Figure 10. Correlation between Availability of Advanced Adaptation Technologies and Climate Hazard Levels in High- and Middle-Income Countries, 2010–15 | 61 |
| Figure 11. Maximum Wind Speed of Selected Storms over the Period | 78 |
| Figure 12. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015 | 117 |
| Figure 13. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015 | 121 |
| Figure 14: Effect of Extreme Weather Events on the Share of Adaptation Inventions in all Technologies Invented, 1995-2015..... | 124 |

| | |
|---|-----|
| Figure 15. Effect of Foreign and Extreme Weather Events on the Filing of Adaptation Patents, 1995-2015..... | 143 |
| Figure 16. Differentiated Effect of Local and Foreign Extreme Weather Events on Adaptation Patent Filing, 1995-2015 | 145 |
| Figure 17. Effect of Extreme Weather Events on the Co-Invention of Adaptation Technologies, 1995-2015..... | 147 |

This dissertation is made of four chapters, all using patent data as a proxy for the innovation in climate change adaptation technologies.

These chapters are based on published and unpublished research papers:

CHAPTER 1: Invention and Global Diffusion of Technologies for Climate Change Adaptation: A Patent Analysis, 2020, World Bank, Washington, DC. © World Bank. <https://openknowledge.worldbank.org/handle/10986/33883> License: CC BY 3.0 IGO.

Revise and Resubmit in the *Review of Environmental Economics and Policy*

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Working paper

CHAPTER 4: Impact of Extreme Weather Events on Adaptation Patents Owners Behavior: a Firm Level Analysis, 2020

Working paper

Introduction

Adapting to climate change: an emergency

As I begin writing this dissertation, the Working Group I of the Intergovernmental Panel on Climate Change (IPCC) releases the first chapter of its Sixth Assessment Report. For the first time, the authors assert that human activities, by releasing greenhouse gases into the atmosphere, have led to a warmer planet. This statement reaffirms that much more ambitious climate mitigation policies are required to induce a quick and drastic reduction of greenhouse gases emissions. By using renewables energy technologies, pricing carbon or increasing energy efficiency of our equipment, these policies intend to diminish the carbon footprint of human activities. Aiming at “reduce or prevent greenhouse gases emissions” (United Nations), climate change mitigation has logically constituted the first of a two-step strategy to curb climate crisis. However, while the COVID-19 crisis, which could have initiate a new green and resilient era, continues to threat public health worldwide, global CO₂ emissions are on the rise again. At the same time, past emissions already increased global surface temperature by more than a degree, contributing to climate change negative impacts, such as an increase in extreme weather events. The uncertainty surrounding both future greenhouse gases concentration in the atmosphere and the reaction of the earth system to a given level of pollution exacerbates the problem. In this context, adapting to climate change is no longer a second option, but a requirement.

Defined by the United Nations as “adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts”, adaptation is not a new concept. For millennia, Homo Sapiens has been able to survive

in almost all places on earth by adapting his behavior and lifestyle to changing local environmental conditions. What constitutes a new challenge is the speed and the intensity of recent and forecasted environmental changes, especially the extreme ones. In the face of this worrying future, and after decades of economic research and policies mostly dedicated to climate change mitigation, adaptation became the new hot topic. To fill the knowledge and action gaps between mitigation and adaptation, initiatives are flourishing all over the world, such as the creation of the Global Commission on Adaptation in 2018. Gathering political, business, scientific and financial stakeholders, the United Nations established this commission to increase the visibility of adaptation issues and initiate a new dynamic for adaptation actions. The European Union followed by adopting its new strategy on adaptation to climate change in 2021. While these efforts signal a growing awareness of the need to create more resilient societies, a crucial lack of scientific and practical knowledge limits the scope of these initiatives. The few studies in economics dedicated to climate change adaptation often relate with the evaluation of global adaptation costs and financial gaps. Even if financial issues remain the main concern for most threatened countries, adapting to climate change will require unprecedented efforts in other areas, such as governance, knowledge production or technological innovation.

Technologies as a tool to adapt

Technologies appear as a promising solution to adapt to climate change, and constitute one of the key areas to reduce the adaptation gap, as identified by the IPCC (Intergovernmental Panel On Climate Change) (2014). The OECD (2021) lists technologies as one of the three “enablers for action on climate resilience”. The Adaptation Gap Report by the United Nations Environment Program (UNEP) (2014) stresses the increasing demand for modern and advanced technologies. These innovative adaptation technologies can be both soft (early warning systems, weather forecasting tools, ...) and hard (dikes, dams, floating houses, thermal insulation, ...) technologies, often combined with low tech and nature based solutions. For example, in coastal areas threatened by storms, the installation of early warning systems and effective weather forecasting software combined with the replanting of mangrove forest allow people to escape from storms when limiting storms damages on infrastructures.

Although technologies are emerging as an essential tool to adapt, little is known about the geography and the drivers of the innovation in adaptation technologies, nor on their efficiency to reduce climate change impacts. This dissertation attempts to fill this gap. More precisely, we explore three sets of questions: 1) What are the current trends in innovation and international transfer of technologies for climate change adaptation and are they available where they are needed most? ; 2) Do technologies reduce the impact of extreme weather events? ; 3) Do innovators respond to these climate shocks?

Across all chapters, the empirical analysis combines two datasets. Innovation and technology transfer are measured with patent data, a proxy for the innovation in and

access to adaptation technologies, both at the country and the firm level. These data are extracted from the World Patent Statistical Database (PATSTAT). Targeting patents protecting adaptation-related technologies has been recently made possible by the release in April 2018 of the so-called new Y02A PATSTAT classification by the European Patent Office (EPO). This classification, covering all patent offices included in PATSTAT, targets patents protecting “technologies that allow adapting to the adverse effects of climate change in human, industrial (including agriculture and livestock) and economic activities”. Over the 43 million patent families included in the entire PATSTAT database, around 250,000 inventions (less than 0.6%) are classified as adaptation technologies. To the best of my knowledge, no empirical studies have used this classification yet.

Identifying climate risk: a focus on extreme weather events

I measure climate risk with original indicators which identify countries' (or innovators') level of exposure to climate shocks. They combine global gridded weather metrics of droughts, precipitations and heatwaves with geolocalised population count and land use data. Such data on a kilometer scale allow me to precisely target the number of people, or agricultural areas, affected by each type of weather events. By constructing these indexes as the deviation from the long-term average, I define extreme weather events as rare events that differ significantly from the mean. The final exposure indicators represent the share of the country's population (or agricultural area) exposed

to a given extreme weather events per year, and serves as a proxy for the local demand or needs for adaptation technologies in the two last chapters of this dissertation.

My contribution

Made of four chapters, the dissertation begins with a descriptive analysis, followed by three econometric analysis.

In the first chapter, **“Invention and Global Diffusion of Technologies for Climate Change Adaptation: A Patent Analysis”**, I describe the global pace of adaptation innovation, identify the leading countries, track technology transfer across borders and relate innovation trends to adaptation needs. I find that the number of patented adaptation inventions has increased between 1995 and 2015, but, unlike climate mitigation patents, it has remained constant as a share of total patented inventions. Adaptation innovation is highly concentrated, and I found limited technology diffusion through the patent system. As a result, I document a striking mismatch between countries’ adaptation needs and technological availability.

In Chapter 2, **“Can Technology Reduce the Impact of Tropical Storms?”**, I provide evidence on the effectiveness of technologies to reduce tropical storm impact. Using the Y02A classification to select storm adaptation technologies, I build a panel of 10 countries for the period 1990-2015. I match data on both people and assets affected by storms with impact data from EM-DAT, and then aggregate them at the country level. I find that storms dedicated technologies significantly reduce both the number of storm-induced

fatalities and the amount of economic damages. I estimate that a ten percent increase in the stock of available storms technologies decreases by around 7.3% the number of storms induced fatalities, and by 7.5% the amount of assets destroyed by tropical storms, which corresponds to an average save of more than PPP2005 US\$ 369 millions per country per year. I also conduct further analysis showing that recently patented technologies are more efficient than older ones, and that only technologies specially designed to cope with storms negative effects are efficient. These observations illustrate the importance of innovation, which must be dedicated to technologies specific to climate change adaptation. However, I also argue that the first best option to adapt remains to escape from risky areas.

In the third chapter, **“Innovation in Adaptation Technologies in Response to Extreme Climate Events: Evidence from Patent Data”**, I analyze the innovation response of countries to past extreme droughts, precipitation and heatwaves. I estimate the effects of these extreme events on the invention and imports of adaptation technologies for the period 1995-2015. My findings are more pessimistic than those of previous studies. These events have a small or insignificant effect on the invention and the imports of adaptation technologies. While droughts seem to increase innovation in the short-term, floods have a delayed effect on innovation, and the effect of heatwaves remains unclear. Consequently, the cumulative effect indicates that countries react to long-term changes in droughts exposure only, by both inventing and importing adaptation technologies. For example, a 20% increase in the average number of people affected by droughts over the last ten years will significantly boost the number of droughts related inventions by

around 5%. I also estimate the impact of these events on the share of adaptation-related innovation in the country's total innovation in order to evaluate whether these shocks redirect national R&D efforts towards adaptation. I find that, except for droughts, extreme weather events do not significantly redirect innovation towards adaptation technologies. It suggests countries do not react to extreme events by inventing nor importing foreign adaptation technologies specifically designed for these events.

Finally, in the fourth chapter, "**Impact of Extreme Weather Events on Adaptation Patents Owners Behavior: a Firm Level Analysis**", I complete the findings of the previous chapter. Extracting firm-level adaptation patent filing data from six of the ten main inventor countries, I analyze how the exposure of firms to local and foreign extreme droughts and precipitation influences their innovation behavior in adaptation technologies. Preliminary results confirm the small but significant effect of these events on firm's adaptation patents filing. Moreover, this effect is limited to events occurring in the home country of the inventor. I also analyze the effect of extreme weather events on the co-invention of patents, defined as patents filed by a foreign firm but invented in cooperation with local innovators. Initial findings suggest no effect of extreme weather events on the propensity to carry-out 'co-innovations'.

I end this dissertation with a general conclusion, where I summarize the findings of the four chapters and their policy implications, and then discuss the limits of my approach and areas for further research.

1 Invention and Global Diffusion of Technologies for Climate Change Adaptation: A Patent Analysis

Antoine Dechezleprêtre^{*a}, Sam Fankhauser^{ab}, Matthieu Glachant^c, Jana Stoever^d and
Simon Touboul^c

Abstract

Technology will play a major role in the global effort to adapt to climate change. However, little is known about the development and diffusion of adaptation technologies. In this paper, we use patent data to describe the global pace of adaptation innovation, identify the leading countries, track technology transfer across borders and relate innovation trends to adaptation needs. We find that the number of patented adaptation inventions has increased between 1995 and 2015, but, unlike climate mitigation patents, it has remained constant as a share of total patented inventions. Adaptation innovation is highly concentrated, with China, Germany, Japan, South Korea, and the United States accounting for nearly two-thirds of global inventions. This concentration of innovation activity could in principle be compensated through international technology transfer, but we find only limited technology diffusion through the patent system. The international diffusion is particularly low in the agriculture sector and coastal and river protection, and there is virtually no transfer of patented knowledge to low-income countries. As a result, we document a striking mismatch between countries' adaptation needs and technological availability.

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Résumé

Les technologies joueront un rôle majeur dans l'effort mondial d'adaptation au changement climatique. Cependant, nous savons peu de choses sur le développement et la diffusion de ces technologies d'adaptation. Dans cet article, nous utilisons des données de brevets pour décrire la dynamique de l'innovation mondiale dans les technologies d'adaptation, identifier les principaux pays innovateurs, mais aussi évaluer le transfert international de ces technologies, et relier la géographie de l'innovation aux besoins d'adaptation. Nous constatons que le nombre d'inventions d'adaptation brevetées a augmenté entre 1995 et 2015, mais que, contrairement aux brevets protégeant des technologies d'atténuation, cette augmentation est identique à celle observée pour l'ensemble de l'innovation mondiale. L'innovation en matière d'adaptation est aussi très concentrée : la Chine, l'Allemagne, le Japon, la Corée du Sud et les États-Unis représentent en effet près des deux tiers des inventions mondiales dans les technologies d'adaptation. Cette concentration de l'innovation pourrait en principe être compensée par un transfert international de technologies, mais nous ne constatons qu'une diffusion limitée de ces technologies via le système de brevets. La diffusion internationale est particulièrement faible dans le secteur de l'agriculture et de la protection des côtes et des rivières, et il n'y a pratiquement aucun transfert de connaissances brevetées vers les pays à faible revenu. En conséquence, nous constatons une inadéquation frappante entre les besoins d'adaptation des pays et la disponibilité des technologies.

CHAPTER 1

Invention and Global Diffusion of Technologies for Climate Change Adaptation: A Patent Analysis

1.1 Introduction

Adaptation to the physical risks of climate change will require change along many dimensions, including adjustments in working practices and location choices (Fankhauser 2017, 2019). An important role could also be played by new technologies that increase resilience to climate risks and extremes, such as better irrigation systems, advanced weather forecasting tools, new medicines and more resilient crop varieties. The extent to which such technologies are being developed and becoming globally available will have a significant impact on countries' ability to deal with the impacts of climate change that can no longer be avoided (Klein and Tol 1997; Miao 2017; GCA 2019).

While the economic literature on climate change mitigation technologies is well-developed (see Popp 2019 for a survey), very little has been written so far about the development of new adaptation technologies and their diffusion. Countries are and will be exposed to climate shocks in very different ways. The economy of many developing countries remains highly dependent on agriculture, and the availability of new climate-resilient crop varieties is a vital issue. For some countries, hurricanes and storms are the

main threats. Whether the different adaptation technologies are made available in the countries that need them most is a crucial, but largely-open question.

The aim of this paper is to start building an evidence based on the pace and geography of innovation in adaptation technologies. Using recently released data on adaptation-related patents, we identify the leading innovation countries and how technologies for climate change adaptation diffuse across borders (international technology transfer). We then relate these patterns to adaptation needs, that is, to the physical risk profiles of different countries. International technology transfer is important because a large fraction of the innovation activity in today's knowledge-based economy takes place in the Global North, while technologies for climate change adaptation are urgently needed in low- and middle-income countries, which are particularly vulnerable to climate shocks (Fankhauser and McDermott 2014).

The analysis relies on patent data from the World Patent Statistical Database (PATSTAT), maintained by the European Patent Office (EPO). The PATSTAT database is updated biannually by the EPO and includes patent filings in 169 national or regional patent offices, covering close to the population of worldwide patent filings. We use the EPO's new "Y02A" category, which identifies patents pertaining to a large range of adaptation technologies and has not yet been used in empirical analyses.

Innovation scholars widely use patent data to map technology fields. In the absence of data on other innovation outputs or inputs (such as R&D expenditures on climate adaptation), patent data represent the best and widest source of available information on technological change related to adaptation. Such data have however some

drawbacks. In particular, relying on patent data restricts the scope of the analysis to solutions for adaptation that are at the technological frontier and excludes the role of non-technological forms of innovation and low-tech options. One consequence is that low-income countries are virtually not present in the data since they hardly use advanced technologies. When analyzing international technology transfer, we also complement patent data with data on foreign direct investment (FDI) – another widely used measure of cross-border technology diffusion.

The adaptation literature is focused almost exclusively on the deployment of existing technology within countries (Markanday et al. 2019), for example irrigation and crop choices in the case of agriculture (Kurukulasuriya et al. 2011; Seo & Mendelsohn 2008); air conditioning and building design in the case of heatwaves (Day et al. 2019; Deschênes & Greenstone 2011; Rapson 2014), physical infrastructure for water management (Dessai & Hulme 2007; Kirshen et al. 2015) and floods protection (Liquiti & Vonortas 2012; Ranger et al. 2013). The lack of attention to technology innovation in the adaptation literature stands in stark contrast to the mitigation literature, where low-carbon technology innovation is a rich field of study.

One of the few papers to analyze adaptation innovation is Conway et al. (2015) who focus on water-related technologies. Using global patent data, the authors describe innovation in this sector and document international collaboration on innovation and technology diffusion. Miao and Popp (2014), Li (2017) and Hu et al. (2018) also use patent data, but with a different perspective. They examine the drivers of adaptation innovation, focusing on the effect of past natural disasters. They find that such events

are associated with an increase in the number of subsequent risk-mitigating innovations, with a magnitude that differs across types of disasters and technologies.

The rest of the paper proceeds as follows. Section 2 reviews how global innovation activity in adaptation technologies has developed over time and space. Section 3 covers the international transfer of adaptation technologies. Section 4 examines the relationship between adaptation technology and physical climate risks (and therefore adaptation needs). Section 5 concludes with implications for policy and further research.

1.2 The Role of Technologies for Climate Change Adaptation

How relevant is technology?

Homo Sapiens has been able to settle in nearly all earth ecosystems. Our species succeeded by developing technologies and skills to adapt to multiple environments and climate risks: buildings, agricultural techniques, transport solutions... Over the centuries, we have thus progressively generated a stock of knowledge and technologies which has given us increasing adaptation capabilities.

What is new is the pace of climate change and the fact that it occurs on a planet with nearly 8 billion inhabitants. In this new context, it can be reasonably assumed that these existing technologies and skills are not sufficient to deal with the current speed and scale of climate change. We give more substance to this claim below. Importantly, this does not require to shift to a new innovation paradigm, but to drastically accelerate the pace of innovation and the diffusion of technologies in sectors and geographical areas where they are the most useful.

Although the Fifth IPCC Assessment Report (IPCC 2014) acknowledges the importance of non-technological solutions and traditional knowledge, it also identifies technology as one of the three areas to reduce the current and future climate change adaptation gap. Looking at specific sectors and climate extremes helps understanding why technologies are important. Take the example of sea-level rise and related hazards in coastal zones (Kleint et al. 2001) . Adaptation first means to improve the description and assessment of local coastal systems. It requires satellite remote sensing, wave rider buoys, tide

gauges, and computerized simulation models. Protecting against sea-level rise and surges then requires more effective and less costly dykes, levees, salt intrusion barriers using resistant materials, detached break waters. Last, reducing the impacts means early warning systems, saline-resistant crops, and new aquaculture solutions, desalination equipment, better drainage systems. Most of these solutions may be made more effective by using advanced technologies. The United Nations Development Programme cites the example of early warning systems which proved their usefulness in preventing fatalities in Bangladesh in 2007 (UNDP 2018). Their estimate is a cost-benefit ratio of up to 500:1. Air cooling offers another illustration: the diffusion of air conditioners has been estimated as responsible for almost the entire decrease in heatwave-induced fatalities observed in the US during the twentieth century (Barreca et al. 2016).

While the Adaptation Gap Report by UNEP (Olhoff et al. 2014) highlights an increasing need for modern and advanced technologies, it also states that needs are less likely to transform into demand in developing economies. This is not specific to adaptation. In all technological areas, the limited availability of researchers and engineers, a low number of past innovations, and low R&D expenditures (Fagerberg 1994; Griffith et al. 2004; Keller 1996; Kneller & Stevens 2006) reduce these countries' ability to recognize, assimilate and apply new technological knowledge and makes them more dependent on traditional indigenous technologies.

These limited technological capacities pose a particular challenge for adaptation as many of these countries stand in locations highly affected by climate change (IPCC 2021) and traditional knowledge is likely to be insufficient given the scale of the problem in there.

As an illustration, the synthesis of the technology needs (TNAs)¹ reported to the UNFCCC by the governments of 25 middle-income and low-income countries indicates that around 75% of the identified technology gaps concern modern or high-technologies, especially for infrastructure, health, water management, disaster risk management or coastal zones (Olhoff et al. 2014).² Note that combining traditional knowledge with modern scientific and technological tools can pay extra dividends, as when Inuit hunters combine their knowledge of wildlife and sea ice with weather station and GPS data to adapt to changing conditions.

Patent data

A difficulty for organizing and monitoring a technological response in this area is that the knowledge of the geography of supply of and demand for these advanced technologies remains patchy. Their economic relevance for adaptation however leads innovators to file patents in order to secure economic returns. In this way, patent data provide a useful tool to draw a more systematic landscape of the past and current patterns and trends of innovative activity in all regions of the world. Patents protect the results of “applicable” research leading to ready-to-use technologies which could be deployed in the short term, not the outcome of basic research performed in public research labs. Publicly funded institutions and universities also develop applicable

¹ More information about Technology Need Assessment available here: <https://unfccc.int/ttclear/tna>

² Low absorptive capacities mean domestic economic actors are less able to imitate an imported technology. In this context, IPR are less useful in securing innovation returns, and thus in providing technology owners with incentives to transfer. This should be kept in mind when using patent-based indicators.

technologies and rely on patent protection. In the data used below, 16% of adaptation patents are filed by universities or non-profit organizations.

In the rest of this paper, we rely on the PATSTAT dataset which contains 19 million inventions (patent families) patented globally between 1995 and 2015 in nearly all world patent offices. In April 2018, the EPO introduced a new classification for patents related to “technologies for adaptation to climate change” (Y02A) which now allow analysts to identify relevant inventions among these millions of patents. Patents classified in this category protect “technologies that allow adapting to the adverse effects of climate change in human, industrial (including agriculture and livestock) and economic activities”,³ which corresponds closely to the UNFCCC (2005) definition of adaptation technologies. The new classification covers all patent offices included in PATSTAT and was applied retrospectively through an algorithm that associates patent classification codes and keyword searches in patents’ titles and abstracts, ensuring full coverage across space and time. We conservatively use 2015 as the last reliable year of data, since it takes four to five years for the various members of a patent family to be comprehensively included in PATSTAT.⁴

³ “Technologies for Adaptation to Climate Change,” Cooperative Patent Classification (CPC) Subclass Y02A, Espacenet website, European Patent Office: https://worldwide.espacenet.com/classification?locale=en_EP#!CPC=Y02A.

⁴ Patents are published up to 18 months after the application. The Patent Cooperation Treaty gives inventors up to 30 months after the first filing (the “priority” filing) to file patents related to the same inventions in other countries. These two processes thus take up to four years, and the data then have to be included in PATSTAT (after transmission of the relevant information to the European Patent Office), which can take several months as well.

The Y02A classification includes some 121,000 adaptation inventions filed between 1995 and 2015, or about 0.6 percent of all inventions included in PATSTAT. Adaptation patents are classified into six subcategories, which cover the main fields of adaptation activities and technologies (Table 1). The technologies are categorized according to the economic sector affected: 'Costal and river protection', 'Water Management', 'Infrastructure', 'Agriculture', 'Health' and 'Indirect adaptation' (see Table 1 for the definition of these categories and some examples). As an example, the second category, titled 'Water Management', groups all patents protecting 'technologies for adaptation to climate change related to Water conservation; Efficient water supply; Efficient water use'. Each category is further divided into multiple items. For instance, the "water management" subcategory includes 52 items, including "rainwater harvesting", "saltwater intrusion barriers" or "water desalination". The former item comprises promising technologies to tackle freshwater shortages during droughts.

Table 1. Technology Fields of Y02A Patents Included in the Study

| Category | Description | Examples |
|------------------------------|--|---|
| Coastal and river protection | Technologies for adaptation to climate change at coastal zones and river basins | Dikes, dams, artificial reefs, groynes, real-time floods forecasting |
| Water management | Technologies related to water conservation, efficient water supply, and efficient water use | Water desalination methods, saltwater intrusion barriers, water filtration systems |
| Infrastructure | Technologies for adapting or protecting infrastructure or their operation | Floating houses, thermal insulation technologies, passive air cooling |
| Agriculture | Technologies for adaptation to climate change in agriculture, forestry, livestock or agroalimentary production | Windbreaks; greenhouse technologies; irrigation systems; plants tolerant to drought, heat, salinity |
| Health | Technologies for adaptation to climate change in human health protection | Malaria medical treatment, catalytic converters to control pollutant emission controls |
| Indirect adaptation | Technologies making an indirect contribution to climate change adaptation | Climate simulation, radar-based weather surveillance, real-time meteorological measurement |

Source: "Technologies for Adaptation to Climate Change," Cooperative Patent Classification Subclass Y02A, European Patent Office (EPO). For the full classification, see: https://worldwide.espacenet.com/classification?locale=en_EP#!/CPC=Y02A.

In a schematic way, the patenting process involves two stages. The inventor files a patent to protect their invention in a first patent office, which is most often that of their home country. They may then extend this protection by filing additional patents in other countries where they expect commercial opportunities for the invention. The set of patents made of these multiple filings protecting the same invention across jurisdictions is called a patent family. Counting the number of patent families (rather than the raw

number of patent filings) provides a measure of the level of inventive activity which avoids double-counting inventions protected in several countries. Counting the number of patents filed in country Y by inventors located in country X (where the invention has generally been first protected) provides a measure of technology transfer from country X to country Y. Many articles use this approach to infer innovative activity and international technology diffusion from patent data (Dechezleprêtre et al. 2011; Eaton & Kortum 1996).

Using patent data to measure innovation is useful for several reasons. First, patent data provide detailed, disaggregated information on the technology itself as well as characteristics of its development, such as place of invention, date of filing, names, location and sector of activity of the inventor and applicant. Second, patent data measure the *output* of the innovation process, while alternative indicators (such as R&D expenditure or the number of researchers employed) measure *inputs* into this process. In addition, these input-based measures are not available at such a technologically disaggregated level. Third, because inventions need to be marketable to be awarded patent protection, they are likely to have an industrial application. Finally, because filing a patent is costly, patents are filed only in countries where there is good prospect for economic returns. As shown in Griliches (1990), Morgan, Kruytbosch, and Kannankutty (2001) and Svensson (2012), most patented inventions are indeed commercialized.

However, using patent data to measure innovation and technology transfer also has drawbacks. Some inventors may employ alternative methods to protect their innovation—in particular, industrial secrecy or lead-time advantages (Cohen et al. 2000).

As a result, patents are filed only in countries where intellectual property (IP) protection is sufficiently strong. This is a potentially important limitation because many of the countries most vulnerable to climate change also weakly enforce IP rights. The data reveal few patents in low-income countries. Whether this indicates a measurement problem or low access to technology is difficult to establish, although complementary indicators (such as tertiary education, a proxy for scientific knowledge production capacity) suggest the latter.

We mitigate the heterogeneity in patenting propensity across countries by looking at the share of a country's total patent filings that concern adaptation technologies. This accounts for differences in the local enforcement of IP rights, which should apply equally to patents in all technology fields, including adaptation technologies. Another difficulty is that the propensity to patent also differs between sectors (Cohen et al. 2000). Therefore, we primarily discuss time trends, which are immune to this problem if heterogeneity in patenting propensity across sectors varies weakly over time.

Finally, the value of individual patents is heterogeneous, including across patent offices. For example, inventions filed at the Chinese Patent Office are known to have a lower unit value than inventions filed at the EPO or at the United States Patent and Trademark Office (Boeing & Mueller 2015, 2016). As a result, the vast majority of these patents are not filed abroad, indicating that inventors anticipate a limited economic potential outside the country. This leads us to restrict parts of our analysis to 'high-value' patented inventions, defined as inventions for which protection has been sought in more than one

country, following a now established methodology (Dechezleprêtre et al. 2011; Pigato et al. 2020).

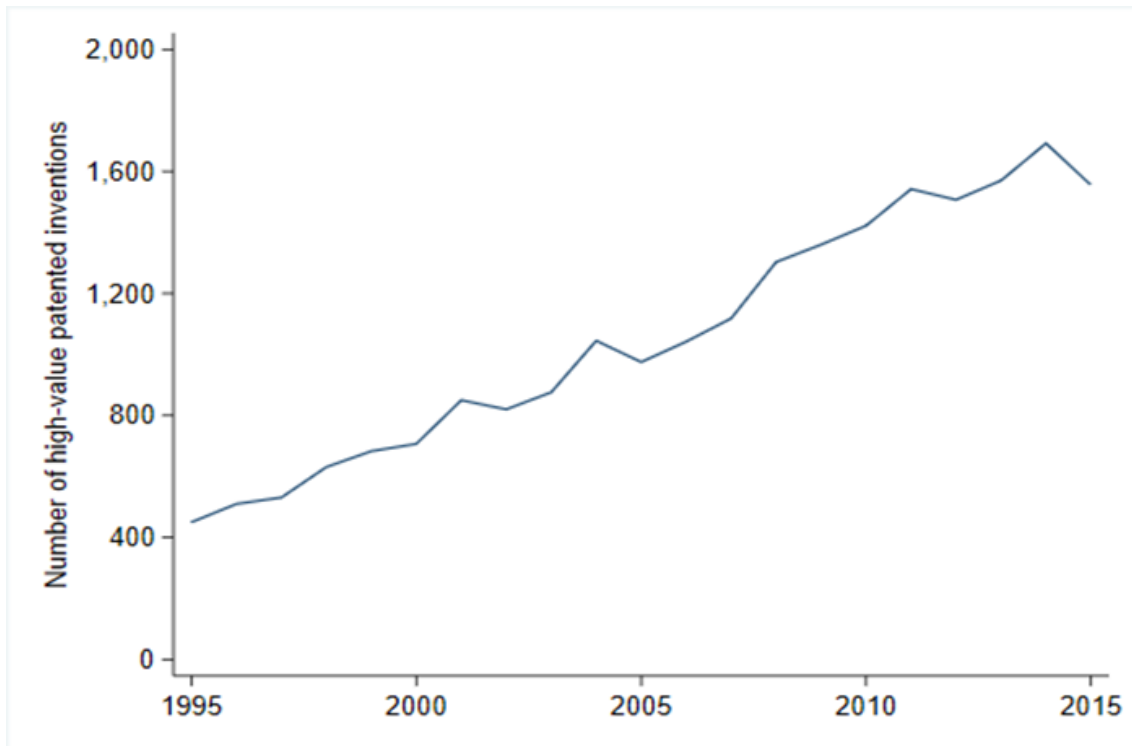
1.3 Invention of Technologies for Climate Change Adaptation

The Growth of Climate Adaptation Innovation

We first use the data to study the global development and distribution of adaptation inventions between 1995 and 2015. The data show a boom in the global number of high-value inventions (defined as those patented in at least two countries): a fourfold increase since 1995 (Figure 1). This corresponds to an impressive 6.7 percent average annual growth rate (Table 2). Technologies related to floods protection have experienced the highest growth rates by far, around 17%.

This upward trend in patenting is likely partly driven by a general increase in patenting propensity rather than by a genuine increase in innovation. To control for this factor, Figure 2 also shows the evolution of the number of patented inventions in all technology fields. The pace of innovation for adaptation then appears to be comparable to this average growth rate. Except for a temporary decoupling at the end of the 2000s, global R&D efforts have not yet been redirected toward climate change adaptation.

Figure 1. Climate Adaptation Innovation, as Measured by High-Value Patents, 1995–2015



Source: Authors' calculations based on the World Patent Statistical Database (PATSTAT) data.

Note: "High-value" inventions are patents filed in at least two patent offices.

Climate change mitigation provides an interesting benchmark for interpreting these stylized facts. To start with, while adaptation inventions averaged around 0.5 percent of global patenting activity annually during 1995–2015, the average share of climate mitigation patented inventions is 5.7 percent over the same period. The order of magnitude between the two numbers sounds in fact consistent with the relative costs of adaption and mitigation. The United Nations Environment Program (UNEP) (2016) estimates the annual cost of adaptation from USD 140 to 300 billion by 2030. By contrast, global investments needed to successfully mitigating carbon emissions is estimated between USD \$1.5 trillion to 3.5 trillion a year by the IPCC (2018).

Table 2. Average Annual Growth of Innovation in Different Fields, as Measured by High-Value Patents, 1995–2015

| Technology field | Average annual growth adaptation (%) | Average annual growth benchmark (%) |
|------------------------------|--------------------------------------|-------------------------------------|
| Coastal and river protection | 17 | 11,2 |
| Water management | 8 | 4,3 |
| Infrastructure | 8 | 6,4 |
| Agriculture | 5,6 | 4,4 |
| Health | 7,6 | 4,4 |
| Indirect adaptation | 12,1 | 9,3 |

Source: Calculations based on World Patent Statistical Database (PATSTAT) data.

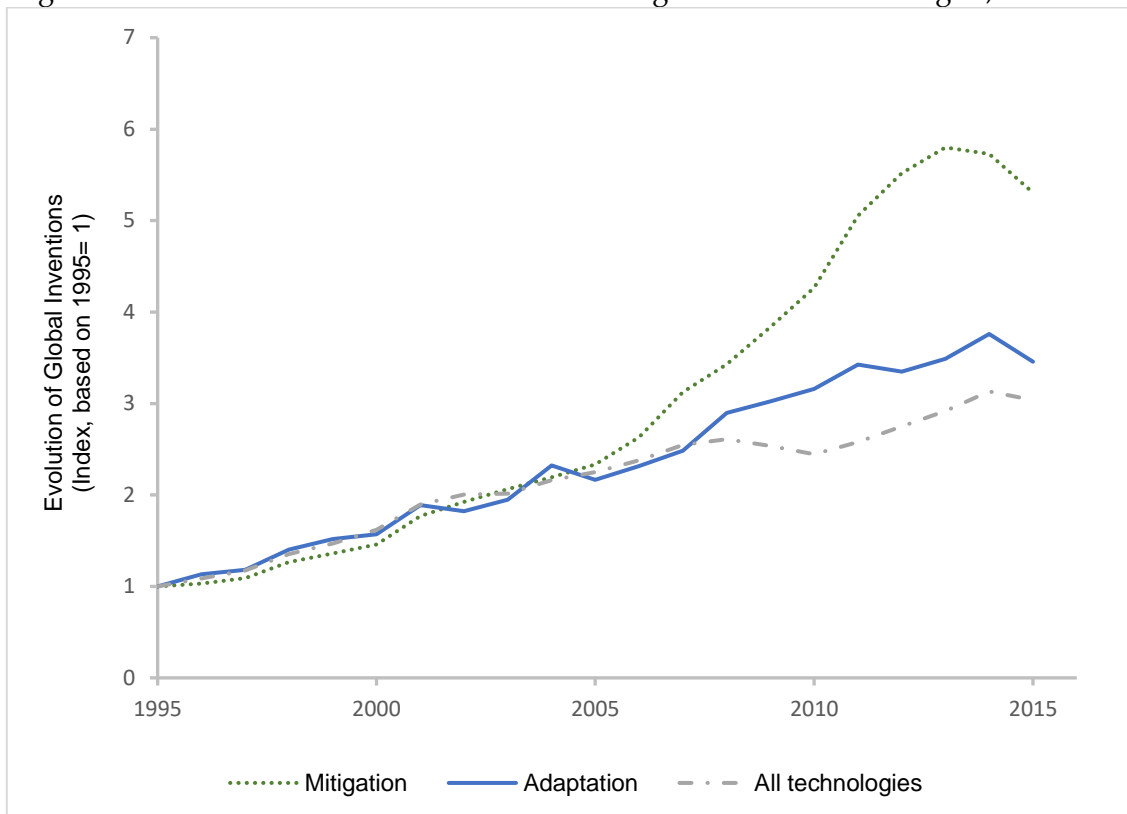
Note: “High-value” patented inventions are filed in at least two patent offices.

The main question when comparing mitigation and adaptation is the pace of innovation.

Figure 2 shows an impressive double-digit annual growth rate over the 1995-2015 period for mitigation-related inventions. Strikingly, the innovation has gone down since its peak in 2013. This rise and fall in innovation in climate change mitigation technologies over the recent period has been documented in previous studies and has been linked to the recent decrease of oil prices (Probst et al. 2021).⁵

⁵ This also explains that the percentage of adaptation-related inventions has gone down since 2012, despite the emerging impact of climate change in many countries. This reduction appears to mostly concern technologies that facilitate both adaptation to climate change and mitigation of carbon emissions such as desalination systems powered with solar panels, or thermal insulation technologies. More than a quarter of the adaptation patents fall into this category. Removing these patents produces a stable percentage (around 0.3 percent of global inventions) throughout the study period (see Figure A 1).

Figure 2. Innovation in Climate Related Technologies and All Technologies, 1995-2015



Source: Authors' calculations based on the World Patent Statistical Database (PATSTAT) data.

Beyond this recent decrease, how to interpret the long-term trend? In particular, how to judge that adaptation-related innovation activity has followed the average trend since 1995? It could be that exposed countries do not need new technologies, but the dissemination of existing solutions and knowledge. We have already challenged this claim above. Put simply, mankind has invented over centuries technological solutions to adapt, it is hard to believe that we do not need to accelerate in this direction when climate change is under way, a key message of the IPCC report on the physical basis of climate change released in August 2021 (IPCC 2021).

The discussion on the difference between the pace of mitigation and adaption innovation leads to qualify this argument. Over the period 2005-2015, innovation in mitigation grew

twice as fast. It is true that reducing carbon emissions is decisive now while most of the climate change, and thereby adaptation, is still to come. The markets for adaptation technologies are thus currently small as suggested by UNEP and IPCC cost estimates mentioned above, an annual cost by 2030 from USD 140 to 300 billion for adaptation against USD 1.5 trillion to 3.5 trillion a year for mitigation. The difference is thus not shocking. In a context where these markets will grow in the future, more public investment is needed to prepare for future adaptation needs. The data suggest that this is what happens: in our sample, the share of patents filed by universities and governmental organizations is 15.5 percent for adaptation against 10.3 percent for mitigation.⁶

Table 2 shows large differences across technology fields. Innovation in the technologies for agriculture adaptation is particularly slow. As indicated by the growth observed for agricultural innovation in general (the third column), this sounds a general trend in the sector. Slow innovation here probably reflects the declining importance of this economic sector in the advanced economies which contribute the most to global innovation. This illustrates the potential existence in all fields of a geographical mismatch. Technological capacities, and thus innovation, are mainly located in the global North while middle-income and low-income countries are and will continue to be more exposed to climate extremes. We explore this hypothesis in the following section by examining the geography of innovation.

⁶ Many of these technologies are also public goods (e.g. infrastructure, floods protection). Again, this may call for more public investment.

Geographic Concentration of Climate Adaptation Innovation

Adaptation innovation appears highly concentrated, with the top five inventor countries (China, Germany, Japan, the Republic of Korea, and the United States) accounting for more than 60 percent of the world’s innovation activity.

Table 3. Top 10 Inventor Countries in Climate Change Adaptation Technologies, 2010–15

| Rank | Country | Average share of world’s high-value adaptation inventions (%) ^a | Country’s top three technology fields |
|------|----------------|--|--|
| 1 | United States | 23.6 | Health, agriculture, indirect adaptation |
| 2 | Japan | 15.8 | Health, agriculture, water management |
| 3 | Germany | 10.8 | Health, infrastructure, agriculture |
| 4 | Korea, Rep. | 7.0 | Health, agriculture, water management |
| 5 | China | 6.5 | Agriculture, health, water management |
| 6 | France | 5.8 | Health, agriculture, infrastructure |
| 7 | United Kingdom | 3.8 | Health, water management, agriculture |
| 8 | Sweden | 2.1 | Agriculture, health, infrastructure |
| 9 | Canada | 2.1 | Agriculture, water management, health |
| 10 | Netherlands | 2.1 | Agriculture, health, infrastructure |

Source: Calculations based on World Patent Statistical Database (PATSTAT) data.

a. “High-value” patented inventions are defined as patents filed in more than one patent office.

The United States is the world leader in adaptation innovation, accounting for nearly a quarter of high-value inventions developed between 2010 and 2015 (Table 3). However, the rapid growth of innovation in China and Korea is notable. These two countries

together produced less than 4 percent of all adaptation inventions in 1995 and increased their shares to 8.9 percent and 7.8 percent, respectively, in 2015.

Such a high geographic concentration is not specific to climate change adaptation. The same top five countries represent 74.3 percent of the world's total patented inventions in all technologies and 75.7 percent of high-value climate mitigation innovations.

The case of China, which ranks fifth in Table 3, deserves further explanation. We discuss here the number of *high-value* inventions, which excludes inventions patented in a single country. If we consider all inventions, including those filed in a single country, China becomes by far the most active inventor in the field, filing more than 48 percent of all adaptation patents in the world, with most of them only filed at home. It is well established that China's patenting behavior is an outlier in that domestic inventors file patents of much average lower quality than in other countries (Boeing & Mueller 2019; Prud'homme & Zhang 2017)⁷.

⁷ The lower quality of Chinese patents is mainly explained by the implementation of policies in China, that aim to incentivise Chinese inventors' patent applications. As an example, the Chinese government subsidies patent filing, leading to a decrease in the cost of patenting and the patenting of lesser economic value technologies.

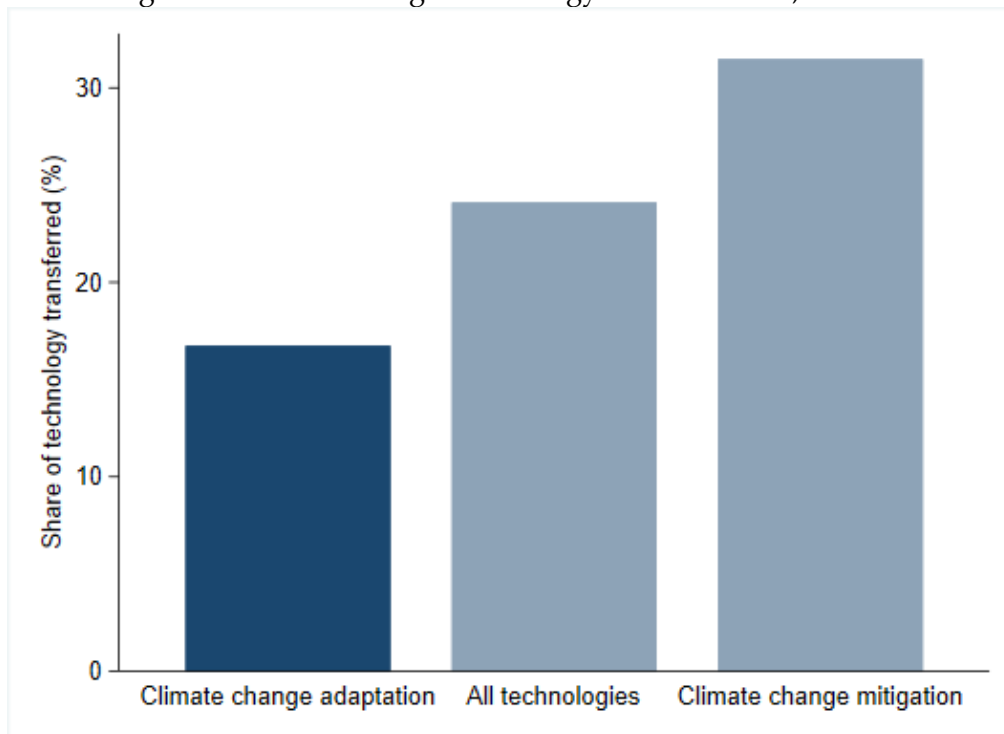
1.4 International Technology Transfer

Cross-Border Technology Transfers

Given the high geographic concentration of innovation in adaptation technologies, it is important to examine to what extent these technologies diffuse across borders, in particular toward countries with the highest adaptation needs. What ultimately matters for countries is access to a technology, and not whether it has been developed in the country.

A first indicator for measuring international diffusion is the share of patented inventions that are filed in at least two different patent offices. The structure of the patent data distinguishes between the inventing (home) and receiving (foreign) countries of a patented invention. The transfer rate is then calculated as the share of a country's inventions that are also filed in at least one foreign country. Figure 3 compares these shares for three technology groups: climate change adaptation, climate change mitigation, and all technologies. With 17 percent of adaptation inventions crossing at least one border, this number is much less than the average for all technologies (24 percent) and about half that of mitigation technologies (31 percent).

Figure 3. Global Average Technology Transfer Rates, 2010–15



Source: Calculations based on World Patent Statistical Database (PATSTAT) data.

Note: The technology transfer rate is the share of a country's technology patents that are also filed in at least one other country.

This low diffusion rate could be explained by two sets of nonexclusive factors: (a) high barriers to technology transfer (such as tariffs, lax IP enforcement, and limited technological capabilities in potential recipient countries); and (b) lower applicability in the sense that individual innovations are not suited to different contexts. The data do not fit with these interpretations. Those inventions that do cross at least one border are patented in around five patent offices on average, a figure broadly similar to the rates for climate change mitigation technologies and for technology overall (Table 4). How, then, can we explain the low transfer rate in Figure 3? A consistent explanation would be that the *average* value of individual adaptation patents is low in relative terms, thereby being less likely to warrant foreign patenting.

Table 4. Average Number of Patent Offices Where Internationally Patented Inventions Are Filed, by Technology Type, 2010–15

| Technology field | Average number of patent offices^a |
|-------------------------------|---|
| All climate change adaptation | 4.88 |
| Coastal and river protection | 4.50 |
| Water management | 4.54 |
| Infrastructure | 4.05 |
| Agriculture | 5.46 |
| Health | 4.80 |
| Indirect adaptation | 5.15 |
| All technologies | 4.46 |
| All climate change mitigation | 4.51 |

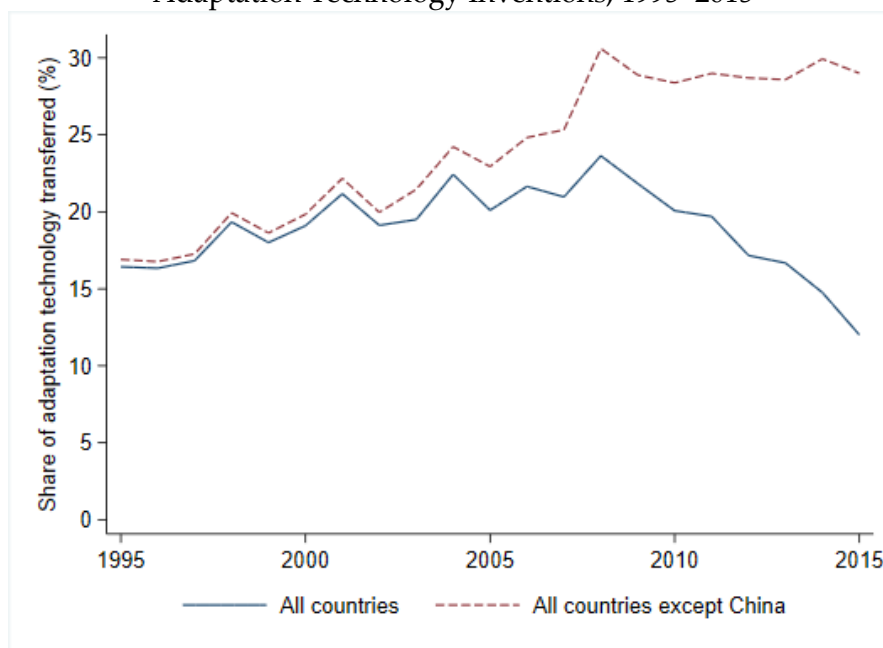
Source: Calculations based on World Patent Statistical Database (PATSTAT) data.

Note: The table includes only inventions patented in at least two countries.

a. The number of patent offices is the number of offices where an international patent (a patent filed in at least one foreign country) is filed.

The share of inventions patented in at least two offices decreased by half between 2008 and 2015 (Figure 4). This drastic reduction corresponds to the Chinese patenting boom, which is mostly composed of domestic patents. This boom pertains to all technologies and can thus be observed in all fields. As shown by the dashed line, Figure 4 indicates no decrease once China is excluded.

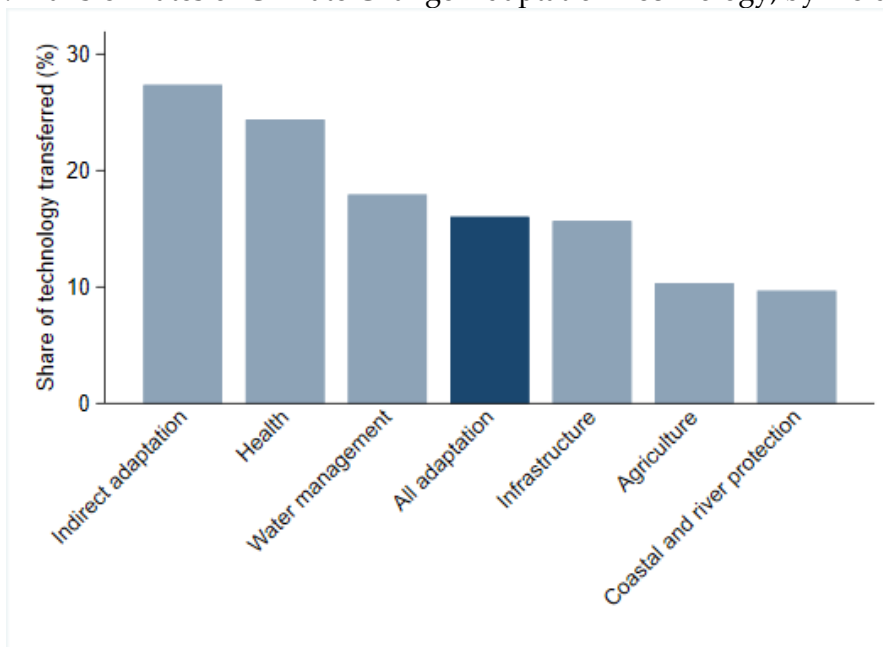
Figure 4. Trends in Climate Adaptation Technology Transfer as a Share of All Adaptation Technology Inventions, 1995–2015



Source: Calculations based on World Patent Statistical Database (PATSTAT) data.

Note: Technology transfer refers to the share of technology patents filed in more than one country.

Figure 5. Transfer Rates of Climate Change Adaptation Technology, by Field, 2010–15



Source: Calculations based on World Patent Statistical Database (PATSTAT) data.

Note: The technology transfer rate is the percentage of patents filed in more than one country. “Indirect adaptation” refers to technologies that contribute indirectly to climate change adaptation, such as climate simulation tools, weather forecasting, and weather surveillance systems.

Looking at Figure 5, we find relatively large differences across sectors. Climate adaptation technologies related to agriculture (10.3 percent) and coastal and river protection (9.7 percent) are transferred less often than the average adaptation technology (17 percent). In contrast, indirect adaptation and health adaptation patents are transferred more regularly, each with more than 24 percent of patented inventions filed in more than one country.

Technology Transfers by Country Income Group

Table 5 gives a more detailed view of international technology flows by considering transfers between different income groups. It also displays the average score for overall technology transfers as a benchmark (in parentheses).

Table 5. Distribution between Country Income Groups of Patented Inventions of Technologies for Climate Change Adaptation, 2010–15 (in percent)

| Origin country | Destination country | | |
|----------------|---------------------|------------------|------------|
| | High income | Middle income | Low income |
| High income | 66 (69) | 27 (24) | 0 (0) |
| Middle income | 5 (7) | 1 (<1) | 0 (0) |
| Low income | <0.1 (<0.1) | <0.01 (<0.01) | 0 (0) |

Source: Calculations based on World Patent Statistical Database (PATSTAT) data.

Note: Distributions are the percentages of patents filed in both an origin country and at least one destination country. Results for all technologies appear in parentheses.

A first notable fact is the overwhelming importance of high-income countries: 93 percent of all exported technologies for climate change adaptation originate from these countries, which also receive 71 percent of all exported inventions. In contrast, low-income countries receive virtually no foreign-patented technologies. As mentioned

previously, it could be that foreign inventors protect their technologies transferred toward low-income countries through secrecy (or do not protect them at all).

As for middle-income countries, they receive 28 percent of all adaptation transfers, the vast majority of which comes from high-income countries, with China accounting for half of these inward transfers. These flows have sharply increased recently: their share was only 7 percent in 1995. However, although China and other middle-income countries have become significant recipients, they export few of their patented technologies.

These numbers are comparable with the distribution averages for all technologies (shown within parentheses), except for the slightly higher role of middle-income countries as technology recipients, which is mostly due to China's particularly high rate as a destination for adaptation patents.

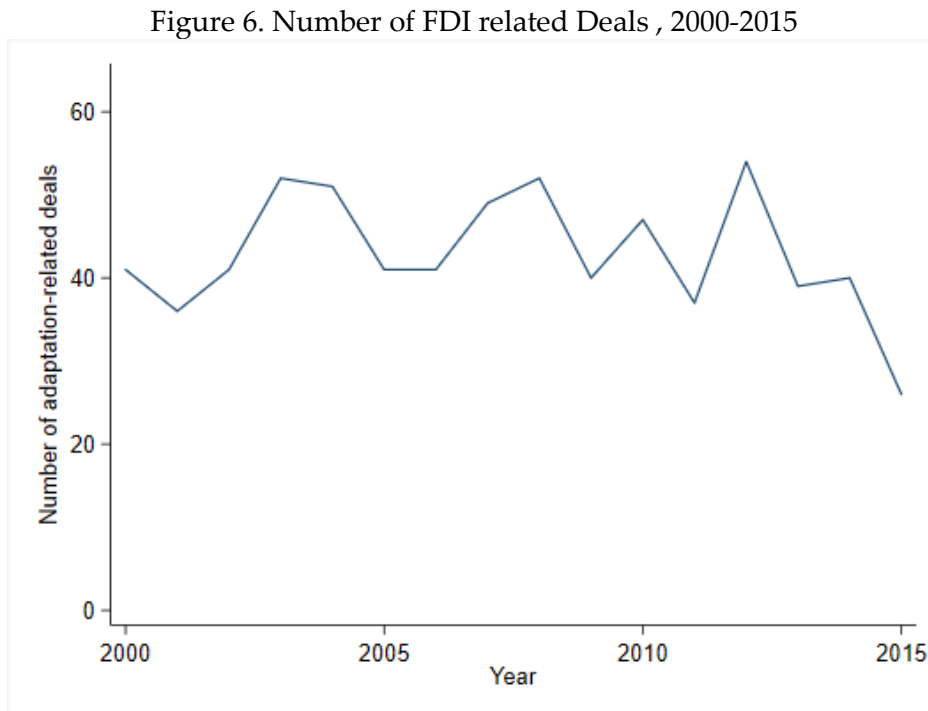
Cross-Border Transfers using FDI measures

To test the robustness of the patent-based results, we also study technology transfers through foreign direct investment (FDI). The objective is to confront the results obtained using patent data with another indicator.

We extract information on FDI deals for the period 1995–2015 from the Zephyr database provided by business publisher Bureau Van Dijk.⁸ Following the methodology of Dussaux et al. (2018), we identify deals where the acquiring firm have filed at least one

⁸ See <https://www.bvdinfo.com/en-gb/our-products/data/specialist/zephyr>.

adaptation patent in the country of the target firm. We then use information on target firms' industrial activity, using the NACE Rev. 2 classification,⁹ to identify activities with a potential link to adaptation technologies (see Annex 3. in the appendix for more details).



Sources: Calculations based on data from Zephyr database (Bureau Van Dijk, Brussels)

The FDI analysis confirms the picture drawn from the patent statistics. The annual number of foreign investment deals that are likely to involve transfer of adaptation technology is roughly constant over the period 2000-2015 (Figure 6). This trend is not

⁹ "NACE Rev. 2" refers to Statistical Classification of Economic Activities in the European Community (NACE, for the French "*nomenclature statistique des activités économiques dans la Communauté européenne*"). It is the [industry standard classification system](#) used in the European Union.

fundamentally different over the same period from the one displayed in Figure 4 which shows the evolution of foreign patenting.

Table 6 compares the share of FDI adaptation deals with the share of international adaptation patent flows (in parentheses) between different country income groups. The situation is broadly similar with a prevalence of deals between high-income countries. This geographical concentration of FDI deals is even stronger than that indicated by patents. Interestingly enough, China receives twice as many FDI adaptation related deals (19% of FDI adaptation deals made worldwide versus 9% of all adaptation patents transferred).

Table 6. Flow of FDI Deals in Climate Change Adaptation Technologies between Country Income Groups, 2010–15 (in percent)

| Origin country | Destination country | | |
|----------------|---------------------|---------------|--------------|
| | High income | Middle income | Low income |
| High income | 73 (66) | 27 (27) | 0 (<0.01) |
| Middle income | 0 (5) | 0 (1) | 0 (0) |
| Low income | 0 (<0.1) | 0 (<0.01) | 0 (0) |

Sources: Calculations based on data from Zephyr database (Bureau Van Dijk, Brussels) and World Patent Statistical Database (PATSTAT).

Note: Results for cross-border transfers of climate change adaptation patents appear in parentheses. N = 243 deals. FDI = foreign direct investment.

1.5 Patenting Activity in Relation to Climate Hazards

Measuring Climate Risks

We next explore the extent to which the patterns of innovation and technological diffusion documented in the previous sections correspond to countries' needs for adaptation technology. Those needs depend in turn on the physical climate risks a country faces.

The Intergovernmental Panel on Climate Change (IPCC) defines climate change risk as “[the] probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur” (IPCC 2014). Risk results from the interaction of three factors: *hazard* (the possible future occurrence of extreme weather and climate events); *exposure* (the inventory of people and economic, social, or cultural assets in places that could be adversely affected); and *vulnerability* (the propensity of exposed elements to suffer adverse impacts).

For both data and conceptual reasons, we use natural hazard indicators as the only unambiguously exogenous factor of climate risk. The degree of vulnerability is influenced by technological capabilities, potentially leading to tautological results. The level of exposure also raises endogeneity concerns (for example, technologies may help people to relocate away from the most-exposed areas) and data availability problems.

No ready-to-use set of indicators quantifies the level of all hazard types at the country level. We therefore combined multiple data sources (see Table 7). We computed our indicators by averaging the value of the raw indicator by country over the period and

then normalized the obtained score between 0 and 1, following the ND-Gain methodology (University of Notre Dame, 2015). A score equals to 0 means no exposure to hazard, whereas 1 corresponds to the maximum of hazard exposure among countries. Hazards were classified into five threats, similar to the hazard typology of IPCC (2014), but with some amendments to facilitate the correspondence with the patent classification. They are summarized in Table 7, and detailed in the appendix (Annex 4). Four of the five indexes are based on projections of future climatic change¹⁰. The only exception is storm risk, which is based on historical events for data reasons. The implicit assumption is that historic shocks are positively correlated with future ones.

The average overall hazard score for both high and middle income countries is roughly the same (around 0.29). It is important to keep in mind that the indicators express risks in physical terms, not adaptation capacities. These numbers thus do not contradict the adaptation literature which has documented a wide adaptation gap between these two groups of countries (Barbier and Hochard 2018; Fankhauser and McDermott 2014; Tol 2018). They also hide significant disparities across hazard categories with high-income countries being more exposed to storms while middle-income countries are more likely to experience heatwaves.

¹⁰ Due to data availability, the droughts indicator is a short-term projection for the period 2020-2040 only.

Table 7. Definitions and Data Sources of the Five Hazard Indicators

| Indicator | Definition | Source |
|----------------------|---|--------------------------|
| Sea level rise | Proportion of land areas, adjacent to the ocean, that are lower than the sea level rise and the average height of storm surge projected by the end of the century | ND-GAIN |
| Temperature extremes | Warm spell duration index (WSDI): periods of excessive warmth using a percentile-based threshold calculated for a five-day calendar window; projected for 2040–70 under the RCP4.5 scenario | Climdex |
| Floods | RX5DAY: monthly maximum precipitation over five consecutive days (mean per year); projected for 2040–70 under the RCP4.5 scenario | Climdex |
| Droughts | Change in annual runoff from the baseline projection to the future projection; projected for 2020–40 under the RCP4.5 emission scenario | Aqueduct |
| Storms | Historical number of storms per capita for the period 1900–2015 | EM-DAT |

Note: Aqueduct = <https://www.wri.org/aqueduct> of the World Resources Institute. Climdex = <https://www.climdex.org/>. EM-DAT = Emergency Events Database of the Centre for Research on the Epidemiology of Disasters. ND-GAIN = University of Notre Dame Global Adaptation Index. RCP4.5 = Representative Concentration Pathway of the IPCC with a greenhouse gas concentration trajectory that stabilizes radiative forcing at 4.5 W m⁻².

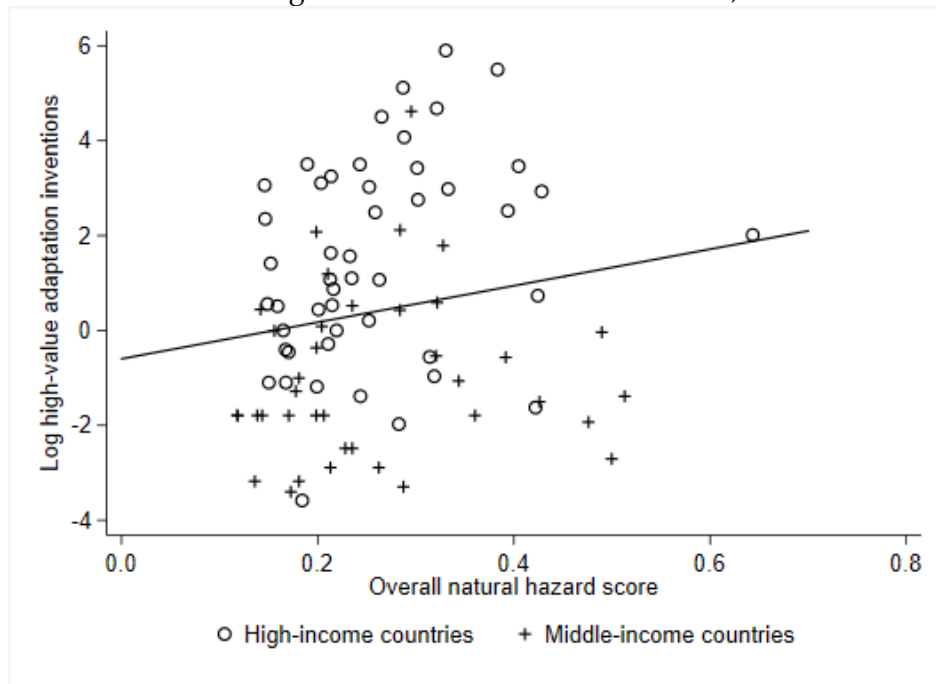
Technology innovation and climate risks

We can now compare the invention of new adaptation technologies to expected climate risks. Figure 7 shows the relationship between a country’s level of patented invention (y-axis) and the average hazard index (x-axis). This hazard index features the arithmetic mean values of the five indicators listed in Table 7, each being normalized so that they range from 0 to 1¹¹. A slight positive, but not statistically significant correlation is observed with no significant differences across income country groups. Focusing on the countries with the highest hazard scores, we see that almost all middle-income countries

¹¹ Choosing an arithmetic mean is conventional. Using a more sophisticated weighting rule would require more data and be less transparent

in this group produce little innovation (they are below the regression line), while high-income countries such as Australia, Japan, Korea, Singapore, and the United States exhibit strong innovation outputs.

Figure 7. Relationship between Adaptation Technology Invention and Climate Hazards in High- and Middle-Income Countries, 2010–15



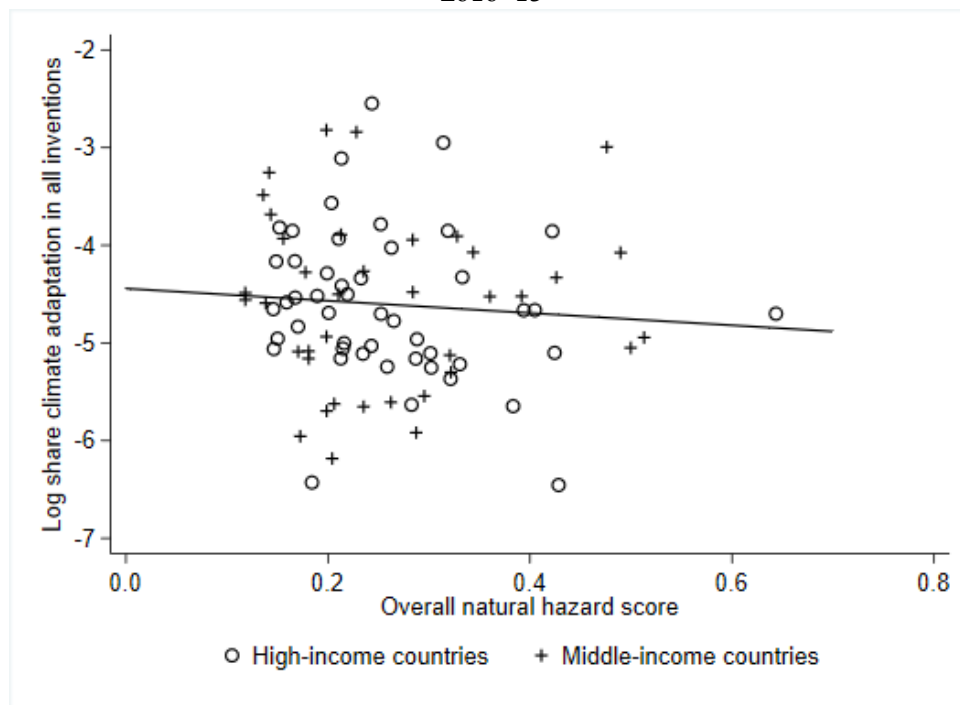
Sources: Calculations based on World Patent Statistical Database (PATSTAT) and hazard indicators (see Table 7).

Note: Each point describes an individual country. Country income categories use World Bank-defined classifications. Low-income countries are excluded for lack of sufficient patent data. The log number of inventions is the 2010–15 annual average. The hazard index is the arithmetic mean of the five hazard indicators listed in Table 7, each being normalized to range from 0 to 1.

Availability of Adaptation Technology by Country Income Level

What drives this gap between middle-income and high-income countries? It could simply reflect the differences in general innovative capacity. Figure 8 supports this statement, as the gap disappears as soon as innovation for adaptation is expressed as a share of total patents. A quasi-flat regression line however provides no evidence of R&D directed toward adaptation. We observe the same trend across the two income groups.

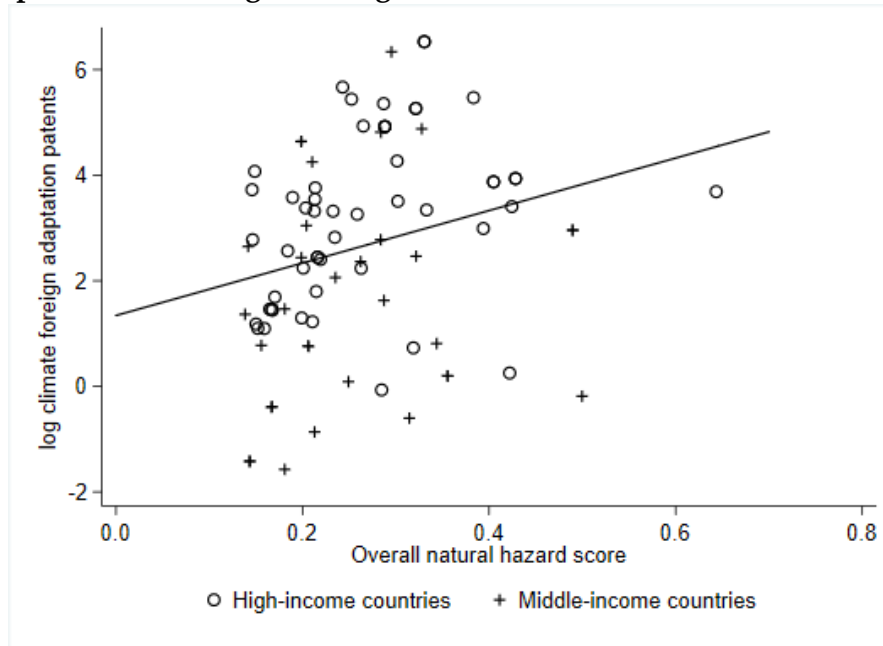
Figure 8. Relationship between Climate Hazards and Adaptation Technology Inventions (as a Share of All Technology) in High- and Middle-Income Countries, 2010–15



Source: Calculations based on World Patent Statistical Database (PATSTAT) and hazard indicators (see Table 7).

Note: Each point describes an individual country. Country income categories use World Bank-defined classifications. Low-income countries are excluded for lack of sufficient patent data. The vertical axis shows the number of adaptation inventions made in the country as a share of all technology inventions made in this country (2010–15 annual average). The hazard index is the arithmetic means of the five hazard indicators listed in Table 7, each being normalized so that they range from 0 to 1.

Figure 9. Relationship between Climate Hazards and Imports of Climate Change Adaptation Technologies in High- and Middle-Income Countries, 2010–15



Sources: Calculations based on World Patent Statistical Database (PATSTAT) and hazard indicators (see Table 7).

Note: Each point describes an individual country. Country income categories use World Bank-defined classifications. Low-income countries are excluded for lack of sufficient patent data. The vertical axis shows the log number of foreign climate change adaptation inventions patented in the country (2010–15 annual average). The hazard index is the arithmetic means of the five hazard indicators listed in Table 7, each being normalized so that they range from 0 to 1.

The availability of technologies for adaptation to climate change is not only a matter of domestic innovation. Countries may also benefit from imports of technologies invented abroad. Do inward flows of foreign technologies compensate for this domestic innovation deficit? Probably not. Figure 9 represents the number of adaptation patents imported by each country as a function of its exposure to overall climate hazard. The slope of the regression line is not fundamentally steeper (+ 0.25 against +0.17 in Figure 7) and statistically significant. However, most middle-income countries again remain below the regression line. Importantly, this technology gap is not specific to adaptation technologies: the average share of a country’s foreign adaptation inventions in its total

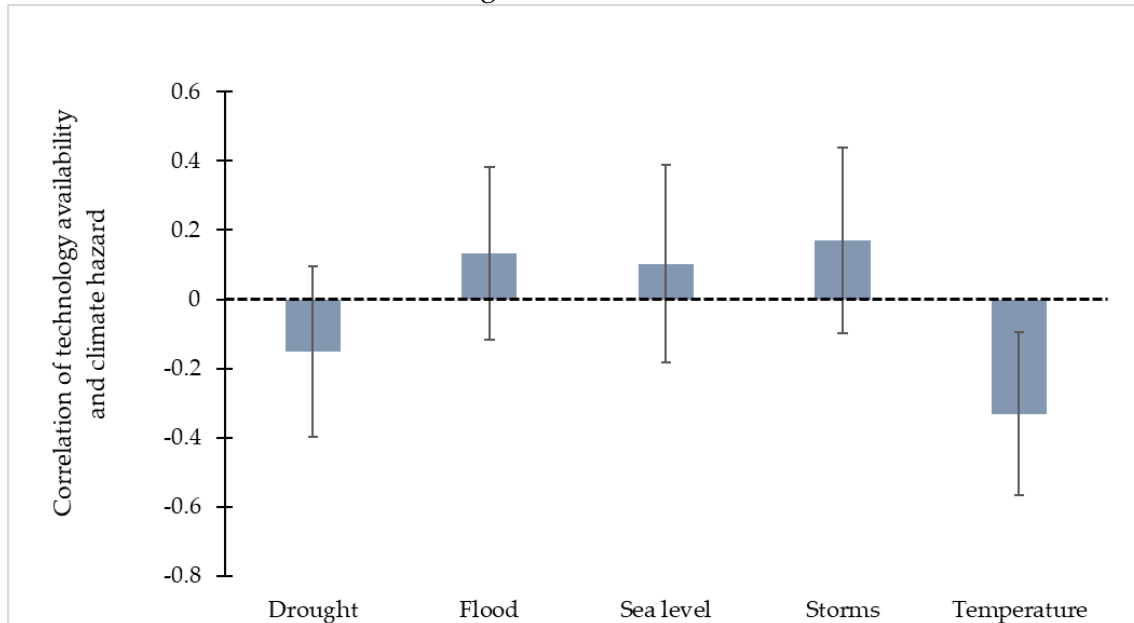
number of inventions received is roughly the same in high-income countries (0.98 percent) as in middle-income ones (0.92 percent).

Availability of Adaptation Technology, by Climate Hazard Type

Beyond this general view, the data also allow us to identify the types of hazard with the widest gaps between the need for and access to new climate adaptation technology. For each of the five hazard types, Figure 10 displays the correlation coefficient between the availability of patented technology (the sum of high-value domestic inventions and imported patented inventions) and hazard levels in high- and middle-income countries. Recall that a correlation is -1 in case of perfect negative correlation and $+1$ in case of perfect positive correlation.

One hazard type shows a statistically significant negative correlation: temperature extremes. The technologies to mitigate this risk include greenhouse technologies, plant varieties adapted to hot environments, aquaculture, and air conditioning technologies. Other correlation coefficients are not significantly different from zero.

Figure 10. Correlation between Availability of Advanced Adaptation Technologies and Climate Hazard Levels in High- and Middle-Income Countries, 2010–15



Sources: Calculations based on World Patent Statistical Database (PATSTAT) and hazard indicators (see Table 7).

Note: The technology variables are averages for the period 2010–15. “Technology availability” is the sum of high-value adaptation inventions (that is, with patents filed in at least two countries) made by a given country and the patents imported by that country. Vertical black lines represent confidence intervals at the 95 percent level.

These patterns could reflect the influence not only of adaptation needs but also of countries’ technological capabilities. In this respect, countries with strong technological capabilities (like China, Japan, western European countries, and the United States) are less exposed to heatwaves than countries such as Costa Rica, Ecuador, and Peru, which have low technological capabilities.

In the climate change negotiations, international funding is viewed as a major tool to increase the local demand for adaptation technologies (UNFCCC 2018). This does not apply to the set of countries studied in the present paper: most bilateral funding

dedicated to adaptation projects¹² are sent to low-income countries with no patenting activity (75 percent of adaptation funding available during the period 2010-2018 are dedicated to projects in countries that do not invent nor receive any patents).

1.6 Conclusion

This paper provides a global snapshot of innovation in, and the international diffusion of, technologies for adaptation to climate change. The reliance on patent data restricts the analysis to adaptation solutions that are at the technological frontier and ignores the role of non-technological forms of innovation and low-tech options. Nevertheless, some important patterns emerge.

Globally, the number of patented inventions in adaptation technologies increased steadily between 1995 and 2015. However, this increase in absolute terms does not translate into a proportional rise in innovation for climate adaptation. When considering the total number of inventions across all technologies in all fields, the share of climate adaptation inventions in 2015 was roughly the same as in 1995. This stagnation of research and development (R&D) efforts toward adaptation stands in sharp contrast to the trend for climate change mitigation technologies, whose share in total (including non-climate-related) innovation nearly doubled during the same period.

¹² For these data, see the Excel files for “Climate-related development finance at the activity level, recipient perspective” on the OECD web page, “Climate Change: OECD DAC External Development Finance Statistics”: <http://www.oecd.org/dac/financing-sustainable-development/development-finance-topics/climate-change.htm>.

Adaptation innovation is concentrated within a limited number of countries. China, Germany, Japan, the Republic of Korea, and the United States together account for nearly two-thirds of all high-value inventions (inventions seeking patent protection in more than one country) filed globally between 2010 and 2015.

This concentration of innovation activity could in principle be compensated by international technology transfer from innovating countries. However, the data reveal limited international technology diffusion through the patent system. Few adaptation inventions are transferred across borders, compared with climate change mitigation technologies and non-climate-related innovations. The international diffusion of adaptation technologies related to agriculture and coastal and river protection is particularly low. It is unclear whether this is because technologies for adaptation are less applicable outside the innovating country than other technologies or because there are higher barriers to their international diffusion.

Cross-border transfers of patented inventions for climate change adaptation predominantly occur between a small group of countries consisting of high-income economies and China. There is virtually no transfer of patented knowledge to low-income countries. To the extent that there is international access to adaptation technologies, it occurs outside the patent system. This pattern is not specific to adaptation technologies. The innovation literature has shown that low-income countries typically rely on low-tech solutions and organizational innovations.

However, our results suggest a mismatch between countries' adaptation needs and technology availability. Innovation and technology diffusion do not seem to be driven

by adaptation needs but by the level of recipient countries' technological absorptive capacities. This could be bad news for global climate resilience, since the countries with weakest technological capacities typically face the highest adaptation needs. This stands in contrast with climate change mitigation. Geography ultimately matters here: innovation for mitigation works better because the needs for mitigation are proportionally much larger in industrialized countries (incl. China) where carbon emissions are concentrated, and these countries have the capabilities to develop and disseminate these technologies. The needs for climate change adaptation are more evenly distributed.

From these observations follow two important policy implications. First, technological capacity building is an essential ingredient to climate change adaptation, although it is of course not a need that is specific to adaptation technologies. Second, economic forces seem unable to transform local adaptation needs into demand for adaptation technology on the markets. Solving this problem requires a better understanding of the market failures that hinder demand, a precondition for designing demand-pull policies in the relevant sectors (with public investments, subsidies, and other policy tools).

The analysis raises more questions than answers. It points to several avenues for future research. The first and most important one is to conduct sector-specific studies to identify the factors that hinder the functioning of the markets for these patented technologies. This is the level of analysis required to derive sound policy recommendations. The second research gap concerns the contribution of these technologies to climate change adaptation in the Global South. How crucial are such frontier innovations? How do they

relate to low-tech solutions and other forms of innovation? How do economic incentives shape technology adoption? Third, the data used in this study include very disaggregated information that could be exploited to better identify which patents are relevant in a given sector or national context. Combined with country-level technology needs assessments, it could be exploited to prioritize the transfer of the most useful patents. These are the initial elements of a research agenda to increase the contribution of technical progress to climate change adaptation.

2 Can Technology Reduce the Impact of Tropical Storms?

Matthieu GLACHANT, Alexandre THOMAS and Simon TOUBOUL

Abstract

This paper provides evidence on the effectiveness of technologies to reduce tropical storm impact. Using the recently released Y02A PATSTAT patent classification to select storm adaptation technologies, we build a panel of ten countries for the period 1990-2015. We match data on both people and assets affected by 366 storms with impact data from EM-DAT, and then aggregate them at the country level. We find that technologies significantly reduce both the number of storm-induced fatalities and the amount of economic damages.

Keywords: climate change adaptation, innovation, extreme weather events, adaptive capacity, technology

JEL codes: O33; O57; Q51 ; Q54; Q55 ; C33

Résumé

Dans ce chapitre, nous évaluons l'efficacité des technologies comme moyen de réduire l'impact des tempêtes tropicales. En utilisant la classification des brevets PATSTAT Y02A, nous sélectionnons les technologies d'adaptation liées aux tempêtes. Nous utilisons un panel de dix pays pour la période 1990-2015. Nous avons accès au nombre de personnes et à la valeur des biens affectées pour chacune des 366 tempêtes sélectionnées, que nous relierons aux dommages humain et matériel causés par chacune de ces tempêtes disponibles dans la base de données EM-DAT. Nous constatons que les technologies réduisent de manière significative à la fois le nombre de décès causés par les tempêtes et le montant des dommages économiques.

CHAPTER 2

Can Technology Reduce the Impact of Tropical Storms?

2.1 Introduction

According to the report by the Center for Research on Epidemiology of Disasters (CRED) and UN Office for Disaster Risk Reduction (UNDRR) (2020), storms¹³, including hurricanes, cyclones and storm surges, killed nearly 200,000 people between 2000 and 2019. The storm that hits Myanmar in 2008 caused 138,000 fatalities alone (UNEP 2009). Over the same period, recorded economic damages amounted to US\$ 1.39 trillion, well ahead of floods, the second costliest type of natural disaster. The report also emphasizes that, given under-reporting worldwide, these figures extracted from the reference EM-DAT database underestimate the actual losses.

Mendelsohn et al. (2012) forecast that climate change will double these damages by the end of the century. In many cases, people, enterprises and governments will adapt to the increase in storm frequency and intensity by changing their behavior, such as moving to a new location, planting windbreaks, or investing in dams or more residential buildings. When doing so, they will rely on technologies increasing resilience to storms, such as advanced weather forecasting tools and coastal protection technologies (Klein & Tol 1997).

¹³ A storm is entered into the EM-DAT database if it fulfills at least one of these criteria: Ten or more people reported killed, one hundred or more people reported affected, declaration of a state of emergency, call for international assistance

Although innovation is likely to have a sizable effect on climate change impacts in the long run, the role of technology in climate change adaptation has received little attention. Among the exceptions, Dechezleprêtre et al. (2020) provide evidence on the geographic distribution and global diffusion of technologies for climate change adaptation based on global patent data. They show that the availability of technologies that mitigate storm impacts in individual countries is not significantly correlated with local storm risks. This may be a serious problem if technologies are effective tools for reducing storm impacts. The empirical literature is almost mute on this question. Miao (2017) examines the impact of patented inventions on human costs, but deals with earthquakes.

The main contribution of this paper is to fill this gap by evaluating the effectiveness of technologies in reducing economic damages and fatalities caused by tropical storms. We investigate whether the increase in storm related technology observed over the past decades has led to a decrease in storm impacts. To answer this question, we rely on longitudinal data describing 366 tropical storms in ten countries for the period 1990-2015. The amount of technologies available in each country is measured by the local stock of patented inventions that can mitigate storm impacts. These patents are identified using the Y02A patent classification recently made available by the European patent Office (EPO). We then combine those with storm-level economic losses and deaths extracted from the EM-DAT database.

A first identification issue is to control for the magnitude of individual events. The power and geographical extent of a storm obviously influence the level of its human and economic impacts. The repercussion are also likely to be correlated with local innovation stocks as innovators presumably infer from the occurrence of storms that their frequency and power will increase in the future, justifying more innovation and patenting. Miao and Popp (2014)

provide empirical evidence of this relationship. We control for storm magnitude by exploiting information taken from the TCE-DAT database on the number of individuals or assets exposed to each storm over the study period (Geiger et al. 2018), along with data from the International Best Track Archive for Climate Stewardship (IBTRACS) version 4.0, which provides gridded data on storm tracks (Knapp et al. 2010), allowing us to precisely identify people or assets exposed to various wind speeds.

Second, the occurrence of past and current storms is serially correlated. The problem is that we measure technology availability with the stock of past inventions, which is also influenced by both past and current storms. This leads us to include past exposures in the model. Note that this variable captures different aspects: a form of learning-by-experiencing of the exposed populations, governments, and businesses that improves their resilience to future weather shocks (Miao 2019), or more negatively, the persisting effect of damages to assets.

We find that technology availability significantly reduces storm-induced fatalities. On average, a ten percent increase in country's patent stock lowers the number of deaths by 7.3 percent. The same increase in patent stock reduces the amount of damage to assets by 7.5 percent, corresponding to an average annual saving of more than US\$ 369 million per country.

As argued before, while many studies evaluate both the direct and indirect impact of storms (Baldwin et al. 2020; Hallegatte 2020; Mohan & Strobl 2021a,b), there is limited economic research on the links between climate extremes and innovation. Two additional studies are however worth mentioning. In contrast with our contribution, both examine the other direction of the causal relationship, i.e. whether natural disasters promote innovation for adaptation. We mentioned above the work by Miao and Popp (2014), who link floods, droughts and earthquakes to patented mitigation technologies. Using this data in a panel

study of 28 countries, they find that recent and severe events boost risk-mitigating innovation. However, Touboul (2021) nuances these results, finding a smaller effect of these events on invention of adaptation technologies, but also on imports of such technologies.

We organize the rest of the paper as follows. First, we describe the data used in this analysis. We then define the methodology used to answer our research question. The next section presents the main results. In the last section, we conclude by summarizing and discussing the results. We also stress the limitations of our study and provide some policy implications.

2.2 Data

Patent data

Patent data are commonly used to measure innovation and technology availability. Other innovation indicators used in the literature are available, including R&D spending, the number of researchers per inhabitant, and the percentage of a country's population that has pursued tertiary education. However, the detailed information contained in patent documents and the way the patent system works make them particularly suitable for this study.

Their main advantage is that each patented invention is classified in a very detailed nomenclature. This makes it possible to identify patents that protect technologies specifically related to adapting to storms and cyclones. In practice, we rely on the World Patent Statistical Database (PATSTAT), maintained by the European Patent Office (EPO), which covers nearly all of the patents filed globally. In April 2018, the EPO released the Y02A classification, which

tags climate change adaptation patents¹⁴. The classification contains six technological subcategories (e.g., “10: coastal and river protection”), themselves divided into numerous items (e.g., “10/14: Sea-walls, surge or tidal barriers” or “10/27: Restoration or protection of coral reefs”)¹⁵. We identify in Y02A the codes pertaining to technologies relevant for storm impact mitigation, i.e. technologies designed to protect people or assets against storm surges, flooding, or strong winds. The full list is given in Table 8 below. We then use these codes to extract the storm-related patents from PATSTAT. The selected storm technologies include real time meteorological measuring technologies, extreme weather resilient electric equipment, water pollution control technologies, and weather surveillance systems. These technologies represent 0.03% of all the inventions patented over the period 1990-2015.

PATSTAT reports the country where the technology is invented, and also gives information on all countries where that invention is protected. As a patent confers an exclusive right to commercially exploit the invention for a certain period of time in the country in which it is filed, a foreign inventor filing a patent in a country signals his or her intention to deploy the protected technology there. Inventions patented by foreign innovator(s) thus feed into the local stock of technologies. Accordingly, our indicator of technology availability takes into account these imported inventions.

¹⁴ https://worldwide.espacenet.com/classification?locale=en_EP#!/CPC=Y02A

¹⁵ The detailed classification is available here: <https://www.cooperativepatentclassification.org/cpc/scheme/Y/scheme-Y02A.pdf>

Table 8. List of Selected Storm Adaptation Technologies

| Technology | Share of storms technologies | Number of technologies | CPC code |
|--|------------------------------|------------------------|-----------|
| Active motion dampening for ports | 5.5% | 825 | Y02A30/36 |
| Artificial reefs | 0.4% | 66 | Y02A10/26 |
| Beach nourishment | 0.8% | 123 | Y02A10/21 |
| Breakwaters | 11.2% | 1677 | Y02A10/15 |
| Cabinets/switch boards | 0.3% | 43 | Y02A30/19 |
| Cliff stabilization | 1.5% | 226 | Y02A10/24 |
| Coastal areas monitoring | 0.3% | 48 | Y02A10/41 |
| Computerized floods control | 3.1% | 466 | Y02A10/46 |
| Disaster preparedness plans | 0.4% | 66 | Y02A10/44 |
| Dune restoration/creation | 0.2% | 24 | Y02A10/23 |
| Dykes, Dams | 1.6% | 239 | Y02A10/13 |
| Early warning systems extreme events | 2.6% | 394 | Y02A50/12 |
| Elevated buildings | 0.5% | 80 | Y02A30/23 |
| Evacuation systems / Curb floodplain | 0.6% | 95 | Y02A10/39 |
| Extreme weather resilient electric equipment | 11.4% | 1699 | Y02A30/14 |
| Floating houses | 0.5% | 78 | Y02A30/21 |
| Floods prevention | 0.3% | 46 | Y02A10/30 |
| Groynes | 0.2% | 34 | Y02A10/17 |
| Hazard insurance | 0.2% | 33 | Y02A10/48 |
| Improve land use | 2.5% | 371 | Y02A40/22 |
| Jetties | 0.6% | 88 | Y02A10/18 |
| Permanent floods barriers | 0.5% | 78 | Y02A10/31 |
| Protection/Restoration coral reef | 0.2% | 24 | Y02A10/27 |
| Pump floods draining | 0.8% | 113 | Y02A30/45 |
| Real time meteorological measuring | 5.6% | 834 | Y02A90/14 |
| Resilient generators | 1.8% | 268 | Y02A30/17 |
| Resilient IT infrastructure | 2.2% | 330 | Y02A30/50 |
| Revetments of the shore | 0.5% | 69 | Y02A10/16 |
| Sea-walls | 1.2% | 181 | Y02A10/14 |
| Sediment management | 0.8% | 124 | Y02A10/28 |
| Storm resilient vessel | 0.5% | 73 | Y02A30/35 |
| Storms shelters/cellars | 5.1% | 762 | Y02A50/14 |
| Temporary floods barriers | 0.2% | 32 | Y02A10/32 |
| Uninterruptible power supply (UPS) | 0.1% | 10 | Y02A30/18 |
| Water pollution control | 16.7% | 2492 | Y02A20/20 |
| Water resources protection | 0.1% | 9 | Y02A20/40 |
| Water supply / treatment | 0.9% | 133 | Y02A30/40 |
| Weather geographic databases/models | 2.2% | 334 | Y02A90/15 |
| Weather surveillance systems | 10.0% | 1486 | Y02A90/18 |
| Weather surveillance systems | 5.1% | 760 | Y02A90/19 |
| Wetland restoration/creation | 0.6% | 83 | Y02A10/22 |

A well-known weakness¹⁶ of patent data is that the unit value of individual patents varies considerably. Simply counting all patented inventions thus provides a noisy measure of technological availability (Dechezleprêtre et al. 2017). To mitigate the problem, we adopt the common solution consisting in counting only the so-called High-Value Inventions (HVI), i.e., inventions filed in at least two countries (Dechezlepretre et al. 2020; Pigato et al. 2020). The cost of patenting in a first country is in fact much lower than the cost of extending protection to other countries. An extension therefore signals that the holder considers the prospects for commercial exploitation of the invention to be sufficient. HVIs represent around half of all inventions over the period 1980-2015. This restriction is particularly important as we include China in our analysis. This country is known to permit the filing of lower-value patents compared to the European and United States patent offices (Boeing & Mueller 2015, 2016). In addition to the restriction to HVIs, we also use country fixed-effects to control for differences in patenting rules across patent offices.

The technology availability variable is $TECH_{it}$, which is the discounted stock of HVI storm-related inventions patented in country i in year t . This variable is constructed using the standard recursive formula:

$$TECH_{it} = PATENT_{it} + \delta TECH_{it-1}$$

where $PATENT_{it}$ is the count of patents filed in year t . We assume $\delta = 0.85$ to capture invention obsolescence (Dechezleprêtre & Glachant 2014; Grafström & Lindman 2017). As Park and Park (2006) found depreciation rates that vary between 12% to 18% depending on

¹⁶ Another caveat is that inventors may prefer to use other ways of protecting their inventions, such as the industrial secrecy (Cohen, Nelson, and Walsh 2000).

the industries, we run a robustness check without discounting the stock, but also with $\delta = 0.9$ and $\delta = 0.75$ (c.f. the results in Table A 9 & Table A 10 in the appendix).

The use of patent data has the effect of limiting country coverage. Many low-income or small countries (e.g. Pacific islands) exposed to tropical storms receive very few patents either because they do not rely on inventions at the technological frontier, which are typically present in patent data, or because inventors estimate that patenting is unnecessary in the absence of sufficient enforcement of intellectual property rights. We also exclude a few middle-income countries (e.g. the Philippines, Indonesia)¹⁷ for data quality reasons.

Storm impact

We extract disaster impact data from the publicly available EM-DAT database¹⁸ compiled by the Centre for Research on the Epidemiology of Disaster (CRED 2015). The EM-DAT database holds records of various mass disasters in the world, from 1900 to the present day. The data comes “from various sources including UN, governmental and non-governmental agencies, insurance companies, research institutes and press agencies”. It includes events that fulfil at least one of the following criteria: 10 or more people were killed; 100 or more people were affected, injured or homeless; a declaration by the country of a state of emergency and/or an appeal for international assistance was made; the event caused significant damage¹⁹. Among other disaster types, the database holds more than 4,000 storm-related disasters, half of them

¹⁷ Data are lacking for these countries in PATSTAT for our period of interest.

¹⁸ The EM-DAT database is available through this link: <https://public.emdat.be/>

¹⁹ For more information about EM-DAT data collection and classification, see: <https://www.emdat.be/guidelines>

being tropical storms, and the other half being extra-tropical, convective and unclassified storms. We extract data on tropical cyclones for which the data is more complete.

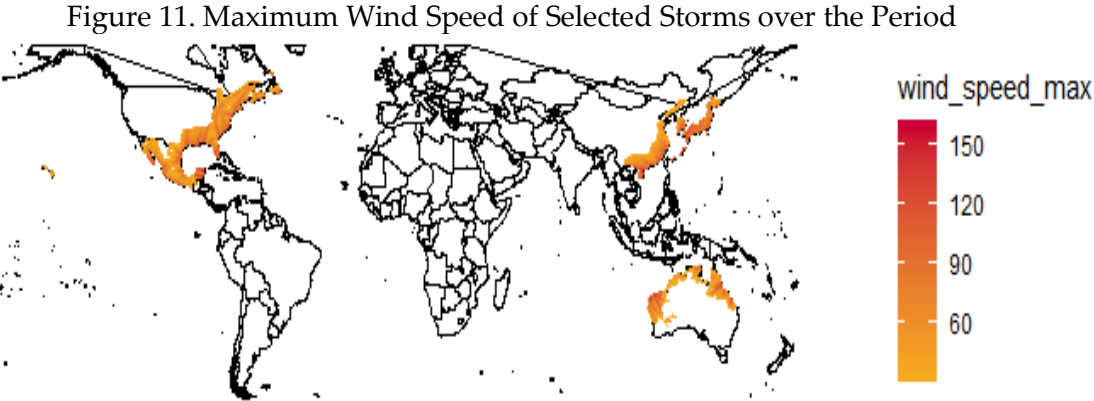
Storm exposure

It is necessary to control for the physical intensity of individual cyclones and the size of the exposed population or assets as they obviously influence a storm's impact and are likely to be correlated with the local stock of technologies for reasons exposed in the introduction. We extract this information from TCE-DAT²⁰ (Geiger et al. 2018). This dataset is based on the widely used IBTrACS dataset (version v03r09) (Knapp et al. 2010), which provides best tracks for more than 7,000 tropical cyclones globally observed between 1950 and 2015. A track consists of the cyclone center coordinates and physical variables with a six-hourly time step. Using variables such as minimal central pressure, maximum sustained wind speed and radius of maximum winds, coupled with a wind speed model (Holland 2008), Geiger, Frieler, and Bresch (2018) construct estimates of the storm wind footprints, i.e. spatially explicit maximum wind speeds²¹ (see Figure 11). They then combine these data with spatially explicit population (Klein Goldewijk et al. 2017) and GDP data (Geiger et al. 2017) to obtain spatially explicit exposure data for each event, at a 0.1° resolution. This allows them to compute estimates of the number of people and the total assets exposed to different wind speed intervals (above 34, 64 and 96 knots). These thresholds correspond to the Saffir-Simpson hurricane wind scale classification of tropical storms, hurricanes and major hurricanes respectively (Schott et al. 2012).

²⁰ Link to TCE-DAT databases: ftp://datapub.gfz-potsdam.de/download/10.5880.PIK.2017.005/TCE-DAT_historic-exposure_1950-2015.csv

²¹ Extreme precipitation is also a driver of storms damages (Collalti & Strobl 2021). However, the lack of storm-level precipitation data forces us to use wind speed only to build our exposure variable.

We create two categories of exposure based on wind speed intervals: people or assets exposed to wind between 34 and 96knots, and those above 96knots. 34-96kn winds are expected to produce “minimal” to “moderate” damage (Jerrard & McNeill 1992) and can already be life-threatening, while winds over 96kn cause “devastating damage” (Simpson 1974). Considering the fact that surges rather than high winds are the primary cause of storm-induced deaths, at least in the U.S. (Rappaport 2014), we build complementary indicators of exposed population and assets, considering only areas close to the coastline (up to 5km).



Source: Authors’ calculations based on TCE-DAT.

Matching these exposure data with impact data from EM-DAT²² is not straightforward. We do so by storm name, impacted country and year. This reduces the number of storms included in the data. Out of the 3,099 EM-DAT registered storms (including 1,637 with a name) and the 3,118 TCE-DAT storms (including 2,576 with a name), we obtain 905 storms that affected 179 countries from 1990 to 2015.²³ In the next step, matching with the patent data leads to a further

²² Although EM-DAT has a Tropical Cyclones category, we consider that all storm types have a chance of matching events that have no storm type registered, or events that later evolved into hurricanes and may not have been registered as a TC in EM-DAT. In practice, this increased the number of matched events (without duplicates) from 876 to 896.

²³ A few storms are registered as a single entry in EM-DAT (e.g. two storms hitting the country a few days apart). For these cases, we sum their exposure statistics.

drastic reduction of the sample size: 366 tropical storms in ten countries for the period 1990-2015.

Past storms exposure

In order to control for the exposure to past storms, we construct stock variables summing up exposures to past storms. As the IBTrACS archive is not very reliable before 1980, we consider only posterior events.

In detail, the variable $PAST_EXPOSURE_{it}$, is the sum of either the population or the assets of country i exposed to storms over 96knots²⁴ occurring between 1980 and $t - 1$. Following Miao (2017), we use the perpetual inventory method:

$$PAST_EXPOSURE_{it} = EXPOSURE_{it} + (1 - \rho)PAST_EXPOSURE_{it-1}$$

We use $\rho = 0.15$, following the literature (Park et al. 2006). We also test for the sensitivity of our results by applying other discount factors (c.f. Table A 9 & Table A 10 in the appendix).

As mentioned previously, matching data from EM-DAT, PATSTAT, and TCE-DAT leads to a sample of 366 storms. This restriction is neither desirable nor necessary for constructing the variable $PAST_EXPOSURE_{it}$ as the computation only relies on data from TCE-DAT. In order to improve the quality of the data, we use the new version of IBTrACS (v.4.0) and the software CLIMADA (version v1.5.1)²⁵ developed by Aznar-Siguan and Bresch (2019) to compute the spatial coverage of winds around the raw tracks provided by IBTrACS. We match the resulting 'extended' tracks at 0.1deg resolution with gridded population data from the History Database

²⁴ Table A 11 & Table A 12 shows the results with the past exposure variables built on people exposed to wind speed above 34 knots and above 64 knots.

²⁵ Detailed information about CLIMADA software can be found here: <https://climada-python.readthedocs.io/en/stable/index.html>

of the Global Environment (HYDE version 3.2)²⁶ (Klein Goldewijk et al. 2017) and with gridded assets data²⁷ (Geiger et al. 2017).

Other variables

We also use World Bank country-level data²⁸, such as GDP per capita (in constant PPP2005 international \$) and population. We complete missing data in World Bank indicators using International Monetary Fund (IMF) data²⁹.

2.3 Descriptive Statistics

Table 9 describes the total number of deaths and damages caused by selected storms for the period 1990-2015 in the ten countries included in our analysis. China is the most affected country, where on average almost four storms reach the land per year. These storms caused around US\$ 150 billion of damages and killed around six thousand people in China between 1995 and 2015. The USA is the country where storms cause the highest material damage, with US\$ 379 billion lost due to storms over the study period. Each storm landing in the US causes at least five times more damages (around US\$ 8 billion) than in other countries. In comparison, Japan is affected by more storms, but suffers ten times less damage, and four times fewer fatalities. This huge difference may be explained by the value of assets or the number of people exposed to storms, but also by the way countries cope with storm impacts, such as the use of

²⁶ HYDE 3.2 data can be downloaded following this link: <https://easy.dans.knaw.nl/ui/datasets/id/easy-dataset:74467>

²⁷ Spatially-explicit Gross Cell Product (GCP) time series are available here: <https://dataservices.gfz-potsdam.de/pik/showshort.php?id=escidoc:2740907>

²⁸ World Bank data can be accessed via the following link: <https://data.worldbank.org/>

²⁹ IMF data can be downloaded here: <https://data.imf.org/?sk=388DFA60-1D26-4ADE-B505-A05A558D9A42&sId=1479329132316>

technologies or softer adaptation to storms, forecasting of storm exposure, and organization of emergency evacuations. The aim of this paper is to disentangle these effects, focusing on the role of technologies in dealing with storm impacts. As shown in column five of Table 9, the United States appears to be the best country equipped in technology, followed by Japan and Australia.

Table 9. Storm Impact and Technology Availability by Country (1990-2015)

| Country | Total deaths Number of people | Total damages Billions PPP Constant 2005 international\$ | Total number of storms matched | Total number of HVI storm technologies |
|--------------------------|---|--|---|---|
| Australia | 25 | 5.43 | 18 | 808 |
| Canada | 5 | 0.28 | 6 | 760 |
| China | 6,001 | 150.75 | 92 | 599 |
| Cuba | 66 | 2.82 | 19 | 5 |
| France | 31 | 0.72 | 13 | 674 |
| Japan | 731 | 39.22 | 57 | 877 |
| South Korea | 549 | 16.69 | 13 | 576 |
| Mexico | 1,167 | 42.82 | 58 | 131 |
| Taiwan | 1,268 | 7.83 | 43 | 195 |
| United States of America | 2,593 | 378.59 | 47 | 2,665 |
| Total | 12,436 | 645.15 | 366 | 4,625 |

Table 10 below describes the variables used in the estimations. Every years, storms killed around 86 people on average, and destroyed 4.9 billion assets (PPP constant 2005). Around 41 million people are affected by storms with wind speeds between 34 and 96 knots, and fifth of them live less than 5 km from the coast. Winds that reach speeds of 96 knots or more threaten 1.4 million people a year, and around 389,000 near the coast. Similarly, each year, assets worth an average of US\$ three trillions are exposed to storms with wind speeds above 34 knots and below 96 knots, of which US\$ 517 billion are located near to the coast. Assets escape extreme wind speeds more than people do, as ‘only’ US\$ 120 billion-worth of area is exposed to such events, of which around a quarter is located less than 5km from the coast. Finally, each country

benefits on average from a stock of around 141 available HVI innovative technologies every year to protect it from storms.

Table 10. Summary Statistics for the Analysis of Technology Efficiency

| 1990-2015 | Fatalities/Deaths | |
|--|-------------------|-----------|
| | Mean | Std. Dev. |
| Dependent variable | | |
| Number of storms induced deaths (persons) | 86.4 | 232.7 |
| Amount of storms induced damages (Billions 2005 PPP international\$) | 4.92 | 15.80 |
| Technology availability | | |
| Stock of storms HVI technologies | 141.0 | 160.6 |
| People exposed to storms (millions) | | |
| Wind speed between 34 & 96 knots | 41.2 | 55.3 |
| Wind speed between 34 & 96 knots within 5km from the coast | 7.8 | 11.9 |
| Wind speed > 96 knots | 1.4 | 2.5 |
| Wind speed > 96 knots within 5km of the coast | 0.4 | 0.8 |
| Assets exposed to storms (billions 2005 PPP international\$) | | |
| Wind speed between 34 & 96 knots | 2,987.1 | 4,359.8 |
| Wind speed between 34 & 96 knots within 5km of the coast | 516.6 | 825.9 |
| Wind speed > 96 knots | 119.5 | 265.9 |
| Wind speed > 96 knots within 5km from the coast | 27.0 | 58.8 |
| Stock of population exposed (millions of people) | | |
| Wind speed > 34 knots | 333.9 | 382.4 |
| Wind speed > 96 knots | 6.8 | 8.0 |
| Stock of assets exposed (billions 2005 PPP international\$) | | |
| Wind speed > 34 knots | 17,751.1 | 18,653.4 |
| Wind speed > 96 knots | 516.2 | 810.2 |
| Log population count (persons) | 18.5 | 1.5 |
| Log GDP per capita (Constant 2010 US\$) | 9.6 | 1.1 |
| Number of countries | 10 countries | |

2.4 Estimation Strategies

To analyze the effect of technologies on storm-induced deaths and damages, we estimate the following equation:

$$\log(\text{IMPACT}_{it}) = \alpha * \text{TECH}_{it-1} + \beta_1 * \text{EXPOSURE}_{it} + \beta_2 * \text{PAST}_{\text{EXPOSURE}_{it-1}} + \gamma * X_{it} + \theta * t + \mu_i + \epsilon_{it}$$

The dependent variable, IMPACT_{it} , is either the number of deaths or the economic damages in PPP constant 2005 international US dollars induced by tropical storms having affected the country i in year t .

TECH_{it-1} is the discounted stock of storm adaptation HVI available in the country in year $t-1$. EXPOSURE_{it} is a vector of two variables: the number of people or value of assets (in PPP constant 2005 international US dollars) exposed to wind speeds between 34 and 96 knots, and those exposed to wind speeds over 96knots. This specification makes it possible to take into account nonlinearities. $\text{PAST}_{\text{EXPOSURE}_{it-1}}$ represents the accumulated stock of country i past exposure to tropical cyclones above 96knots, until year $t - 1$. X_{it} is a vector of control variables, including the yearly country's GDP per capita and its population. t is a time trend and μ_i is a vector of country-fixed effects.

As the number of fatalities is a count variable, we can estimate the equation above using either a Poisson or a Negative Binomial estimation. However, as shown in Table 10 above, the variance does not equal the mean, whereas it is an expected condition for Poisson to be consistent (Land et al. 1996). This suggests overdispersion in the data, therefore we choose to use a Negative Binomial estimation and we compare the results with those obtained with a log-linear OLS estimation. In the case of economic damages, however, a log-linear estimation with OLS seems more natural. We thus choose a log-linear specification for the base model

and compare the results with those of the negative binomial regression. In all cases, we cluster standard errors at the country level. We include country fixed effects to control for time-invariant country characteristics, such as indigenous knowledge regarding storms, institutional organization, education and trade openness level, as well as development level, such as income group. Moreover, we include a time trend to account for global increased awareness about the impact of climate change and weather events, and a potential increase in knowledge about the effective use of technologies³⁰.

³⁰ In the appendix, we estimate a more flexible model including year fixed effects. Table A 7 & Table A 8 show similar results to our base specification, although the significance decreases for some estimates.

2.5 Results

Fatalities

Table 11 below shows the effect of adaptation technology availability and experience of past storms on storm-induced fatalities over the period 1990-2015³¹.

Table 11. Effect of Technologies on Storm-Induced Fatalities

| DEATHS (1990-2015) | | | |
|---|--------------------------|------------------------|--------------------------|
| | <i>Storm patents</i> | | <i>All patents</i> |
| | Negative Binomial | OLS | Negative Binomial |
| Stock of HVI technologies at t-1 | -0.508*** (0.189) | -0.303*** (0.0627) | -6.58e-05 (4.35e-05) |
| Population exposed to storms at t | | | |
| 34knots to 96knots | 0.00923*** (0.00147) | 0.0133*** (0.00344) | 0.120 (0.0806) |
| Over 96knots | 0.143 (0.115) | 0.0989* (0.0483) | 1.873* (1.105) |
| Stock of people exposed to past storms over 96knots (t-1) | 0.0124 (0.0353) | 0.0107 (0.0258) | 0.344* (0.184) |
| Log GDP per capita (PPP constant 2005 international\$) | -0.573*** (0.171) | -0.874*** (0.163) | 0.835*** (0.161) |
| Log country's population (millions) | -3.196* (1.653) | -1.938 (2.026) | 7.129*** (2.711) |
| Time trend | X | X | X |
| Country FE | X | X | X |
| Observations | 144 | 144 | 144 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis.

Table 11 shows that adaptation technologies effectively protect people from storm impacts. As shown in the first line of columns one and two, the stock of past adaptation technologies specially designed to cope with the negative effect of storms significantly reduces the number of deaths. A ten percent increase in the average country's patent stock (around 15 HVI patents)

³¹ Table A 1 in the appendix shows that results remain the same if we restrict the period of analysis to 1995-2015

lowers the number of deaths by 4.4 percent (Log-linear) to 7.3 percent (Negative binomial). This represents an average of up to six lives saved per country per year. We perform a placebo test using the stock of all technologies, not specific to storms. Results are provided in column three of Table 11 and the effect is insignificant with a coefficient near to zero, confirming that what matters is the availability of storm-specific technologies. Finally, as shown in Table A 5 (appendix), storm technologies are slightly more efficient in protecting people living near the coast.

Unsurprisingly, the second and third lines show that fatalities significantly increase with the number of people exposed. Moreover, the higher the wind speed, the higher the coefficient, even though few storm events reach extreme wind speeds, leading to an insignificant coefficient. One million people more exposed to wind speeds of between 34 and 96 knots leads to 1% more deaths on average, whereas the same number of people exposed to wind speeds of over 96 knots increases the number of deaths by 16% on average. Also, people exposed to the same wind speed face a greater risk if they live close to the coast, as shown by the higher coefficients for the variable representing people living within 5km of the sea in Table A 5 (appendix). People living along the coastline are almost four times more likely to die (3.7%) if they are exposed to winds between 34 to 96 knots than other people exposed to the same wind speed. This can be explained by the additional threats (storm surge, beach erosion, etc.) induced by storms when they hit coastal areas. All of these results make sense.

It is worth noting that the impact of the stock of population exposed to storms above 96kn in the past is insignificant although the coefficients are positive. The sample size may explain the weak efficiency of these estimates.

Damages to assets

Table 12 below shows the effect of technology availability on the amount of damages to assets for the period 1990-2015³².

Table 12. Effect of Technologies on Storm Induced Damages to Assets

| DAMAGES (1990-2015) | | | |
|---|-----------------------|---------------------|---------------------------|
| | <i>Storm patents</i> | | <i>All patents</i> |
| | OLS | Negative Binomial | OLS |
| Stock of HVI technologies at t-1 (hundreds) | -0.502* (0.232) | -0.494** (0.215) | -0.000111** (3.77e-05) |
| Assets exposed to storms at t | 34knots to 96knots | 0.191** (0.0589) | 0.200** (0.0653) |
| | Over 96knots | 1.586 (1.242) | 2.102* (1.163) |
| Stock of assets exposed to past storms over 96knots (t-1) | 0.0300 (0.171) | 0.403** (0.181) | 0.0193 (0.145) |
| Log GDP per capita (PPP constant 2005 international\$) | 1.049** (0.364) | 0.980*** (0.226) | 1.121** (0.347) |
| Log country's population (millions) | 10.41 (6.128) | 6.840** (2.874) | 10.25 (6.135) |
| Time trend | X | X | X |
| Country FE | X | X | X |
| Observations | 131 | 131 | 131 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis.

We can see that storm adaptation technologies also protect assets from being destroyed by storms. An increase in ten percent of available storm-related patented inventions decreases the damages by around 7.5%, corresponding to average savings of more than US\$ 369 million PPP2005 per country per year.

Table A 2 in the appendix shows that results remain the same if we restrict the period of analysis to 1995-2015

Like for deaths, the effect is stronger near the coast (Table A 6). Although all technologies have a significant (and negative) impact on storm induced damages (third column), this effect is close to zero.

The rest of the table yields results similar to those obtained for fatalities. The more assets exposed to storms, the more damages. The effect is also higher for assets near the coast (Table A 6) and assets exposed to higher wind speeds. A ten percent rise in the average assets exposed to wind speeds of between 34 and 96 knots increases the amount of damages by up to 6%.

A difference visible in Table 11 is however the significantly positive impact of past events on damage to assets obtained with the negative binomial estimation. This result could be explained by asset immobility, low rebuilding costs due to insurance (Sadowski & Sutter 2008), and by our 'short' time period (25 years) which does not allow us to identify major infrastructure reallocation.

2.6 Conclusion

International institutions and climate adaptation policies promote technologies as an essential tool to adapt to future climate change. Despite the focus on technologies as a major solution, little is known about the actual effectiveness of such technologies in reducing the impact of extreme weather events, one of the main growing threats caused by climate change. In this paper, we take the example of tropical storms and then fill this gap by analyzing the effect of access to patented adaptation technologies and experience of past storms on storm-induced fatalities and economic damages. We aggregate, at the country level, storm-level data on both storm impact (damages and fatalities) and exposure of people or assets to various wind speeds in ten countries to build a country-level panel data for the period 1990-2015. We use patent data from PATSTAT to analyze the influence of technical knowledge accumulation on the impact of such events.

The overall message arising from the analysis is that the local availability of advanced technologies for adaption to tropical storms significantly reduces fatalities and damages to assets induced by tropical storms threats. Our best estimate is that a ten percent increase in the average country's stock of storm-related patented inventions (around 15 HVI patents) lowers the number of deaths by 7.3 percent. This represents an average of up to six lives saved per country and per year. The same increase reduces the damage to assets by the same percentage (7.5 percent), corresponding to an average saving of more than US\$ (PPP2005) 369 million per country per year. Comparing these numbers is a delicate task, but using an arguably high statistical value of life (e.g. around US\$ 10 million according to the US Department of Transportation), technologies appear relatively more effective in reducing damages. This is

ultimately driven by the fact that a single storm kills an average of 34 people but causes over US\$ (PPP2005) 1.76 billion damages.

In conclusion, it is worth reminding that the scope of this analysis is limited. Our reliance on patent data means that we can only examine the role of advanced and specialized adaptation technologies. Low-tech or indigenous technical solutions, which are often non-patented, may also be effective in mitigating storm impacts, especially in developing countries. Incidentally, this explains why these countries are not included in our sample as they innovate and adopt technologies outside the patent system. Moreover, our analysis focuses on the effectiveness of technologies in mitigating the direct impact of storms. The following analyses could also assess how these technologies can help mitigate the indirect effects of disasters, for example by assisting in post-disaster recovery (Hallegatte 2014a). Last, tropical storms are not the only type of climate disaster likely to become more frequent in the future.

3 Innovation in Adaptation Technologies in Response to Extreme Climate Events: Evidence from Patent Data.

Simon Touboul³³

Abstract

This study analyses the innovation response of countries to climate extremes. Using patent data and original climate indicators at the country level, we estimate the effects of past extreme droughts, precipitation and heatwaves on the level of inventions and imports of adaptation technologies for the period 1995-2015. Our results nuance those of previous studies since we find a very weak effect of extreme events on the invention and importation of adaptation technologies. Our best estimate is that a twenty percent increase in the average share of people affected by extreme events in the ten years following an event leads to an increase of up to 4.7% and 3.5% more inventions and imports of adaptation technologies respectively. Moreover, we do not find evidence of a long-term redirection of innovation towards adaptation technologies.

Keywords: climate change adaptation, innovation, extreme weather events, adaptive capacity

JEL codes: O33; O57; Q51 ; Q54; Q55 ; C33

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Résumé

Cette étude analyse l'innovation technologique des pays en réponse à des événements extrêmes climatiques. En utilisant des données sur les brevets et des indicateurs climatiques originaux à l'échelle des pays, nous estimons les effets des sécheresses, précipitations et vagues de chaleur extrêmes sur le niveau des inventions et des importations de technologies d'adaptation pour la période 1995-2015. Nos résultats nuancent ceux des études précédentes puisque nous trouvons un effet très faible des événements extrêmes sur l'invention et l'importation de technologies d'adaptation. Notre meilleure estimation est qu'une augmentation de vingt pour cent de la part moyenne de personnes touchées par des événements extrêmes dans les dix années suivant un événement entraîne une augmentation des inventions et des importations de technologies d'adaptation allant jusqu'à 4,7 % et 3,5 % respectivement. En outre, nous ne trouvons pas de preuve d'une réorientation à long terme de l'innovation vers les technologies d'adaptation.

CHAPTER 3

Innovation in Adaptation Technologies in Response to Extreme Climate Events: Evidence from Patent Data.

3.1 Introduction

Despite the many uncertainties surrounding climate change, climatologists agree that the number of extreme weather events will increase all over the world (Rahmstorf & Coumou 2011; Rummukainen 2012), especially in countries currently affected by such events (Sillmann & Roeckner 2008). The World Economic Forum (2020) identified 30 major global risks, and extreme weather is the risk with the highest impact and with the highest probability of occurring. In addition, extreme weather events, although infrequent, account for almost all of the economic damage and deaths caused by all weather variations (Pielke et al. 2008). Estimated costs vary from 94\$billion to 130\$billion a year for the period 2000-2012 (Kousky 2014). These events are also difficult to forecast, and so particularly threatening for the future of our economies.³⁴

One potential adaptation strategy to cope with the negative effect of such extreme weather events is the use of technologies (UNFCCC 2006). Homo Sapiens has been able to settle in nearly all earth ecosystems. Our species succeeded by developing technologies and skills to adapt to multiple environments and climate risks: buildings, agricultural techniques, transport

³⁴For more information about the economics of natural disasters, see (Hallegatte 2014b).

solutions... Over the centuries, we have thus progressively generated a stock of knowledge and technologies that gave us increasing adaptation capabilities. What is new is the pace of climate change and the fact that it occurs on a planet with nearly 8 billion inhabitants. In this new context, it can be reasonably assumed that these existing technologies and skills are not sufficient to deal with the current speed and scale of climate change. Importantly, this does not require to shift to a new innovation paradigm, but to drastically accelerate the pace of innovation and the diffusion of technologies in sectors and geographical areas where they are the most useful. Although the Fifth IPCC Assessment Report (IPCC 2014) acknowledges the importance of non-technological solutions and traditional knowledge, it also identifies technology as one of the three areas to reduce the current and future climate change adaptation gap. Looking at specific sectors and climate extremes helps understanding why technologies are important. Take the example of adaptation in the agricultural sector (Clements et al. 2011). Farmers must first understand how climate change will affect their production in the future. Improved climate prediction modeling, coupled with better real-time weather measurement systems, can help them better apprehend the effect of climate change. Among the many impacts of climate change, the increase in the number and intensity of droughts poses a major threat to agricultural systems. The use of more efficient irrigation systems and rainwater harvesting technologies, for example, can mitigate their effects. At the same time, farmers can switch to new crop varieties that are more resistant to drought or heat. In addition, changes in practices, such as conservation tillage or terracing, offer other options for coping with climate hazards. Many of these adaptation solutions can be made more effective by using advanced technologies.

Adaptation technologies have already proven their usefulness in the past in mitigating the impact of climate extremes. Barreca et al. (2016) highlight the efficiency of residential air conditioning systems in reducing deaths due to high temperature in the US. Touboul, Thomas, and Glachant (2021) also show that countries where there are more storms dedicated technologies available suffer less economic damages and fatalities induced by tropical storms. Analyzing how countries innovated and adopted technologies in response to past events may bring lessons for future adaptation strategies and policies. Empirical evidence is unfortunately lacking (Popp 2019).

In this paper, we use patent data as a proxy for technology inventions and imports, and analyze the effect of three weather events (droughts, extreme precipitation and heatwaves) for the period 1995-2015. More precisely, we proceed in two steps. First, we estimate a distributive lag model to examine the dynamics of the level of innovation and cross-border flows of adaptation technologies following extreme weather events. We also look at the long-term cumulative effects. Second, we estimate the impact of these weather events on the share of adaptation-related innovation in the country's total innovation, in order to evaluate whether these shocks redirect national R&D efforts towards adaptation.

A first contribution of the study is the use of a patent database targeting adaptation technologies based on the Y02A PATSTAT classification. The Y02A class released by the European Patent Office (EPO) on April 2018 groups all patents protecting "technologies that allow adapting to the adverse effects of climate change in human, industrial (including agriculture and livestock) and economic activities". To the best of our knowledge, this classification has not been previously exploited in an applied econometric study. We extract around 247 thousand patent applications from a panel of 65 countries for a 21-year period

(1995-2015). Detailed information contained in patent documents allows us to precisely target technologies related to each of the three weather events covered in this paper. Using this classification, we cover more adaptation technologies, and more countries than previous studies (Miao and Popp 2014a and Li (2017)).

The second contribution of this paper is to use historical weather gridded data instead of standard data reporting economic damages or fatalities. Most previous studies analyze the effect of natural events on innovation relying on reported damages, coming mainly from the only publicly available disasters database EM-DAT, provided by the Centre for Research on the Epidemiology of Disasters (CRED). In addition to data coverage issue arising from heterogeneous information reporting (Kousky 2014), estimating the direct effect of damages on innovation may induce endogeneity issues. As argued by Miao and Popp (2014), both damages and innovation in adaptation technologies may be driven by unobservable factors, such as institutional change or improved knowledge of climate change. In order to improve the completeness of the data and to rule out endogeneity issues, we construct indicators of exposure to extreme weather events at the country level based on global gridded data available at a very fine scale (1° longitude-latitude maximum). Geolocalised data allow us to shrewdly target areas impacted by the events. They also permit to isolate extreme weather events, responsible for most of the all-weather induced damages, and whose intensity and frequency may evolve differently from more moderate events under climate change (IPCC 2012; Rummukainen 2013). To account for the potential impact of such events on human activities, we combine weather indicators with population or agricultural land use gridded data to identify people or agricultural areas exposed to extreme events. We finally aggregate local weather information at the country level following Diaz et al. (2018) methodology. We end up

with indicators of the share of the country's population or agricultural area affected by droughts, extreme precipitation leading to flash floods and heatwaves.

The third contribution is to consider three innovation-related variables: the level of invention induced by local weather events, the level of imported adaptation technologies from foreign inventors and the share of adaptation technologies in all patented technologies, to analyze a potential directed technical change toward adaptation solutions. While the Adaptation Gap Report by UNEP (2014) highlights an increasing need for modern and advanced technologies, it also states that these needs are less likely to transform into demand in developing economies (Olhoff et al. 2014). In all technological areas, the limited availability of researchers and engineers, a low number of past innovations, and low R&D expenditures (Fagerberg 1994; Griffith et al. 2004; Keller 1996; Kneller & Stevens 2006) reduce these countries' ability to invent adaptation technologies, but also to recognize, assimilate and apply new technological knowledge. It makes them more dependent on traditional indigenous technologies and on new adaptation technologies invented abroad. Dechezleprêtre et al. (2020) shows that most adaptation technologies are invented in few developed countries and China, and the transfer of such technologies is highly concentrated between high income countries. These limited technological capacities poses a particular challenge for adaptation as many of these developing countries stand in locations highly affected by climate change (IPCC 2021) and traditional knowledge is likely to be insufficient given the scale of the problem in there. As an illustration, the synthesis of the technology needs assessment (TNAs)³⁵ reported, to the UNFCCC by the governments of 25 middle-income and low-income countries, indicates that around 75% of the identified technology gaps concern modern or high-technologies, especially

³⁵ More information about Technology Need Assessment available here: <https://unfccc.int/ttclear/tna>

for infrastructure, health, water management, disaster risk management or coastal zones (Olhoff et al. 2014).³⁶ Note that combining traditional knowledge with modern scientific and technological tools can pay extra dividends, as when Inuit hunters combine their knowledge of wildlife and sea ice with weather station and GPS data to adapt to changing conditions. Dechezleprêtre et al. (2020) also suggests that, despite the general trend of increasing extreme weather events over the last decades (IPCC 2021), the share of adaptation technologies in all technologies remains stable for the period 1995-2015. It suggests countries do not reallocate their innovation efforts towards adaptation technologies despite the rising threats of climate change on their economy. The effect of extreme weather events on directed technical change remains an empirical question we investigate in the last part of our analysis.

We first find a small effect of extreme weather events on the invention and imports of adaptation technologies. A one percentage point increase in the average share of people affected by extreme droughts within the last 10 years boosts the invention of adaptation technologies by up to 4.7%. Both extreme droughts and heatwaves have a positive effect on innovation in the years following the event. However, the impact of extreme precipitation comes later, eight years after the event occurs. We also extend these observations to the import of foreign adaptation technologies. Countries import significantly more droughts related technologies shortly after extreme droughts occur. Moreover, the long-term average effect of droughts is positive and significant. In particular, droughts affecting agricultural area significantly boost technology imports, while they have no clear effect on inventions. It seems that developing countries, for which the agricultural sector represents an important economic

³⁶ Low absorptive capacities mean domestic economic actors are less able to imitate an imported technology. In this context, IPR are less useful in securing innovation returns, and thus in providing technology owners with incentives to transfer. This should be kept in mind when using patent-based indicators.

outcome, import foreign technologies they cannot invent locally. The second part of our analysis suggests countries are not redirecting their innovation towards adaptation technologies in the long term. Extreme droughts induce a significant increase in the share of adaptation technologies in all technologies two years after the event occurs only, and the effects of extreme precipitation and heatwaves on the share of adaptation technologies invented remain low and insignificant. These observations nuance those of previous studies, as we depict a more worrying situation. First, while we show that countries spontaneously invent technologies in response to extreme weather events, we find lower and limited impacts of extreme weather events on the invention of adaptation technologies. Second, taking into account the possibility of importing technologies does not lead to a much more reassuring conclusion. Third, we observe almost no directed technical change towards adaptation technologies following extreme weather events, suggesting that countries do not prepare for future shocks by implementing new technologies specific to climate change adaptation.

This article is organized as follow. The next section presents the data used in the analysis, with a particular emphasis on extreme weather events indicators building. Then, we show some descriptive statistics to characterize our data. We next present our econometric strategy, before exposing the results of our analysis. The final section presents our main conclusions.

3.2 Measuring Innovation and Exposure to Climate Extremes

In this study, we use patent data as a proxy for the invention and imports of adaptation technologies. We also create original weather indicators measuring the percentage of the country's population or agricultural area affected by extreme events by year, for three kinds of events: droughts, extreme precipitation leading to flash floods and heatwaves. The final dataset covers up to 65 countries during the period 1995-2015.

Patent Data

Patents as indicators of innovation and technology transfer

Patents constitute one way of protecting hardware technologies, but also software and processes. They so constitute a common approach to study innovation and knowledge transfer between countries, through the filing of patents in foreign countries. Other indicators, such as R&D spending, the number of researchers per inhabitants or the percentage of a country's population that has pursued tertiary education may also be used to measure innovation. However, the detailed information contained in patent documents and the way the patent system works make patents particularly attractive for this study. First, patents represent the output of the effort in innovation, allowing us to measure the direct effects of extreme weather events on the entire innovation process. Moreover, they contain detailed information, including countries where the technology has been invented, as well as a precise description of the technology itself. It is of primary interest, as we need to identify technologies specifically related to droughts, floods or heatwaves. We target such technologies using the Y02A PATSTAT classification released by the European Patent Office (EPO) in April 2018. This new classification captures patents protecting "technologies that allow adapting to the adverse

effects of climate change in human, industrial (including agriculture and livestock) and economic activities". Covering almost all patent offices, this classification is built ex-post by patent experts from the EPO who use CPC and IPC codes, as well as text searching algorithms in patent documents. Patent data also give us information on all countries where the patent is filed. Using this information, we can identify both technologies invented in the country by local inventors, and technologies transferred from a foreign country, identified by patents filed in the country but protecting a technology invented abroad.

However, patent data also have drawbacks. First, countries could use technologies that are not patented. This is especially true for low income and some middle-income countries. These countries cannot ensure intellectual property rights to technology inventors, who will therefore favor the use of trade secrets over patents to protect their invention (Cohen et al. 2000). Because patent filling rules, especially novelty and innovation criteria, are different among countries, we also have to control for differences in propensity to patent across sectors and across countries. We partly control for these issues by adding year and country fixed effects and by running separate estimations for the three types of extreme events.

Note that the use of patent data prevents analysis at the subnational level. These data only contain information on the identity of the inventor (a firm, an individual, a university ...), his/her/its address and the country of residence of this inventor. The address of the inventor is usually the address of the firm's headquarters, which is not a priori the same place where the technology is going to be used. Second, innovators do not only respond to local events, but they create technologies for, at least, the national market. Third, foreign technologies are patented at the national level and we have no information about local use of the patented

technologies. Because of the three previous arguments, we also have to build and use weather indicators at the country level.

Construction of invention and import indicators

We use patent families as a proxy for invention or imports of technologies to avoid double counting of the same technology. A patent family groups all patent documents protecting the same invention. Several studies have used this indicator (Dechezleprêtre et al. 2011; Eaton & Kortum 1996). Experts established various classifications to associate individual patents to an invention. In this study, we use the DOCDB family indicator, as it has been built for and by the EPO and it is the source of raw patent data for PATSTAT. The DOCDB family is an ex-post hand built reference by EPO experts (for an overview of patent families, see Martinez (2010)).

To identify patents protecting adaptation technologies, we used the Y02A classification released in April 2018 by the EPO. This classification divides adaptation technologies into six categories, corresponding roughly to economic sectors: Coastal and river protection, Water management, Infrastructure, Agriculture, Health and Indirect adaptation.³⁷ The category 'Agriculture' covers mainly adaptation technologies related to droughts, such as droughts resistant crops or efficient irrigation systems. Other Y02A classes encompass technologies mitigating various weather events. For example, the 'Infrastructure' category gathers floods related technologies (floods resilient equipment and floating houses for example) and heat-specific technologies (rotary buildings, passive climatisation, thermal insulation, etc.). We identify the technologies dealing with droughts, floods and heatwaves by exploiting the subcategories' titles of the Y02A classification (see Annex 1 for the entire classification scheme).

³⁷ For more detailed information on the Y02A classification, see: https://worldwide.espacenet.com/classification?locale=en_EP#!/CPC=Y02A

Based on several sources, we select technologies that are obviously well suited to mitigate these weather events.³⁸

Weather Indicators

To target how countries are affected by extreme weather events, we built original exposure indicators in three steps. First, we use gridded data at $1^\circ \times 1^\circ$ spatial resolution³⁹ to precisely determine, among hundreds of locations per country, the ones exposed to extreme weather events. For each hazard, we have a balanced panel of yearly value of our indicator at the station (location) level, identified as a fix pair of (longitude; latitude) coordinates. These data are built on weather observations at the local level, and are increasingly used by researchers to study the effect of local environmental conditions on country level or geolocalised economic outcomes (for example, De Cian et al. 2019). Second, we match weather gridded data with population or land use geolocalised data to identify people or agricultural areas affected by weather events. Lastly, we compute our country level indicator, as the share of people (agricultural area) affected by extreme weather events on total country's population (agricultural land).

Data sources

The droughts indicator we use is the Global Precipitation Climatology Centre Drought Index (GPCC-DI), a water supply anomaly indicator (Ziese et al. 2014). The extreme precipitation index is built on a precipitation indicator called Rx5day. This indicator, provided in PANGAEA (Mistry 2019), reports the annual maximum consecutive 5-days precipitation at each location. We compute a precipitation anomaly indicator following Miao (2019). It is

³⁸ The list of the selected technologies and the corresponding CPC codes is available in the Annex 2.

³⁹ Precipitation and heatwaves indicators are available at a $0.25^\circ \times 0.25^\circ$ resolution.

defined as the difference between the annual value of the Rx5day indicator and its long-term local average value over the period, divided by the local standard deviation of this indicator. Because floods and landslides hazards are also function of specific local conditions (basin's topography, presence of a large river, etc.), we use a country level indicator of physical exposure to floods, extracted from the Index for Risk Management (INFORM) database⁴⁰ (De Groeve et al. 2014). We estimate the effect of extreme precipitation on countries for which the INFORM Risk Index is either Moderate, High or Very High.

Finally, the heatwaves indicator is based on the Excess Heat Factor (EHF), particularly adapted to analyze impact of heatwaves on human health. We use indicators provided in the Mistry PANGAEA database to identify the number of heatwaves (Heatwaves Number (HWN)) and their magnitude (Heatwaves Magnitude (HWM)) by year by location. Because selected heatwaves proof adaptation technologies are designed to cope with high temperature, we also need to exclude 'cold' places from our analysis. We target 'hot places' using the TXx indicator also available in PANGAEA, reporting the maximum temperature reached for the station within a year.

Each of these indicators are expressed as deviations from long-term averages. It allows us to distinguish, for example, a location affected by droughts temporary conditions from an arid area (Barrios et al. 2010; Eriyagama et al. 2009).

Table 13 below resumes the data sources used to build our weather indicators.

⁴⁰ More information about INFORM are available here: <https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk>

Identifying weather extremes

Because we are interested in the effect of extreme events on the invention or imports of adaptation technologies, we need to differentiate extreme events from moderate ones. More precisely, we identify three intensities of events per year and per location: no event, moderate events or extreme events. The droughts indicator (GPCC-DI) we use is specifically designed to identify different droughts intensities⁴¹. However, there is no global definition of what constitutes an extreme heatwave nor an 'extreme' excess of precipitation. To overcome this issue, we target extreme heatwaves and extreme precipitation using the average propensity of land area affected by moderate and extreme droughts as follow. We choose the values of the heatwaves (precipitation) indicator corresponding to extreme or moderate events so that the global share of land affected by extreme or moderate heatwaves over the period 1960-2015 is the same as the percentage of land affected by either extreme or moderate droughts. Table 13 below shows the thresholds value defined for each category of hazards.

To do so, we first calculate the average percentage of the country's area affected by each droughts intensity for all countries over the period 1980-2015. We do not take into account the population nor the agriculture.

Then, we identify the intensity of the event occurring at each location per year, according to the value of the GPCCDI indicator. As shown in Table 13, a value between -1 and -1.5 indicates the location suffered moderate droughts during the year. If the value of the indicator is below -1.5, the location was impacted by extreme droughts. Finally, the region escape from droughts if the value of the indicator is above -1. Then, we sum the number of stations (pair of

⁴¹ see Ziese et al. (2014) for more detailed information

longitude;latitude coordinates) affected by each intensity of hazard by country and year, and create our first final indicator, as follows:

$$\text{Area_affect}_{e,i,c,y} = \frac{\sum_{Sc} \text{Intensity}_{i,s,y}}{N_{sc}} \quad (1)$$

where $\text{Area_affect}_{e,i,c,y}$ represents the share of country c area affected by each natural hazard e of intensity i by year y . This indicator is computed as the sum of stations affected by either no event, a moderate event or an extreme one over the total number of stations in the country. It is the sum over all the stations of country c (Sc) of the dummy variable $\text{Intensity}_{i,s,y}$ equals to 1 if the station s is affected by an event e of intensity i at year y (where i represents either no event, moderate or extreme event) on the total number of stations N_{sc} in country c . Doing so, we get the annual share of each country's area affected by either a moderate drought, an extreme drought, or escaping from dry conditions. We then average the share of countries' area affected by each intensity of hazard for the entire period over all countries, to get the global average impact of droughts on countries, as shown in Table 14.

Second, we calibrate our heatwaves and precipitation indicators to obtain the same global average proportion of country's area affected by each intensity of events (the resulting proportions are shown in Table 14 below). This method leads us to define places affected by extreme precipitation as those where the value of the Rx5day anomaly index is above 2 (see Table 13). Similarly, locations experiencing heatwaves are those where the maximum temperature reached within a year (TXx) is at least 38°C, and the number of heatwaves (HWN) at least equals to one. Then, moderate heatwaves have a magnitude (HWM) between zero and three, and extreme ones above three.

Table 13. Weather Event Indicators Building

| Climate event | | Droughts | | Floods | | Heatwaves | |
|-----------------|----------|--------------|------|----------------|-----------|---|-----------|
| Indicator | | GPCCDI value | | Rx5day anomaly | | EHF Magnitude (HWM) value and temperature threshold (TXx) | |
| Event | No event | 4+ | -1 | $-\infty$ | 1 | 0 or Tmax<38°C | |
| intensity level | Moderate | -1 | -1.5 | 1 | 2 | 0 | 3 |
| | Extreme | -1.5 | -4 | 2 | $+\infty$ | 3 | $+\infty$ |

} Tmax>=38°

People and agricultural areas affected by weather events

Finally, we merge our climate indicators with population or land use gridded data. Population and land use data come from the History Database of the Global Environment (HYDE version 3.2) (Klein Goldewijk et al. 2017). We extract gridded count population data, and land use data for two types of agricultural activities (cropland and pasture). As previously, we compute the share of the country’s population (2) or agricultural area (3) affected by either no event, a moderate or an extreme event as follow:

$$\text{Pop_affect}_{e,i,c,y} = \frac{\sum_{Sc}[\text{Population}_{s,y} * \text{Intensity}_{i,s,y}]}{\sum_{Sc}[\text{Population}_{s,y}]} \quad (2)$$

$$\text{Agri_affect}_{e,i,c,y} = \frac{\sum_{Sc}[\text{Agri_area}_{s,y} * \text{Intensity}_{i,s,y}]}{\sum_{Sc} \text{Agri_area}_{s,y}} \quad (3)$$

Where Population_{s,y} represents the number of people living at station s at year y, Intensity_{i,s,y} is a categorical variable representing the intensity i of the event occurring at station s at year y, and Agri_area_{s,y} the area of station s dedicated to both cropland and pasture at year y.

3.3 Descriptive Statistics

As shown in Table 14, on average, weather events impact less than one fifth of the countries' land area, and extreme weather events affect between 5% to 8% of the stations. By construction of the indicators, moderate and extreme droughts, precipitation and heatwaves hit countries in the same proportions. For the period 1995-2015, the data set includes around 95,000 patent applications specific to droughts, 53,000 for floods and 99,000 related to heatwaves. Note that around 8,000 patents are common to all three events, whereas 67% of all the selected applications are extreme event specific.

| 1995-2015 | | Droughts | Floods | Heatwaves |
|---|----------|----------|--------|-----------|
| Number of patents related with the hazard | | 95,154 | 53,483 | 98,737 |
| Number of countries in climate databases | | 158 | 210 | 211 |
| Average percentage of stations affected by | No event | 85% | 85% | 80% |
| | Moderate | 9% | 11% | 12% |
| | Extreme | 7% | 5% | 8% |

Source: Calculation based on PATSTAT (patents), Global Precipitation Climatology Centre Drought Index (GPCC-DI) and Mistry PANGAEA.

Table 15 shows descriptive statistics for all the variables used in our estimations. We cover at least 54 countries. As mentioned in the previous section, the use of patent data forces us to exclude many low and middle income countries without a patent system. The remaining countries invent and import twice as many droughts and heatwaves technologies as floods technologies. At the same time, those countries are more impacted by extreme heatwaves and droughts than extreme precipitation, suggesting that countries both invent and import technologies according to the events affecting them.

Table 15. Descriptive Statistics on Regression Sample

| 1995-2015 | Droughts | | Floods | | Heatwaves | |
|--|-----------|-----------|-----------|-----------|-----------|-----------|
| | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std. Dev. |
| Dependent variable | | | | | | |
| Number adaptation inventions | 22.1 | 101.7 | 10.9 | 51.0 | 23.2 | 91.7 |
| Share of adaptation inventions in all technologies | 0.24% | 0.55% | 0.16% | 0.47% | 0.16% | 0.43% |
| Number adaptation imports | 17.5 | 36.0 | 10.0 | 24.3 | 21.3 | 45.6 |
| Share of adaptation imports in all technologies | 0.21% | 0.86% | 0.12% | 0.62% | 0.17% | 0.39% |
| Percentage of null observations (Inventions / imports) | 37% / 24% | | 48% / 35% | | 52% / 36% | |
| Independent variable | | | | | | |
| Agricultural area affected by extreme event | 5.9% | 8.6% | - | - | - | - |
| Country's population affected by extreme event | 5.9% | 9.0% | 4.7% | 10.2% | 8.0% | 18.6% |
| Protection of property rights Index | 10.1 | 2.6 | 5.7 | 1.8 | 5.9 | 1.7 |
| Freedom to trade | 7.83 | 1.17 | 7.77 | 1.17 | 7.81 | 1.09 |
| Number of countries | 54 | | 65 | | 58 | |

Source: Calculation based on PATSTAT (patents) and extreme event indicators (see Table 13).

Detailed information at the country level (Table A 13 in the appendix) shows a high concentration of the global invention of adaptation technologies. China, USA, South Korea and Japan represent around 80% of all technologies invented related to each of the three events. These countries are also the top inventor of overall technologies. However, the same countries import 'only' one third of all adaptation technologies transferred worldwide. It suggests that inventing or importing adaptation patents can be two distinct strategies. More generally, invention and import of adaptation technologies by countries are not perfectly correlated, as

the correlation coefficients between invention and imports of technologies are 0.50, 0.53 and 0.62 for droughts, floods and heatwaves related technologies respectively. As an example, Canada invents 288 heatwaves related adaptation patents but imports seven times more (2083) foreign heatwaves technologies. Conversely, Japan invents four times as many heatwaves related technologies (8297) as it imports (1955) (Table A 13). This difference stresses the need for the analysis of the two channels separately.

Table A 13 also gives detailed country level information on average exposure to climate extremes. Among countries in our droughts dedicated estimation, Portugal is the country where the population and the agriculture is the most affected by extreme droughts on average (9% for both), whereas Belarus people suffer few extreme droughts events, and their agriculture is also few exposed to droughts (3% in average). Population of Luxembourg is the most exposed to extreme precipitation, with around 9% of Luxembourgers under such events per year, whereas people in Malta almost never experienced it (0.3%). Finally, Tunisia is also the most exposed country to heatwaves with on average 62% of its population exposed to such events. Many countries never reach the temperature threshold of 38°C and are not considered as having faced any heatwaves in our study.

3.4 Methodology

Econometric models

Amount of innovation in adaptation technologies

To analyze the influence of extreme weather events on the domestic invention of adaptation technologies, we estimate the following distributive lag model:

$$INV_{e,c,t} = \exp\left(\sum_{k=1}^{10} \alpha_{t-k} * EVENT_{e,c,t-k} + \gamma * IPR_{c,t} + \delta_t + \mu_c + \epsilon_{ect}\right) \quad (A)$$

Our dependent variable is the number of patented inventions ($INV_{e,c,t}$) made by inventor country c , at year t to adapt to weather event e (this event is either droughts, floods or heatwaves). For patent data, t corresponds to the year of application of the earliest patented technologies of the patent family. The number of adaptation technologies invented is a function of various time lagged shares of the country's population affected by extreme events of type e occurring in country c , k years before t , $Event_{e,c,t-k}$. These variables represent the share of the country's population affected by an extreme event at year $t-k$, as defined in equation (2) above. Because droughts also threaten agriculture and food security, variations in droughts adaptation technologies are strongly related with the agricultural sector. We estimate a variant where $Event_{e,c,t-k}$ equals the share of agricultural country's area affected by extreme events (equation (3)). Heatwaves also have an effect on both agriculture and people, but most of our heatwaves related adaptation patents are infrastructure related technologies. Similarly, flash floods mainly threaten people and their infrastructure. It explains why we limit our analysis on agriculture to droughts.

We also include a measure of the strictness of intellectual property protection in the country ($IPR_{c,t}$). This index, extracted from the Economic Freedom of the World database provided by the Fraser Institute⁴², allows us to control for country- and time-specific variations of the propensity to patent a given invention.

Last, the equation includes country and time fixed effects (μ_c and δ_t respectively). Using year-fixed effects allows us to control for time specific trends, such as global weather events, economic shocks affecting the entire world as well as global climate policies. Country-fixed effects correct our estimation for country's time constant specifics, such as country's culture, climate conditions sensitivity or baseline environmental conditions. We cluster standard errors by country to control for over dispersion in the data (Miao & Popp 2014; Pigato et al. 2020).

The equation does not include any further standard controls, such as the population, the GDP per capita for reasons that deserve further explanation. Extreme weather events influence many economic outcomes. This has been established for instance by (Elliott et al. 2015; Hsiang & Jina 2014). They destroy assets in the short term and then induce more investments to rebuild affected infrastructures, they modify labor productivity as well as reduce agricultural yields (see Botzen, Deschenes, and Sanders (2019) for a review). Many of these consequences are likely to influence both the supply and the demand for innovation in the affected economy. Including them in the equation would then create a problem of overcontrolling or bad controls (Angrist & Pischke 2008). The coefficient α_{t-k} would then represent the marginal impact of the events on innovation holding these factors fixed whereas they are precisely the channels

⁴² The Economic Freedom of the World database is available here: <https://www.fraserinstitute.org/economic-freedom/dataset?geozone=world&page=dataset&min-year=2&max-year=0&filter=0>

through which climate extremes influence innovation. We follow here Hsiang (2016) who recommends to exclude these standard control variables from climate econometric models. The fundamental reason is that climate shocks are exogenous, and thus more immune to endogeneity than traditional economic or policy variables.

Along the same lines, we analyze the effect of extreme events on the imports of adaptation technologies estimating the following model:

$$IMP_{e,c,t} = \exp\left(\sum_{k=1}^{10} \alpha_{t-k} * EVENT_{e,c,t-k} + \gamma * IPR_{c,t} + \rho * TRADE_{c,t} + \delta_t + \mu_c + \epsilon_{ect}\right) \quad (B)$$

The dependent variable, $IMP_{e,c,t}$ represents the number of patents imported by the country c , country where the events occurred. Imported patents are all the patents filed in the country c for whom this country is not the inventor (or one of the several inventor countries). In addition to the protection of property rights index, the control variables include an indicator of trade openness ($Trade_{c,t}$), to account for country's openness to foreign products, including foreign patented technologies. The variable is provided by the Fraser Institute. We also use country and time fixed effects (μ_c and δ_t respectively), and clustered the standard errors by country.

In models (A) & (B), the annual number of patents invented or imported is a count variable. We could use either a (Quasi-Maximum Likelihood) Poisson or a Negative Binomial model. The important difference between the mean and the variance shown in Table 15 suggests Poisson overdispersion in our data, and so the use of a Negative Binomial estimation⁴³. However, conditional fixed effect estimator does not exist for Negative Binomial estimation. Alternatively, we used unconditional fixed effect estimator by adding country and year fixed

⁴³ The Pearson dispersion statistic for the Poisson estimation, equals to around 7, confirms the need for a Negative Binomial estimation.

effects as dummy variables in our regression (Allison & Waterman 2002; Greene 2007). We also correct for possible serial autocorrelation between the multiple consecutive lags of our climate variables by clustering the standard errors at the country level (Bertrand et al. 2004). Table 15 above also shows that for many years, countries do not invent (nor receive) any adaptation patents. To deal with this excess of zeros in our dependent variable, it is possible to use a Zero Inflated Negative Binomial (ZINB) model. This model includes a binary component that estimates the probability of excess zeros, called the inflation equation. In the body of the paper, we report the results for the Negative Binomial model for both inventions and imports of adaptation technologies. Results obtained from Zero Inflated Negative Binomial or Poisson estimations are detailed in the appendix (Table A 17 to Table A 20).

Share of innovation in adaptation technologies

Previous models examine the impact of climate extremes on the level of adaptation-related innovation. However, adaptation-related innovation may substitute for other innovations that have become less useful in the context of climate change. The increase in the frequency of events would then not only modify the level of innovation in adaptation technologies, as investigated by the previous models, but it would also decrease it in other areas, thus modifying the composition of innovation taken as a whole. In general terms, climate extremes would redirect technical change (Acemoglu et al. 2012).

To examine this aspect, we consider the following equation:

$$\text{SHARE_ADAPT}_{e,c,t} = f\left(\sum_{k=1}^{10} \text{EVENT}_{e,c,t-k}; X_{c,t}; \delta_t; \mu_c\right) \quad (\text{C})$$

Where $\text{SHARE_ADAPT}_{e,c,t}$ represents the share of adaptation technologies related to extreme event e , invented (imported) on the total number of technologies invented (imported) by country c at year t . $X_{c,t}$ is a vector of control variables including the protection of property rights index only in the case of inventions, and both protection of property rights and trade openness indicators for imported technologies.

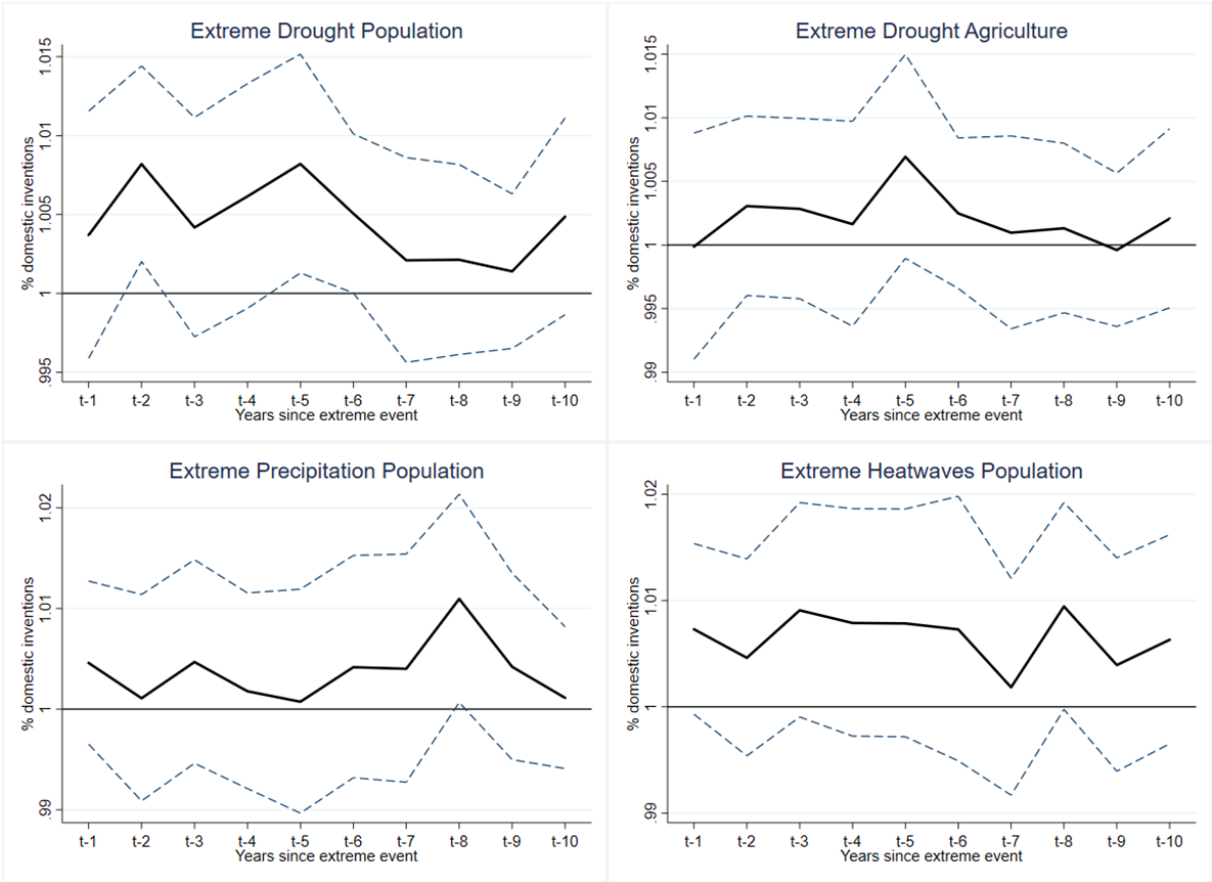
The share of adaptation technologies in all technologies is a skewed continuous variable bounded between zero and one but containing many zeros. We will then estimate the effect of extreme weather events on the proportion of adaptation technologies in all technologies using a Poisson fixed effects estimation.

3.5 Results

The level of invention in adaptation technologies induced by extreme events

Figure 12 shows the estimation of model(A). We find a small effect of extreme weather events on countries innovation in adaptation technologies.

Figure 12. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015



* Dotted lines indicate 95% confidence intervals computed from standard errors clustered at the country level. Shares of extreme events are expressed as percentage points for clarity. The y axis represents the effect of a one percent increase in the country's population affected by extreme events. Table A 14 in the appendix reports the estimates.

Domestic extreme weather events appear to have a positive effect on the invention of adaptation technologies. Countries react shortly to droughts affecting population by inventing adaptation technologies. Extreme droughts have a positive effect up to six years after the event occurs. Then, the effect decreases substantially. Countries respond later to extreme droughts

affecting their agricultural area. Their effect remains insignificant and smaller than for droughts affecting the population during the ten years following the event, except for a peak five years after the event. Finally, extreme precipitation and heatwaves threatening people show similar trends. Even if the impact of heatwaves is higher over the entire period, they both peak eight years after the event occurs.

To analyse the magnitude of the effects of extreme events on inventions (or imports) of adaptation technologies, we convert the extreme event regression coefficients to percentage points changes, as represented in Figure 12 above. To do so, we use the transformation $100 * (e^{\beta} - 1)$, where β is the value of the coefficient reported in Table A 14 in the appendix (also true for Table A 15). To make the interpretation of the results more intuitive, let us consider a typical country where an average 5% of the population is affected by extreme weather events per year. Consequently, a one percentage point increase in the share of the population affected by an extreme event, whose effect is shown in Figure 12, corresponds to a 20% increase in the average number of people affected per year in our typical country. Such increase in people affected by droughts leads to 0.8% more adaptation technologies invented two and five years after the event occurs. The magnitude of this effect is similar for extreme precipitation and heatwaves, with a rise of up to 1.1% of the number of adaptation patents invented.

While we have shown that inventors spontaneously address extreme weather events by inventing adaptation technologies several years after the event has occurred, most important is their long-term ability to innovate. We analyse the long-term impact of extreme weather events by computing the cumulative effect of the several lags. Since we are interested in the effect of these events over the long term, we calculate the 10 years cumulative effect of these events. The cumulative effect is equal to the sum of the extreme events annual coefficients

displayed in Figure 12 (see Annex 7 for more detailed information on the computation of the events' cumulative effect).

Table 16. Long-term Cumulative Effect of Extreme Weather Events on the Invention of Adaptation Technologies

| Inventions | Droughts | | Floods | Heatwaves |
|--|--------------------|--------------------|-------------------|-------------------|
| | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| 10 year extreme weather events cumulative effect | 0.046** (0.023) | 0.021 (0.028) | 0.024 (0.030) | 0.065 (0.045) |
| Protection of property rights | 0.139 (0.097) | 0.134 (0.109) | 0.139 (0.123) | 0.106 (0.093) |
| Period | 1995-2015 | | | |
| Observations | 1,040 | 1,096 | 1,204 | 1,143 |

* p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors (into brackets) clustered at the country level in parentheses. Long-term cumulative effects are computed for ten years lags. We only report the coefficient for the long-term cumulative effect and our control variable, but the delayed effect remains similar to those presented in Table A 14 in the appendix.

Table 16 shows this long run cumulative effect is significant for droughts affecting population only. We apply the exponential transformation mentioned above to interpret the coefficients. For our typical country, we found that a 20% increase in the average number of people affected by droughts over the last ten years will significantly increase the number of droughts related inventions by around 5%. The higher coefficient, although insignificant, is for heatwaves. A similar 20% rise in the number of people affected by heatwaves leads to 7% more adaptation patents filed in the country on the long run, whereas droughts affecting agriculture and extreme precipitation have a smaller effect and insignificant long-term effect. The small effect of droughts affecting agriculture is in line with the findings of previous studies analysing adaptation in the agricultural sector and weather impact on crops yields (Burke & Emerick 2016; Wing et al. 2021).

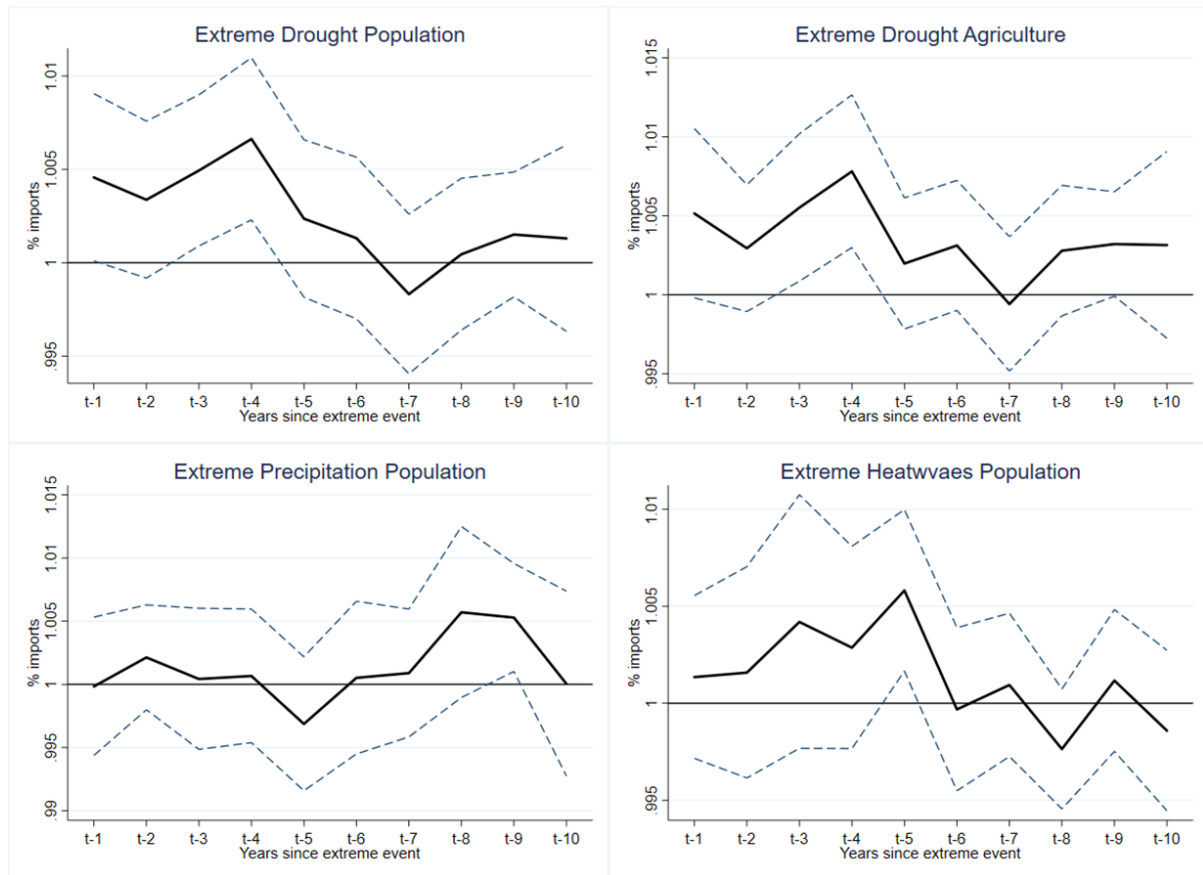
Finally, a better protection of property rights has a positive but insignificant effect on the propensity to patent. This result may be due to the small variation of this indicator over time, whose effect is captured by country fixed effects. Moreover, we are already reducing our sample to countries where patents are filed and which therefore mostly provide a certain level of protection.

Finally, we compare the results obtained with those from Zero Inflated Negative Binomial or Poisson presented in the appendix (Table A 17 to Table A 20). Except that Poisson regressions are more lax and may lead to higher significance of the coefficients, results remain the same, using either Negative Binomial or Zero Inflated Negative Binomial models.

The level of imports of adaptation technologies

Figure 13 shows the effect of past extreme events on the number of adaptation patents filed by inventor located in foreign countries. This figure shows that countries not only invent adaptation technologies when they are affected by an event, but they also import technologies from foreign countries. The effects observed in Figure 13 below are similar to those observed for inventions.

Figure 13. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015



* Dotted lines indicate 95% confidence intervals computed from standard errors clustered at the country level. Shares of extreme events are expressed as percentage points for clarity. The y axis represents the effect of a one percent increase in the country's population affected by extreme events. Table A 15 in the appendix reports the estimates.

A noticeable difference is the stronger impact of droughts threatening agriculture on the imports of technologies. The delayed effects of droughts affecting population and agricultural areas on technology imports are roughly similar. However, droughts affecting agriculture have a greater (and significant) impact on imports than on domestic technology invention. This difference suggests that non-inventor countries compensate a lack of innovation capacities by importing technologies. As their economy rely much more on the agriculture than developed countries that have the capacity to invent their technologies, they strongly react by importing foreign adaptation technologies to protect future harvest and their

economy. The ten-year average cumulative effect of these events on imports, reported in Table 17 below, supports this observation. An average one percentage point increase in the share of agricultural land affected by droughts over the past 10 years augments the number of imported adaptation technologies by 3.5%, while they had an insignificant and almost two times smaller effect on domestic innovation. On the contrary, the effect of droughts affecting population on imports is 80% lower than on domestic inventions.

Table 17. Long-term Cumulative Effect of Extreme Weather Events on the Imports of Adaptation Technologies

| Imports | Droughts | | Floods | Heatwaves |
|--|---------------------|---------------------|---------------------|---------------------|
| | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| 10 year extreme weather events cumulative effect | 0.025* (0.014) | 0.035** (0.015) | -0.009 (0.018) | 0.014 (0.015) |
| Protection of property rights | 0.069 (0.053) | 0.049 (0.048) | 0.061 (0.048) | 0.048 (0.038) |
| Freedom to trade | 0.159*** (0.060) | 0.171*** (0.060) | 0.270*** (0.053) | 0.189*** (0.060) |
| Period | 1995-2015 | | | |
| Observations | 1,059 | 1,038 | 1,173 | 1,184 |

* $p < 0:10$, ** $p < 0:05$, *** $p < 0:01$. Standard errors (into brackets) clustered at the country level in parentheses. Long-term cumulative effects are computed for ten years lags. We only report the coefficient for the long-term cumulative effect and our control variable, but the delayed effect remains similar to those presented in Table A 15 in the appendix.

Extreme heatwaves and precipitation also boost imports of adaptation technologies. The effect of heatwaves increases until five years after the event took place, and then diminishes. Extreme precipitation has a later effect than heatwaves or droughts, with a significant impact on imports only nine years after the event. However, as shown in Table 17, the magnitude of the heatwaves long-term effect on imports is five times lower than on inventions, and still

insignificant. Similarly, the long-term average effect of extreme precipitation on imports is below the one on inventions, and slightly negative.

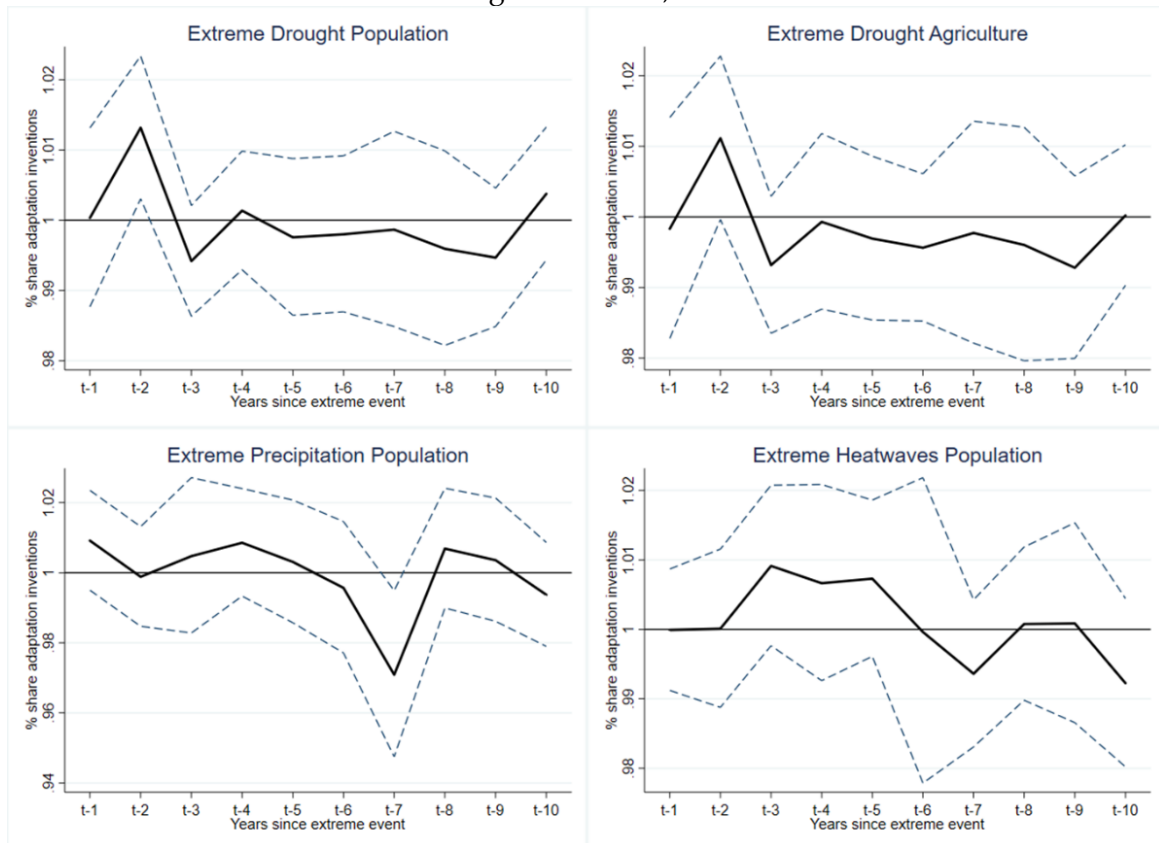
Finally, while the enforcement of intellectual property protection has no clear effect on technology imports, trade openness appears to be a strong driver of adaptation patents imports.

Directed technical change

Estimations presented above suggest countries react to extreme weather events by inventing and importing adaptation technologies. However, the omission of several control variables to avoid “bad controls” or “over controlling effect” makes it difficult to draw accurate conclusions. In particular, we cannot know whether countries respond to such events by innovating specifically in adaptation technologies, because we do not control for global innovation trends. In addition, many factors we do not control for may induce the long-term lagged effects observed above, which could lead to omitted variable bias.

To fill this gap, we estimate the effect of extreme weather events on the share of adaptation technologies invented (and imported) in all technologies (model (C)). The results of these estimations presented in Figure 14 allow us to analyze the intensity and the dynamic of a potential directed technical change.

Figure 14: Effect of Extreme Weather Events on the Share of Adaptation Inventions in all Technologies Invented, 1995-2015



* Dotted lines indicate 95% confidence intervals computed from standard errors clustered at the country level. Share of extreme events are expressed as percentage points for clarity. The y axis represents the effect of a one percent increase in the country's population affected by extreme events. Table A 16 in the appendix reports the estimates.

We observe a positive and significant effect of extreme droughts affecting both people and agricultural area two years after the event occurs. This effect then decreases and becomes insignificant for the rest of the period. It suggests extreme droughts significantly redirect innovation toward adaptation on the very short term. This effort dedicated to adaptation can explain the short-term rise in the invention of adaptation technologies following extreme droughts. However, the sustained and long-term cumulative effect observed for the rest of the period seems to come from technological innovation in general. While countries significantly redirect innovation towards adaptation technologies in the first years following extreme droughts, we do not observe the same effects for extreme precipitation and heatwaves. Their

effects are slightly positive until six years, before falling down. We also observe a negative and slightly significant effect of extreme precipitation seven years after the event occurs, suggesting that the positive effect of such events on the level of innovation is only a reflection of the innovation in all technologies.

3.6 Conclusion

Summary of the findings and policy implications

Whereas extreme climate events are among the most threatening consequences of climate change, adaptation technologies can help to reduce the expected damages they will cause to human society. Scientists plan climate change will increase frequency and intensity of extreme events, especially in countries already affected by such kind of events. In this paper, we rely on a new patent data classification targeting adaptation technologies to analyze how countries historically reacted to domestic weather shocks, by inventing or importing adaptation technologies. We built original climate indicators reflecting the percentage of the country's population or agricultural area affected by extreme events per year.

Focusing on three kinds of events (droughts, extreme precipitation and heatwaves) occurring in up to 65 countries, we find innovators weakly react to extreme weather events by inventing and importing new adaptation technologies. Extreme droughts and heatwaves have significant short-term effects, while the effect of precipitation appears eight years after the event occurs. Our study also suggests extreme droughts have a significant cumulative effect on the invention and imports of adaptation technologies, meaning that countries more affected in average by such events over the last ten years invent (and import) more adaptation

technologies. For example, an average one percentage point increase in the share of people affected by extreme droughts over the past ten years increases by 4.6% the number of domestic adaptation patented inventions, and induces 2.5% more imports.

However, the second part of the analysis suggests that, except for droughts, extreme weather events do not significantly redirect innovation towards adaptation technologies. The effect of extreme precipitation and heatwaves on the share of adaptation technologies invented (or imported) on all technologies remains insignificant whatever the number of lags considered. Extreme droughts seem to induce a short-term reallocation of the innovation efforts towards adaptation up to two years after the event occurs, which cannot explain the longer-term impact of such events on the number of droughts related adaptation technologies invented.

Such observation suggests that the future increase in the frequency of extreme weather events will not significantly boost innovation in adaptation technologies. Public policies may be needed to scale up the switch towards adaptation technologies. Policy makers may first promote the local supply of innovation in adaptation technologies by implementing R&D grants dedicated to these technologies. This option is highly dependent on the ability of stakeholders to accurately identify technologies useful for adapting to climate change, and is limited to the major technology inventor countries. However, public stakeholders can also increase demand for adaptation technologies as a public good. It appears to be a more appropriate solution, especially for countries with low technological capacity, which often depend on foreign technologies and therefore cannot influence the supply of adaptation technologies. A first step to increase demand is to generate accurate knowledge about the country's adaptation needs. Countries have to better understand the impacts of extreme weather events today while identifying how climate change will modify their current

exposure. Then, they should clearly diagnose and expressed their adaptation technology needs, through their Technology Needs Assessment (TNA) reports and National Adaptation Plans (NAPs). Since private innovation is mainly driven by economic profit, foreign, but also local inventors need to identify commercial opportunities for their technologies. Last, countries also have to create an enabling environment for investment in adaptation projects. As shown in the analysis of adaptation technology imports, trade openness remains an essential driver to attract foreign technologies. Non-innovator countries must ensure that inventors could export their technologies and guarantee ownership of these technologies.

Limitations and future research areas

Despite the broad geographical and technological coverage of our analysis, the use of patent data forces us to rely only on rich countries. Poorest countries do not report patent data, mainly because they do not have institutional capabilities to ensure intellectual property rights. Inventors will in return prefer industrial secrecy than patents to protect their technologies in such countries. It constitutes a major limitation of our analysis, as the poorest countries are expected to be the most impacted by climate change. Patents also lead us to consider mainly innovation in technologies at the technology frontier. Many non-patented technologies, as well as low- tech solutions are used but do not appear in our data. For the two reasons mentioned above, finding proxies other than patent data should be the target of future research to analyze innovation and use of technologies in such countries. Another limitation of our study is the focus on three extreme weather events. We have shown that countries react differently to various events, and one should so complete the understanding of this topic by analyzing the effect of other extreme events, such as dust storms, storm surges or wildfires.

Finally, this study focuses only on one adaptation strategy, i.e. the invention and use of adaptation technologies. Migration of people away from exposed areas, change in institutional organizations, education and insurance system improvements constitute other solutions to adapt to a changing climate (Hallegatte et al. 2011; Zilberman et al. 2012). To efficiently adapt to climate change, countries will need to innovate in various solutions and combine them in a smart way. Looking at innovation in other adaptation options, such as institutional organization or local and international adaptation finance, and understanding how they influence the development of adaptation technologies opens a broad scope for future research.

4 Impact of Extreme Weather Events on Adaptation Patents Owners Behavior: a Firm Level Analysis

Simon Touboul

Abstract

Extracting applicant-level adaptation patent data from six countries, I analyze how the exposure of firms to local and foreign droughts and precipitation influence patent owners innovation behavior in adaptation technologies. Focusing on the period 1995-2015, preliminary results first confirm that extreme weather events have a small impact on adaptation patent filing. Second, I find that patent owners only react to extreme weather events occurring in their home country. It suggests innovators do not capture average foreign demand for adaptation technologies, and that technology transfer is not an efficient channel yet for non-innovator countries to access adaptation technologies. Finally, I find no evidence of co-innovation between companies with strong technological capabilities and inventors from affected countries.

Keywords: climate change adaptation, innovation, extreme weather events, adaptive capacity

JEL codes: O33; O57; Q51 ; Q54; Q55 ; C33

Résumé

Dans ce chapitre, j'extraie des données de brevets d'adaptation à l'échelle des détenteurs individuels dans six pays. J'utilise ces données individuelles pour analyser comment l'exposition des entreprises aux sécheresses et précipitations locales et étrangères influence le comportement d'innovation des titulaires de brevets dans les technologies d'adaptation. En se concentrant sur la période 1995-2015, ces résultats préliminaires confirment d'abord que les événements climatiques extrêmes ont un faible impact sur le dépôt de brevets d'adaptation. Ensuite, je constate que les détenteurs de brevets ne réagissent qu'aux événements climatiques extrêmes qui se produisent dans leur pays. Cela suggère que les innovateurs ne saisissent pas la demande étrangère pour les technologies d'adaptation, et que le transfert de technologie n'est pas encore un canal efficace pour que les pays non-innovateurs accèdent aux technologies d'adaptation. Enfin, je ne trouve aucune preuve de co-innovation entre les entreprises ayant de fortes capacités technologiques et les inventeurs des pays touchés par ces extrêmes climatiques.

CHAPTER 4

Impact of Extreme Weather Events on Adaptation

Patents Owners Behavior: a Firm Level Analysis

4.1 Introduction

Do extreme droughts and precipitation lead technology inventors to file adaptation patents in the affected countries? In this chapter, I pursue the work done in chapter 3, observing innovator and patent owners behavior facing extreme weather events. I investigate patent filings of adaptation technologies following extreme droughts and precipitation occurring in both the home country of the inventor and abroad. Using patent data, I know the identity of the innovator(s) and all the countries where a given patent has been filed. This information permits the analysis of the effect of extreme weather events on the invention of new adaptation technologies, but also their patenting to foreign countries, a proxy for knowledge transfer. A more detailed analysis of technology transfers helps to clarify the conclusions of the first and third chapters, but also to assess the impact of extreme events as drivers of adaptation patent transfers. Moreover, the identification of patents invented by multiple innovators makes the analysis of 'co-invented' patents possible, including co-innovation between companies with strong technological capabilities and innovators located in the affected country, who better know local adaptation needs. Such cooperation, especially when the affected country has low technological capability, also constitutes an active transfer of knowledge. Co-innovation appears to be a promising solution for the implementation of adaptation technologies. It gives

affected countries access to adaptation technologies better suited to their needs, as adaptation solutions often present strong local specificities (IPCC 2014).

In this analysis, I focus on inventors located in six countries⁴⁴, namely France, Germany, Japan, the Netherlands, United Kingdom and the United States of America. These countries concentrate around 60% of all adaptation technologies patented over the period 1995-2015. I target more than 4,000 innovators using their BvDid number, and cover more than 75% of all adaptation inventions made by these countries over the period. I quantify recipient countries exposure to droughts and floods using the same weather indicators as in the previous chapter.

My work mainly relies on two sides of the economic literature. First, I provide further evidence on innovation in adaptation technologies and exposure to extreme weather events. I complement the work did in this thesis and by other researchers, such as Miao and Popp (2014) and (Li 2017). Second, my work relates to studies on firms innovation following demand shocks in their home country and abroad. In a recent paper, Aghion et al. (2018) and Cai, Wu, and Zhang (2020) show that a growth in firms' export market extension boosts firms innovation. Similarly, as argued by Liu and Ma (2020) and Coelli, Moxnes, and Ulltveit-Moe (2020), trade liberalization in foreign countries induce firms innovation.

To the best of my knowledge, it is the first study to investigate the effect of extreme weather events on firms' patent filing in their partner countries. Using a logistic regression, I conduct my analysis in three parts. First, I use a distributive lag model to analyze the dynamic of the innovation following extreme weather events occurring in the home country of the inventor and abroad. I confirm that, as shown in chapter three, such events have a small effect on

⁴⁴ These six countries are among the top 10 countries inventing the most adaptation patents.

adaptation patent filing. Then, I analyze the heterogeneous reaction of firms to events occurring in their home country or abroad. I find that firms react much more strongly to events occurring in their home country. The effect of foreign weather events remains small and insignificant over the entire period. This last observation constitutes a serious issue if we believe that patent filing is a proxy for technology transfer. It suggests countries with low innovation capabilities do not access adaptation technologies through spontaneous technology transfer from foreign inventors. It is in line with the mismatch between future adaptation needs and current adaptation technology availability described in the first chapter, and suggests firms are not able to capture foreign demand for adaptation technologies. Finally, I attempt to analyze the effect of extreme weather events on the co-invention of patents, defined as patents filed by a foreign firm but invented in cooperation with local innovators. Preliminary results suggest no effect of extreme weather events on the propensity to carry-out 'co-innovations'.

The remainder of this analysis is organized as follow. In the next part, I describe the data used in this analysis, and I provide descriptive statistics. Then I detail my econometric strategy, before presenting the initial findings of my study. I conclude in the last section, with a strong emphasis on areas for future research.

4.2 Data Issues

Data sources

Firm level patent data

I extract patent data from the PATSTAT database provided by the European patent Office (EPO). I select adaptation patents within the Y02A classification, restricting the classification to technology classes related with droughts or floods (see list of the selected CPC codes in the Appendix). Using the docdb family codes, I rely on patent families to count the number of patent filed in a country. Patent data allow me to identify both the country where the patent is invented and all countries where a given patent (patent family) has been filed. For a given patent family, I define the application year as the filing year of the very first patent in this family. I target the company inventing the technology using the BvDid number provided by PATSTAT. More than 645,000 firms are identified with a BvDid number, and they invent half of the 42 million inventions listed in the entire PATSTAT database.

In addition, patent data also give detailed information on inventors' cooperation in the innovation process. Using the docdb patent family indicator, I access the set of inventors involved in the invention of the same technology. With this information, I define 'co-invention' or 'co-innovation' as patent families whose include the cooperation between multiple inventors. For the third part of this analysis, I focus on patents co-invented by a selected firm (see below) and a foreign innovator located in the country affected by the event.

Climate indicators

I am interested in the effect of extreme droughts and extreme precipitation leading to flash floods on the filing of adaptation patents. I use the original weather indicators described in the previous chapter to compute the share of country's population affected by each of the two extreme events per year from 1980 to 2015⁴⁵.

4.3 Sample Restriction

I restrict the sample to patent families filed between 1995 and 2015. To improve data relevance, I select firms located in 6 countries among top 10 inventor countries, namely the United States of America, Japan, Germany, France, United Kingdom and the Netherlands, as explained below. These six countries account for more than 62% of all adaptation patents invented worldwide for the period 1995-2015 (see chapter 1 for more details).

Table 18. Share of Adaptation Technologies Invented by Identified Firms (1995-2015)

| Inventor Country | All adaptation | Droughts | Floods |
|-------------------------|-----------------------|-----------------|---------------|
| Canada | 50.9% | 38.5% | 46.5% |
| China | 17.9% | 20.6% | 28.5% |
| Germany | 75.4% | 47.2% | 43.7% |
| France | 73.3% | 41.8% | 65.6% |
| United Kingdom | 73.8% | 53.9% | 60.9% |
| Japan | 70.7% | 64.3% | 79.1% |
| South Korea | 44.6% | 42.0% | 52.5% |
| Netherlands | 88.8% | 93.8% | 96.6% |
| Sweden | 66.4% | 51.7% | 50.5% |
| USA | 83.9% | 59.1% | 62.6% |

Source: Authors' calculations based on World Patent Statistical Database (PATSTAT) data.

⁴⁵ Raw data on extreme precipitation are only available from 1981.

From the top 10 inventor countries, I first remove China because the firms identified with a BvDid number only represent 18% of all adaptation inventions made by China, and these Chinese firms are filing their inventions almost only in China (see Table 18 above and Table 19 below). Similarly, I exclude Canada, South Korea and Sweden for two reasons. First, inventors identified with a BvDid cover less than 70% of all adaptation inventions made by these countries during the period 1995-2015 (Table 18). Second, as shown in Table 19, inventors from these countries filed their droughts or floods related patents in a few number of countries.

Table 19. Number of Patent Offices Where Firms Filed at Least One Adaptation Patent, by Inventor Country (1995-2015)

| Inventor Country | All | Droughts | Floods |
|-------------------------|------------|-----------------|---------------|
| Canada | 30 | 8 | 5 |
| China | 14 | 7 | 4 |
| Germany | 67 | 37 | 37 |
| France | 63 | 26 | 27 |
| United Kingdom | 63 | 25 | 28 |
| Japan | 61 | 26 | 24 |
| South Korea | 36 | 11 | 11 |
| Netherlands | 48 | 41 | 39 |
| Sweden | 54 | 21 | 6 |
| USA | 71 | 49 | 38 |

Source: Authors' calculations based on World Patent Statistical Database (PATSTAT) data.

I further restrict my sample to pairs of (firms ; patent office) which exchanged at least 10 patents (all technologies) over the period. As shown in Table 20 below, I end up with 2,764 pairs of (firms; country) exchanging droughts patents and 2,180 pairs transferring floods patents, corresponding to 1,114 and 984 patent owners respectively filing their patents in 50 or 47 countries. The detailed number of adaptation inventors per country is available in Table A 21 in the appendix.

4.4 Descriptive Statistics

Table 20 below details the average value and standard deviations of the variables used in my regressions.

Table 20. Descriptive Statistics on Regression Sample

| | Droughts | | Floods | |
|--|-----------------|-----------|---------------|-----------|
| | Mean | Std. Dev. | Mean | Std. Dev. |
| Dependent variables | | | | |
| Dummy adaptation patent filed | 0.087 | 0.282 | 0.086 | 0.281 |
| Dummy adaptation patent co-invented | 0.002 | 0.042 | 0.001 | 0.035 |
| Independent variables | | | | |
| Recipient country's population affected by extreme event (%) | 6.10 | 7.62 | 4.30 | 6.29 |
| Protection of property rights Index | 7.16 | 1.40 | 7.28 | 1.33 |
| Freedom to trade | 8.11 | 0.90 | 8.18 | 0.85 |
| Number of pairs (firms; patent office) | 2,764 | | 2,180 | |
| Number of inventor firms | 1,114 | | 984 | |
| Number of recipient countries | 50 | | 47 | |
| Period | 1995-2015 | | | |

Source: Authors' calculations based on World Patent Statistical Database (PATSTAT) data.

I first observe the equal propensity to file a droughts or a floods related adaptation patent in a given year, around 9%. Similarly, the propensity to be involved in co-invention is roughly similar for droughts and for floods related technologies. However, people are more exposed to droughts (6.1%) than to extreme precipitation (4.3%), suggesting inventors do not react strongly to people exposure by filing adaptation patents. Finally, general recipient countries characteristics (protection of property rights and trade openness indexes from the Fraser Institute) are identical between both samples, suggesting droughts and floods patents are filed in roughly the same countries.

4.5 Empirical Strategy

Model specification

To study whether firms filed adaptation patents in countries affected by extreme droughts or precipitation, I estimate a finite distributive lag model at the pair (firm;patent office) level. In equation (1) below, I first estimate the average effect of local and foreign extreme weather events on adaptation patent filing in the affected countries. Then, I estimate the same model disentangling the effect of local and foreign weather events using equation (2). Finally, I mimic previous estimations to analyze extreme weather events propensity to induce co-innovation (equation (3)). Such models allow me to analyze the temporal heterogeneous impact (dynamic) of past weather events on adaptation patent filing.

I estimate equation (1), (2) and (3) for both droughts and floods related adaptation patents⁴⁶, as follow:

Adaptation patent filing

$$\text{Patent}_{f,c,t,e} = f\left(\sum_{k=1}^{10} \alpha_{t-k} * \text{EVENT}_{e,c,t-k} + \gamma * \text{IPR}_{c,t} + \rho * \text{TRADE}_{c,t} + \theta_{f,c} + \theta_t + \epsilon_{f,c,t,e}\right) \quad (1)$$

where $\text{Patent}_{f,c,t,e}$ is a dummy variable equals to 1 if firm f files at least one adaptation patent in country c at year t , related to extreme event e (droughts or floods). $\text{EVENT}_{e,c,t-k}$ is our indicator of people exposure to extreme droughts or precipitation. It is the share of recipient country c population affected by extreme weather events e at year $t-k$ (see chapter 3 for more details). I also include two control variables to measure country's time variant characteristics,

⁴⁶ We also run the same estimation on droughts affecting agricultural area as a robustness check. Results are presented in the appendix Table A 25 to Table A 27).

namely the protection of property rights index ($IPR_{c,t}$) and the trade openness index ($TRADE_{c,t}$), both available in the Economic Freedom of the World database provided by the Fraser Institute. We also add firm-country fixed effect ($\theta_{f,c}$) and year fixed effect (θ_t) in the estimation. ϵ_{fct} is the error term.

Heterogeneous impact of local and foreign weather events

$$Patent_{f,c,t,e} = f\left(\sum_{k=1}^{10} \omega_{t-k} * EVENT_{e,c,t-k}^{home} + \sum_{k=1}^{10} \varphi_{t-k} * EVENT_{e,c,t-k}^{foreign} + \lambda * X_{c,t} + \theta_{f,c} + \theta_t + \epsilon_{f,c,t,e}\right) \quad (2)$$

where $EVENT_{e,c,t-k}^{home}$ is the share of country c population affected by extreme weather event e when country c is the home country of the inventor, and $EVENT_{e,c,t-k}^{foreign}$ the share of country c population affected by extreme weather event e when country c is not the home country of the inventor. $X_{c,t}$ is a vector of control variables containing the protection of property rights and the trade openness indexes.

Co-invention of adaptation patents

$$Co_Patent_{f,c,t,e} = f\left(\sum_{k=1}^{10} \beta_{t-k} * EVENT_{e,c,t-k}^{foreign} + \gamma * IPR_{c,t} + \rho * TRADE_{c,t} + \theta_{f,c} + \theta_t + \epsilon_{f,c,t,e}\right) \quad (3)$$

where $Co_Patent_{f,c,t,e}$ is the co-invention (co-innovation) variable. It is a dummy variable equals to 1 if firm f files in country c one or several adaptation patents related to extreme event e and co-invented with an inventor located in this country c , at year t . Control variables include country c openness to trade and property rights indexes as in equation (1) and (2).

Estimation strategy

In each of the equations above, the dependent variables are binary variables equal to zero or one. I choose to use a logistic estimator (logit). I run a year and pair (firm; country) fixed effect regression, and cluster standard errors by pairs. The year fixed effect allows me to control for global events, such as globalization or global climate change effects. It also controls for worldwide climate change or adaptation related policies, such as the effect of the COPs. The pair fixed effect controls for time invariant patenting activity relationship between the firm and the country. It controls if a group based in the country where the patent is filed owns the firm, or if the inventor firms belongs to a group owning other firms in this country. It also checks for cultural or historical relationship between the firm and the country, including long-term relationship between the home country of the firm and the recipient country. Finally, this 'pair' fixed effect also controls for patent office invariant characteristics, such as the average exposure to extreme events or special arrangements between countries regarding patent filings. In the appendix, I also provide the results of estimations including inventor country specific time trends, to control for potential trends in innovation and growing awareness of the impact of climate change. I cannot add an inventor country time fixed effect as it will capture the effect of extreme events occurring in the home country of the inventor, which are part of the variables of interest. Similarly, adding a patent office year fixed effect would hide the effect of the variable of interest, and cannot be included.

4.6 Results

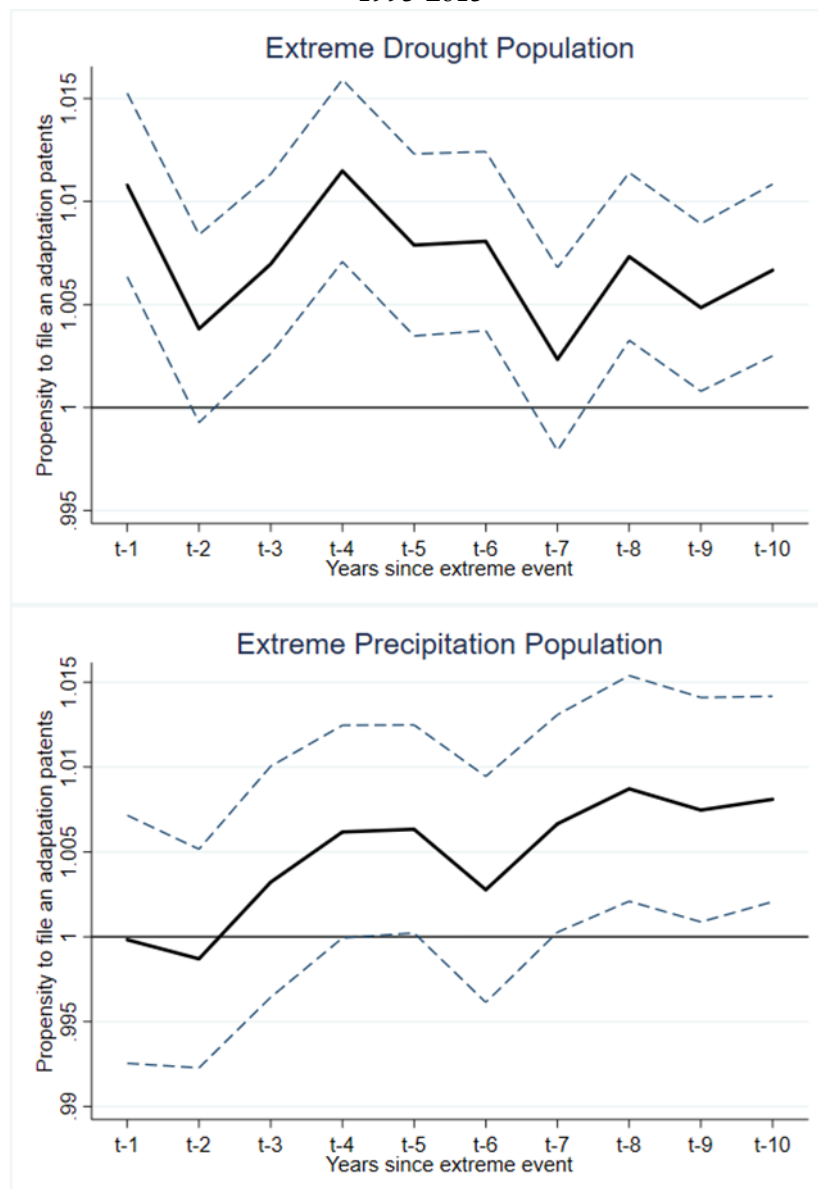
Preliminary results from this analysis are divided in three parts. I first describe the average dynamic effect of extreme weather events, occurring in both the home country of the inventor and abroad, on the propensity to file adaptation patents in the affected countries. Second, I disentangle this effect between home and foreign extreme weather events. Finally, I look at the effect of foreign extreme weather events on the propensity to 'co-invent' adaptation patents.

Average extreme weather events effect

Figure 15 below shows the dynamic effect of extreme weather events on the patenting of adaptation technologies.

I first confirm the observations made in the third chapter regarding the small effect of extreme weather events on innovation. By adding more observations and focusing on the best inventor countries, I improve the significance and so the robustness of the findings reported in the previous chapter. I find the effect of extreme droughts affecting people peaks four years after the event occurs. Then, this effect slightly decreases until the end of the period, but remains positively significant. In average, a one-percentage point increase in the share of people affected by droughts rises firm's propensity to file a patent in this country by up to 1.2%. The effect of extreme precipitation on adaptation patent filing is also made clearer in this chapter. Their effect grows almost linearly with the number of lags over the entire period. A one-percentage point increase in the share of country's population affected by extreme precipitation significantly boosts the propensity to file a floods related patent by 0.9% at the maximum.

Figure 15. Effect of Foreign and Extreme Weather Events on the Filing of Adaptation Patents, 1995-2015



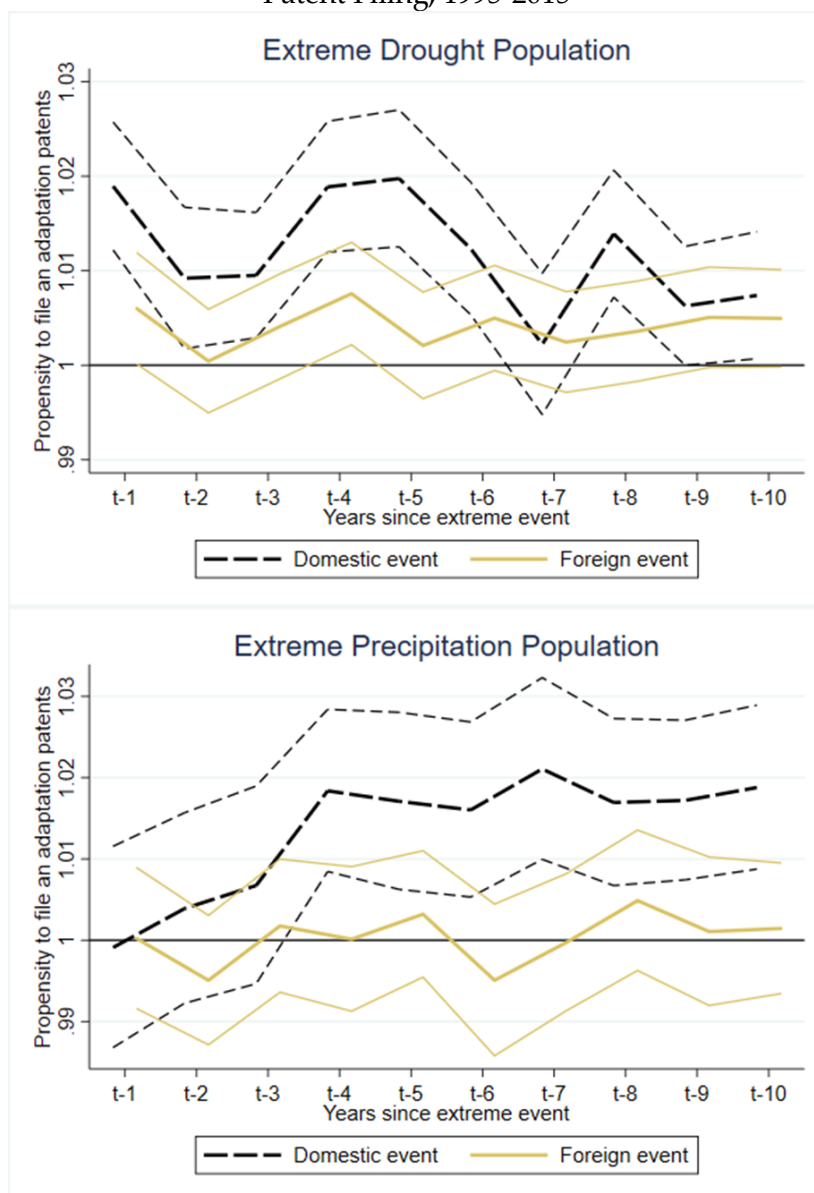
* Dotted lines indicate 95% confidence intervals computed from standard errors clustered at the pair (firm;country) level. Shares of extreme events are expressed as percentage points for clarity. The y axis represents the effect of a one percent increase in the country's population affected by extreme events. Table A 22 in the appendix reports the estimates.

The results remain stable controlling for inventor country specific time trend (column (B) in Table A 22 in the appendix), meaning adaptation patent filing is not driven by a differential trend in propensity to patent among inventor countries (as suggested by Figure A 3 and Figure A 4 in the appendix).

Differentiated effect of local and foreign extreme events

After confirming the small average effect of weather event on firms patenting behavior, I now want to disentangle this effect between local and foreign weather events. Making such a difference allows me to analyze the effect of extreme weather events on the invention and the transfer of adaptation technologies. Figure 16 below shows the results of the estimation of equation (2). Dashed black lines show the estimated coefficients and confidence intervals for extreme weather events occurring in the home country of the inventor, while solid lines in sand color reveal the impact of foreign weather shocks. First, the black line always stands above the solid line for both estimations on droughts and precipitation, with confidence intervals at the 95% level significantly different for some years. It means local weather events have a higher impact on adaptation patent filing than foreign ones. Because inventors usually filed their invention first in their home country, we can read the dotted line as the dynamic impact of extreme weather events on firms' inventions. Consequently, local weather events drive the results observed above while foreign ones have a constantly small and insignificant effect.

Figure 16. Differentiated Effect of Local and Foreign Extreme Weather Events on Adaptation Patent Filing, 1995-2015

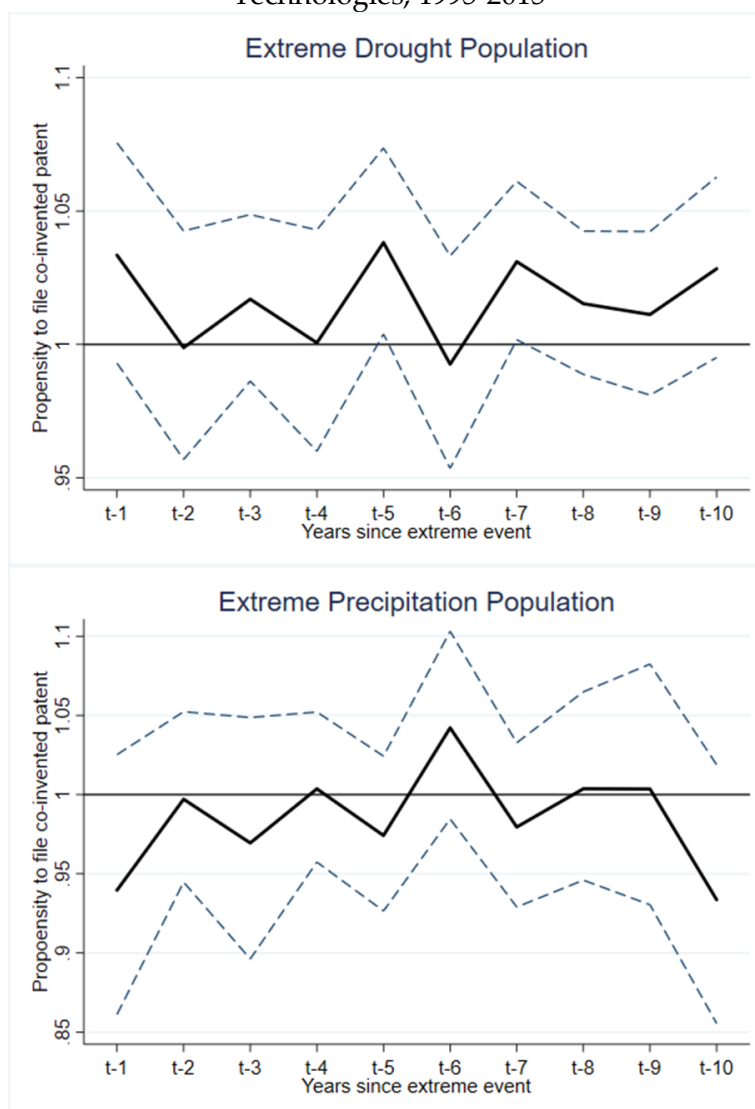


* Dotted lines indicate 95% confidence intervals computed from standard errors clustered at the pair (firm;country) level. Shares of extreme events are expressed as percentage points for clarity. The y axis represents the effect of a one percent increase in the country's population affected by extreme events. Table A 23 in the appendix reports the estimates.

Do extreme weather events lead to co-invention?

In the last part of this analysis, I evaluate if extreme weather events lead to co-innovation. Figure 17 above shows no evidence on the effect of extreme weather events on co-invention. Despite small significant effects five to seven years after the event occurs, the propensity to implement co-inventions following extreme weather events remains low and insignificant for the rest of the period. These small effects are in line with observations made in the previous part of this analysis. However, the large standard errors may be explained by the small number of observations included in this last part. These rare collaborations constitute in themselves a worrying result, suggesting affected countries do not access technical expertise from major inventors to help them creating new technologies designed for their local specific needs.

Figure 17. Effect of Extreme Weather Events on the Co-Invention of Adaptation Technologies, 1995-2015



* Dotted lines indicate 95% confidence intervals computed from standard errors clustered at the pair (firm;country level). Shares of extreme events are expressed as percentage points for clarity. The y axis represents the effect of a one percent increase in the country's population affected by extreme events. Table A 24 in the appendix reports the estimates.

4.7 Conclusion

This preliminary analysis provides a deeper understanding of firms patenting behavior following extreme weather events. Covering most of the adaptation technologies invented by six of the top 10 adaptation inventor countries for the period 1995-2015, I provide the first firm level evidence on the innovation in adaptation technologies following extreme weather events. I first confirm the small effect of extreme droughts and precipitation leading to flash floods on firms' innovation in adaptation technologies. Moreover, I also argue that firms only react to events occurring in their home country, and find no evidence of technology transfer to foreign countries. As firms usually ask for patent protection first in their own country, I argue that I observe the invention of technologies following extreme events, but not the extension of their protection to other countries. This finding may explain partly the gap between adaptation needs and adaptation technology availability observed in the first chapter of this dissertation. Countries with low technology capabilities may indeed not have the required skills to invent technologies designed for their needs, and this study shows they will not spontaneously receive them from foreign inventors neither. I also observe that the effects of local extreme events on innovation are quite small, as doubling the average number of people affected by extreme droughts only leads to a 12% increase in the propensity to file a droughts related patent. Moreover, this analysis only cover 'rich' countries (those that usually receive patents), so the overall picture may be much worse. Finally, I find no evidence of an increase in technological cooperation following extreme weather events, suggesting affected countries do not associate with highly skilled innovators to create new technologies fitting their specific local adaptation needs.

4.8 Limitations and Areas for Further Improvements

The fourth and last chapter of this dissertation presents preliminary results of a first attempt to describe firms patenting behavior following extreme droughts and precipitation. Even if this analysis deserves further improvements, it makes the findings of the previous chapter more robust. This last chapter also opens promising areas for future research. In this last paragraph, I list the limitations of this analysis and ideas for further studies.

First, while I cannot control more for patent office characteristics to avoid problems of overcontrolling, I could add more background information about innovators. Further studies could rely on the BvD id number to match PATSTAT with Orbis⁴⁷ database for example, and get more material about technology inventors and patent owners. Such data permit to distinguish public institutions from privately owned firms, as well as further investigate the link between the innovator and the patent office. Second, I consider in the analysis that firms equally react to events happening in all foreign countries where they usually file patents. However, one could think that the ‘closer’ the company is to the recipient country, the more sensitive it is to variations in demand for climate adaptation technologies. Gathering commercial or investment data between the firm and the patent office may help to measure this proximity and improve our understanding. The results regarding the difference between home and foreign countries may indeed partly be due to this “proximity”. Collecting more data on firms may also improve the methodology, and allow researchers to identify the main drivers of technology transfers. One may be interested in measuring the effect of national adaptation

⁴⁷ More information about the Orbis database is available via this link: <https://www.bvdinfo.com/en-gb/>

plans, blended finance, or international adaptation projects funding on the transfer of adaptation technologies.

Finally, my attempt to study co-inventions deserves further analysis. I am targetting only few co-invented patents among all the inventions. While it suggests that technological cooperation between affected countries and major inventors is rare, I am not able to identify the drivers of such international collaboration. Project level analysis may help to identify the enablers and barriers of such cooperation (if it exists), but also evaluate the relevance and limits of the use of patent data to investigate such promising solutions.

Conclusion

This dissertation explores innovation in adaptation technologies around three axes. First, I give an up-to-date description of the geography and recent trends in the invention and transfer of adaptation technologies. Second, I provide some of the first evidences of technology efficiency to mitigate negative weather impacts. Third, I confirm extreme weather events boost the innovation in adaptation technologies but I nuance their effect on both the invention and the diffusion of such technologies.

The remainder of this last section is organized as follow. In the first part, I summarize the main findings and their policy implications. Then, I end this dissertation listing the limitations of my approach and purposing areas for future research.

Main conclusions and their policy implications

Promote technologies as an efficient adaptation tool

Chapter 2 provides one of the first empirical evidence on the global efficiency of adaptation technologies to mitigate climate change negative impact, based on tropical storms induced damages. I argue that technologies are an efficient tool to protect both people life and assets from storms, estimating that millions of US\$ damages may be avoided using more adaptation technologies. The analysis also suggests that recently patented technologies are more efficient than older ones and that only technologies specifically designed to tackle storms impact are efficient. This chapter shares the view of many international institutions and experts asking for more innovation specifically dedicated to adaptation technologies.

Global efforts needed in innovation for adaptation technologies

While recent adaptation technologies limit climate change impacts, innovation in adaptation technologies remains very low. In the first chapter of this dissertation, I describe both the geographical distribution and the recent trends of the innovation in adaptation technologies. Using for the first time a new patent classification gathering adaptation technologies, I report a worrying situation. First, the share of global adaptation patents invented in all technologies over the last 20 years remains stable, meaning countries do not devote more efforts to the invention of adaptation technologies than to innovation in general. As an illustration, the average annual growth rate in innovations dedicated to adaptation technologies is around 7%, far behind the 11% observed for mitigation technologies over the same period. Second, only few patent families protect adaptation technologies, too few to efficiently limit the damages caused by extreme weather events in the past. Adaptation related inventions represent only 0.5% of all technologies invented over the period while mitigation technologies almost reached 6%. The difference in both the trends and the amounts of inventions dedicated to either adaptation or mitigation illustrates that, until now, innovation efforts have been mostly dedicated to mitigate global warming before adapting to a changing climate. The geography of the innovation in adaptation technologies is equally disquieting. Innovation is highly concentrated among few countries, as ten countries account for 80% of all adaptation technologies invented. This geographical imbalance of the innovation, enforced by a lack of technology transfers, leads to a mismatch between the actual availability of adaptation technologies and future country's adaptation needs.

International transfer of adaptation technologies is a major issue

Patent data also allow me to identify the transfers of technologies between countries. Technology transfers could compensate for the geographical concentration of adaptation inventions, but it is not the case. I report in the first chapter that adaptation technologies are two times less transferred internationally than mitigation ones. Moreover, two thirds of these transfers occurred between high income countries. In the last chapter, I also show that inventors do not spontaneously transfer their technologies in foreign countries affected by extreme weather events. Patent owners do not seem to capture external demand for their technologies, while observations in chapter one suggest adaptation patented technologies are not more locally specific than average technologies. This finding suggests countries with low innovation capacity are denied access to adaptive technologies. This is an important result as most of the poorest and non-inventor countries are among the most vulnerable ones.

Recent increase in adaptation finance may help to fill this gap. By developing blended finance strategies or conditioning grants funding to the exchange of adaptation technologies, international agreements can facilitate access to these technologies for the poorest countries. Other solutions, such as restructuring the patent system to improve international cohesion, royalty free patents or an extension of the polluter-pay principle beyond finance (countries that are not responsible for climate change will be the most impacted) should be explored. I think the way Covid-19 forces countries all over the world to think about global resilience and the mechanisms put in place by international institutions to encourage both international solidarity and the engagement of the private sector provides multiple avenues to inform thinking on adaptation.

A limited spontaneous response of innovators to extreme weather events

While climate change will increase both frequency and intensity of extreme weather events globally, chapter three reveals that countries react little to these events by either inventing their own adaptation technologies or importing foreign ones. The fourth and last chapter confirm the low response of innovators to natural disasters, and suggest they only react to events taking place in their home country. Such situation could be improved by stimulating the demand for adaptation technologies. First, promoting concrete examples of effective implementation of adaptation technologies could help to boost the demand while encouraging proactive adaptation. For example, the UNFCCC Special Climate Change Fund is financing demonstration (pilot) projects and knowledge hubs to help stakeholders better evaluate the potential of these technologies. Second, increasing the generation and sharing of knowledge regarding current and future adaptation technology needs at both country and local scales may help innovators better identify market opportunities for their technologies. Guides summarizing key adaptation knowledge (Hallegatte et al. (2020) is an example) can also help stakeholders better understand how to integrate the use of technology into comprehensive adaptation strategies. Third, the implementation of clearly detailed adaptation plans both at the national and subnational level, combined with a specific support for innovation in adaptation technology, can influence both supply and demand for adaptation technologies.

Limitations and future research areas

Measuring innovation using patent: additional issues for climate change adaptation

I already listed the limits of the use of patents as a proxy for the invention and transfer of technologies, but this indicator presents additional issues specific to climate change adaptation. First, whereas mitigating climate change requires mostly 'high' technologies, communities may also refer to low tech and indigenous solutions to adapt. The use of patents prevents me from measuring the innovation and the availability of such technologies. Second, many countries do not have a functional patent system, mainly because their institutions are not strong enough to ensure intellectual property rights to patent owners. In these countries, mostly the middle and low income ones, technologies are used out of the patent system. While mitigation technologies are needed in countries emitting the most, roughly the richer and top inventor countries, the majority of the most vulnerable countries are part of low or middle-income groups. Although decades of research dedicated to mitigation technologies have used patent data, growing interest for adaptation technologies may need the finding of additional proxies. Even if it is difficult to find another global measure to track adaptation technologies, I think in-depth analysis of internationally funded adaptation projects may constitute a promising area to get information on countries uncovered using patents. As countries receiving international support for adaptation actions are the poorest one, using text searching or other techniques in projects description may help to identify the interest of these countries for adaptation technologies. I began to implement such strategy during my thesis by gathering all adaptation projects funded by organizations listed in the Climate Fund Inventory database provided by the OECD. Unfortunately, time constraints and technical issues caused this initiative to fail.

A deeper understanding of the drivers of innovation and technology transfer is crucial

In my view, this dissertation leaves two major questions open. First, we can ask why inventors do not react to foreign extreme weather events by transferring their technologies. Second, the reasons behind the heterogeneous reaction of inventors to the different events remain unclear. A deeper understanding of the economic mechanisms leading to this observation would provide valuable information to design better adaptation policies. The effect of adaptation finance, such as multilateral or bilateral agreements, on the transfer of technologies should be analyzed, as well as other general factors that may boost or hinder innovation or technology transfers (trade barriers, bilateral trade agreements, intellectual property rights enforcement...). The first question above suggests patent owners do not capture foreign demand for their adaptation technologies. Many issues remain on the ways we could integrate more the private actors in the adaptation efforts.

Are technologies efficient to mitigate all climate change impacts?

While I establish that adaptation technologies can mitigate storms negative impacts, many questions remain regarding overall adaptation technologies efficiency. First, I limit the analysis to storms related technologies, and my observations have to be confirmed for other climate events. In particular, technologies efficient today may not be sufficient or appropriate for future climate conditions. The creation and implementation of so-called 'no-regret' or flexible solutions have to be favored to ensure long-term resilience (Hallegatte 2009). Second, this dissertation focuses on adaptation solutions at the technology frontier. However, the combination of indigenous skills and low-tech strategies with high-tech options are essential to decrease economic cost of technological solutions while improving community understanding and acceptance of new technologies. Moreover, detailed evaluations of the

performance of all available adaptation technologies may be conducted to dedicate innovation efforts towards the most promising technologies. Case studies and detailed technology level analysis could also provide information on the environment needed to successfully use or implement technological solutions. Taking into account local specificities, such as technological knowledge, both current and future climate conditions, and political barriers, is essential for the effective implementation of adaptation technologies. Finally, technology is not the only solution to adapt. Understanding the linkages between technologies and softer forms of adaptation levees (new insurance scheme, educational and knowledge improvement, organizational innovations ...), and the limits of the use of technologies is essential to avoid maladaptation and unnecessary costs.

From technology availability to effective use of technologies

Finally, although I describe the inter-country diffusion of adaptation technologies, I do not address intra-country distribution of such technologies. Using patents, filed at the country level, I only describe “vertical” diffusion of adaptation technologies, forgetting the “horizontal” dissemination within countries. However, the access to, but also the efficiency of adaptation technologies may substantially vary between regions. First, climate change threats may greatly differ among places. Second, different regions rely on various economic sectors each with specific technological needs. Third, local population characteristics (technology acceptance, climate change sensitivity, representations within political classes ...) are not the same across regions. Again, while the global analysis conducted in this dissertation summarizes some key findings, more detailed analysis of case studies, projects funding descriptions or local adaptation plans are key to understand the on-the-ground deployment of adaptation technologies.

Appendix

Annex 1. PATSTAT Y02A classification (August 2018)

CPC COOPERATIVE PATENT CLASSIFICATION**Y GENERAL TAGGING OF NEW TECHNOLOGICAL DEVELOPMENTS; GENERAL TAGGING OF CROSS-SECTIONAL TECHNOLOGIES SPANNING OVER SEVERAL SECTIONS OF THE IPC; TECHNICAL SUBJECTS COVERED BY FORMER USPC CROSS-REFERENCE ART COLLECTIONS [XRACs] AND DIGESTS***(NOTES omitted)***Y02 TECHNOLOGIES OR APPLICATIONS FOR MITIGATION OR ADAPTATION AGAINST CLIMATE CHANGE***(NOTES omitted)***Y02A TECHNOLOGIES FOR ADAPTATION TO CLIMATE CHANGE****NOTE**

This subclass covers technologies for adaptation to climate change, i.e. technologies that allow adapting to the adverse effects of climate change in human, industrial (including agriculture and livestock) and economic activities.

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|--------------|---|--------------|---|
| 10/00 | at coastal zones; at river basins | 10/46 | . . . Computerized flood control, risk assessment or mapping |
| 10/11 | . Hard structures | | |
| 10/12 | . . Reservoirs; Polders | 10/48 | . . Hazard insurance |
| 10/13 | . . Dykes; Dams | 20/00 | Water conservation; Efficient water supply; Efficient water use |
| 10/14 | . . Sea-walls, surge or tidal barriers | 20/10 | . Relating to general water supply, e.g. municipal or domestic water supply |
| 10/15 | . . Self-contained breakwaters | | |
| 10/16 | . . Revetments of the shore | 20/102 | . . Tanks |
| 10/17 | . . Groynes | 20/104 | . . . for municipal applications |
| 10/18 | . . Jetties or landing bridges | 20/106 | . . . for domestic applications |
| 10/20 | . Soft structures | 20/108 | . . Rainwater harvesting |
| 10/21 | . . Land claim or beach nourishment | 20/109 | . . Obtaining drinking water from air humidity |
| 10/22 | . . Wetland restoration or creation | 20/112 | . . Obtaining drinking water from open water |
| 10/23 | . . Dune restoration or creation | 20/114 | . . Water wells |
| 10/24 | . . Cliff stabilization | 20/116 | . . . Vertical well filter pipes |
| 10/25 | . . Artificial seaweed | 20/118 | . . . Borehole wells |
| 10/26 | . . Artificial reefs | 20/119 | . . . having horizontal or inclined filter pipes |
| 10/27 | . . Restoration or protection of coral reefs | 20/12 | . . Multipurpose dams or barriers |
| 10/28 | . . Sediment management | 20/124 | . . Water desalination |
| 10/30 | . Flood prevention; Flood management or accommodation; Storm water management | 20/126 | . . . characterized by the method |
| 10/31 | . . Permanently installed flood barriers | 20/128 | Evaporation methods, e.g. distillation |
| 10/32 | . . Temporarily installed flood barriers | 20/129 | using solar energy |
| 10/33 | . . Infiltration of water into the ground | 20/131 | Reverse-osmosis |
| 10/34 | . . Flood-proof sanitary latrines | 20/132 | Freezing |
| 10/35 | . . Revetments for protection of river banks or dykes | 20/134 | Electrodialysis |
| 10/36 | . . Equalizing tanks in the sewage system for regulating the run-off | 20/138 | powered by a renewable energy source |
| 10/37 | . . Bioswales | 20/141 | the source being wind power |
| 10/38 | . . Changing the natural surface of ground to re-route water | 20/142 | the source being solar thermal or photovoltaics |
| 10/383 | . . . Weirs | 20/144 | the source being wave energy |
| 10/386 | . . . Locks | 20/146 | . . Use of grey water |
| 10/39 | . . Evacuation systems | 20/148 | . . . using household water from wash basins or showers |
| 10/395 | . . Curb floodplain development for flood management | 20/15 | . . Leakage reduction or detection in water storage or distribution |
| 10/40 | . Monitoring; Forecasting; Planning | 20/152 | . . Water filtration |
| 10/41 | . . of coastal areas | 20/154 | . . . of domestic water |
| 10/42 | . . Real-time flood forecasting | 20/156 | . . . of municipal or industrial water |
| 10/44 | . . Disaster preparedness plans | 20/16 | . . Water quality or standards enforcement |
| | | 20/18 | . . Solar- or wind-powered water pumping |

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| 20/20 | . . Water pollution control technologies | 30/248 | Recycled materials, e.g. made of used tires, bumpers or newspapers |
| 20/202 | . . . for households | | |
| 20/204 | . . . Keeping clear the surface of open water from oil spills | 30/249 | . . . Glazing |
| 20/206 | . . . Monitoring water for contaminating materials | 30/25 | Vacuum glazing |
| 20/208 | . . Off-grid powered water treatment | 30/251 | Aerogel glazing systems |
| 20/211 | . . . Solar-powered water purification | 30/252 | . . . Wooden or plastic window or door frames with extra insulation |
| 20/212 | . . . Solar-powered wastewater sewage treatment, e.g. spray evaporation | 30/253 | . . . Roofs with adaptation potential |
| 20/214 | . . . Water treatment at point of use for potable water | 30/254 | Roof garden systems |
| 20/216 | . . . Wastewater treatment tanks | 30/255 | Roof coverings with high solar reflectance |
| 20/218 | . . Water metering with adaptation potential, e.g. aiming at water saving, leakage detection or avoidance, fraud or theft detection | 30/256 | . . . Floors specially adapted for storing heat or cold |
| 20/22 | . . Pricing strategies aiming to limit water consumption or spillage, e.g. progressive pricing, fraud detection or fostering water saving | 30/257 | . . . Light dependent control systems for sun shading |
| 20/30 | . Relating to industrial water supply, e.g. used for cooling | 30/259 | . . Passive climatisation |
| 20/302 | . . Use of lower-grade water | 30/26 | . . . using air flow into the conditioned premises or facilities |
| 20/304 | . . Recirculation | 30/261 | . . . by improving the thermodynamic properties of the premises or facilities |
| 20/40 | . Water resources protection or enhancement | 30/27 | . . Relating to heating, ventilation or air conditioning [HVAC] technologies |
| 20/402 | . . River restoration | 30/272 | . . . using solar thermal energy |
| 20/404 | . . Saltwater intrusion barriers | 30/274 | . . . using waste energy, e.g. from internal combustion engine |
| 20/406 | . . Aquifer recharge | 30/276 | . . . of the sorption type |
| 20/408 | . . Draining or infiltration of impermeable surfaces for groundwater enrichment | 30/277 | Absorption based systems |
| 20/411 | . . Water saving techniques at user level | 30/278 | Adsorption based systems |
| 20/412 | . . . Reducing amount of water used by toilet flushing | 30/30 | . . in transportation |
| 20/414 | . . . Water-saving for showers or bath tubs | 30/31 | . . Relating to road transportation |
| 30/00 | Adapting or protecting infrastructure or their operation | 30/32 | . . . Permeable parking lots |
| 30/10 | . in energy generation or distribution | 30/33 | . . . Ground surface material |
| 30/12 | . . Weather forecasting for energy supply management | 30/333 | Warm-mix asphalt |
| 30/14 | . . Extreme weather resilient electric power supply system, e.g. strengthening power lines or underground power cables | 30/336 | Engineered cementitious composite [ECC] |
| 30/16 | . . Flood resilient electric equipment | 30/34 | . . Relating to waterways transportation |
| 30/17 | . . . Generators | 30/35 | . . . Storm resilient vessels |
| 30/18 | Uninterruptible power supply [UPS] systems; Backup generators | 30/36 | . . . Active motion-dampening systems for ports |
| 30/19 | . . . Cabinets or switch boards | 30/38 | . . Relating to railways transportation |
| 30/20 | . in buildings, dwellings or related infrastructures | 30/40 | . Relating to water supply or wastewater treatment |
| 30/21 | . . Floating houses | 30/45 | . . Specially adapted pumping equipment e.g. for flood draining |
| 30/22 | . . Rotary buildings | 30/50 | . Resilient IT infrastructure |
| 30/23 | . . Elevated buildings | 30/60 | . Planning or developing urban green infrastructure |
| 30/24 | . . Structural elements or technologies for improving thermal insulation | 30/62 | . . Integration of district energy or distributed or on-site energy generation, e.g. combined heat and power generation or solar energy, in city layout |
| 30/241 | . . . Thermal insulation technologies with adaptation potential | 30/64 | . . for reducing heat island effects, e.g. by minimizing paved surfaces or by planting trees |
| 30/242 | Slab shaped vacuum insulation | 30/68 | . . Sloping ground terrains in public areas |
| 30/243 | Slab shaped aerogel insulation | 40/00 | Adaptation technologies in agriculture, forestry, livestock or agroalimentary production |
| 30/244 | characterized by the use of locally available building materials | 40/10 | . in agriculture |
| 30/245 | of vegetal origin, e.g. thatching or straw | 40/11 | . . Specially adapted for crops |
| 30/246 | of animal origin, e.g. wool or feathers | 40/12 | . . . Precision agriculture |
| 30/247 | using indigenous Earth materials, e.g. clay or stone | 40/13 | . . . Abiotic stress |
| | | 40/132 | Plants tolerant to drought |
| | | 40/135 | Plants tolerant to salinity |
| | | 40/138 | Plants tolerant to heat |
| | | 40/14 | . . . with increased yield |
| | | 40/143 | using agrochemicals |
| | | 40/146 | Transgenic plants |
| | | 40/15 | . . . Fungal symbiosis |
| | | 40/16 | . . . Pest or insect control |

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| 40/162 | Genetically modified [GMO] plants resistant to insects | 40/237 | Efficient irrigation techniques, e.g. drip irrigation, sprinkler or spray irrigation |
| 40/164 | Genetically modified [GMO] plants resistant to nematodes | 40/238 | Irrigation information systems |
| 40/166 | Ecological pest control, i.e. using competitors or parasites against crop pests | 40/239 | Lining of canals with plastic films |
| 40/168 | Rainguards for rubber trees | 40/24 | Concentrate irrigation in periods of peak growth |
| 40/17 | Aeroponics seed potato production | 40/241 | using brackish water |
| 40/18 | Related to fertilizer management | 40/242 | Limiting land conversion or deforestation |
| 40/19 | Integrated nutrient management, e.g. appropriate fertilizer use | 40/243 | Afforestation or reforestation |
| 40/20 | Sustainable fertilizers of biological origin | 40/25 | Greenhouse technology |
| 40/201 | Fertilizers made from animal corpses or parts thereof | 40/252 | Constructional details of greenhouses |
| 40/202 | from fish or from fish-wastes | 40/254 | Dismountable or portable greenhouses; Greenhouses with sliding roofs |
| 40/203 | from meat-wastes or from other wastes of animal origin, e.g. skins, hair, hoofs, feathers, blood | 40/256 | Lighting systems for greenhouses |
| 40/204 | Apparatus for their manufacture | 40/258 | Shading devices for greenhouses |
| 40/205 | Fertilizers from human or animal excrements, e.g. manure | 40/26 | Lamellar or like blinds |
| 40/206 | Guano | 40/262 | Inflatable structures |
| 40/207 | from human fecal masses | 40/264 | Devices or systems for heating, ventilating, regulating temperature, or watering |
| 40/208 | Apparatus for the manufacture | 40/266 | Collecting solar energy |
| 40/209 | Fertilizers made from waste originating from industrial processing of raw material of agricultural origin or derived products thereof | 40/268 | Air-conditioning systems |
| 40/21 | Solid waste from mechanical processing of material, e.g. seed coats, olive pits, almond shells, fruit residue, rice hulls | 40/27 | Watering arrangements |
| 40/211 | Waste from chemical processing of material, e.g. distillation, roasting, cooking | 40/272 | Efficient watering |
| 40/212 | Waste from biochemical processing of material, e.g. fermentation, breweries | 40/274 | Electric devices |
| 40/213 | Fertilizers from waste water, sewage sludge, sea slime, ooze or similar masses | 40/28 | specially adapted for farming |
| 40/214 | Fertilizers from household or town refuse | 40/282 | Changing farming practices to conserve soil moisture or nutrients; Reduce run-off or control soil erosion |
| 40/215 | Apparatus for the manufacture | 40/284 | Mulch stubble or straw |
| 40/216 | Biological compost | 40/286 | Crops rotation |
| 40/22 | Improving land use; Improving water use or availability; Controlling erosion | 40/288 | Avoiding mono-cropping; Crop diversification |
| 40/221 | Change land topography to improve water uptake or to reduce wind erosion | 40/29 | using lower planting densities |
| 40/222 | by subdividing large fields | 40/292 | Terracing |
| 40/223 | Grass waterways maintenance | 40/294 | Agro-forestry, silviculture or mixed farming solutions |
| 40/224 | by roughening land surface | 40/296 | Bushfire prevention; Prescribed fire, i.e. controlled burning to reduce fuel buildup |
| 40/225 | Windbreaks | 40/298 | Forest fire control |
| 40/226 | Floating agriculture | 40/30 | Timing of farming operations |
| 40/227 | Control of sand encroachment | 40/302 | Advance sowing dates to offset moisture stress during warm periods |
| 40/228 | Wetland restoration or protection | 40/40 | Management of saline soils |
| 40/229 | Biochar technologies | 40/50 | Evapotranspiration |
| 40/23 | Improving water use or availability; Controlling erosion | 40/51 | specially adapted for storing agricultural or horticultural products |
| 40/231 | in rain-fed agriculture | 40/52 | Racks for drying purposes |
| 40/232 | Soil conservation | 40/53 | Natural, e.g. solar drying |
| 40/233 | Methods for working soils | 40/55 | Silos for storing seeds or grain |
| 40/234 | Moss gardening | 40/57 | Off-grid powered storage |
| 40/235 | in irrigated agriculture | 40/58 | using renewable energies |
| 40/236 | Tillage conservation | 40/60 | Ecological corridors or buffer zones |
| | | 40/70 | in livestock or poultry |
| | | 40/72 | Climate tolerant animal varieties, e.g. selective breeding |
| | | 40/73 | Providing additional fodder for cattle during the dry season, e.g. by using fodder banks |
| | | 40/74 | Optimising pasture management |
| | | 40/75 | Environmental control in livestock or poultry housing, e.g. of temperature or humidity |
| | | 40/76 | using renewable energy |
| | | 40/78 | Livestock or poultry disease management, wherein the disease is affected by climate change |

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| 40/80 | . in fisheries management | 50/22 | . . . Air sterilisation or disinfection |
| 40/81 | . . Aquaculture, i.e. culture of aquatic animals | 50/23 | . . Emission reduction or control |
| 40/812 | . . . of fish | 50/232 | . . . Catalytic converters |
| 40/814 | Prevention or treatment of fish diseases | 50/2322 | for exhaust after-treatment of internal combustion engines in vehicles |
| 40/816 | Hatching, e.g. incubators | 50/2324 | Three way catalysts, i.e. for controlled oxidation or reduction of exhaust gases, e.g. stoichiometric equivalence ratio |
| 40/818 | Alternative feeds for fish aquaculture | 50/2325 | Selective Catalytic Reactors [SCR] |
| 40/82 | . . . of shellfish | 50/2326 | for industrial applications |
| 40/822 | of bivalves, e.g. oysters or mussels | 50/2327 | in chemical or petrochemical processes, |
| 40/824 | of crustaceans, e.g. lobsters or shrimps | 50/2328 | Burners or incinerators e.g. of waste or waste gases |
| 40/826 | . . . Floating cultivation devices, e.g. rafts or floating fish-farms | 50/234 | . . . Physical or chemical processes, e.g. absorption, adsorption or filtering, characterised by the type of pollutant |
| 40/828 | Connecting or mooring devices therefor | 50/2341 | Carbon monoxide [CO] |
| 40/83 | . . . Artificial fishing banks or reefs | 50/2342 | Carbon dioxide [CO ₂] |
| 40/832 | made of tyres | 50/2343 | Lead [Pb] |
| 40/834 | assembled of components | 50/2344 | Nitrogen oxides [NO _x] |
| 40/836 | floating | 50/2345 | Nitrogen dioxide [NO ₂] |
| 40/838 | of monolithic form, e.g. blocks | 50/2346 | Ammonia [NH ₃] |
| 40/84 | Arrangements for sinking or mooring thereof | 50/2347 | Ground-level ozone |
| 40/845 | . . . Feeding devices | 50/2348 | Sulfur oxides [SO _x] |
| 40/86 | . . Information Technologies [IT] supporting fishing | 50/2349 | Sulfur dioxide [SO ₂] |
| 40/88 | . . Seaweed farming; Management of sea grass beds | 50/235 | Volatile organic compounds [VOC] |
| 40/90 | . in food processing or handling | 50/2351 | Atmospheric particulate matter [PM], e.g. carbon smoke microparticles, smog, aerosol particles, dust |
| 40/92 | . . in food processing | 50/2352 | the particulate matter coming from a source on-board a vehicle, e.g. removed by diesel particulate filters [DPF] |
| 40/922 | . . . Technologies for reducing water consumption | 50/2353 | the particulate matter coming from stationary sources, e.g. power plants, steel mills, smelters, cement plants, refineries or incinerators |
| 40/924 | . . . using renewable energies | 50/2354 | Cyclones |
| 40/926 | Cooking stoves or furnaces using solar heat | 50/2355 | Filters |
| 40/928 | Cooking stoves using biomass | 50/2356 | Scrubbers, spray chambers, pack towers |
| 40/94 | . . relating to food conservation | 50/2357 | Electrostatic precipitators |
| 40/941 | . . . using natural products | 50/2358 | . . . Biological purification of waste gases |
| 40/942 | using natural sugars | 50/2359 | with gas-solid contact |
| 40/943 | using natural acids, e.g. vinegar, citric | 50/24 | . . Pollution monitoring |
| 40/944 | using vegetal oils | 50/241 | . . . specially adapted for public areas |
| 40/945 | Salt based conservation | 50/242 | . . . characterized by the pollutant |
| 40/946 | using brine | 50/243 | Carbon monoxide [CO] |
| 40/947 | . . . Off-grid thermal processing | 50/244 | Carbon dioxide [CO ₂] |
| 40/948 | Sun drying | 50/245 | Nitrogen Oxides [NO _x] |
| 40/949 | Food smoking | 50/246 | Ammonia [NH ₃] |
| 40/95 | of edible seeds | 50/247 | Ozone [O ₃] |
| 40/96 | . . relating to food management or storing | 50/248 | Sulfur oxides [SO _x] |
| 40/961 | . . Biopackaging, e.g. packaging containers made from renewable materials, bioplastics or biodegradable materials | 50/249 | Volatile Organic Compounds [VOC] |
| 40/962 | . . . Wood Barrels | 50/25 | Atmospheric particulate matter [PM] e.g. carbon smoke microparticles, smog, aerosol particles, dust |
| 40/963 | . . . Off-grid food refrigeration | 50/30 | . Against vector-borne diseases, e.g. mosquito-borne, fly-borne, tick-borne or waterborne diseases whose impact is exacerbated by climate change |
| 40/964 | Devices using naturally cold air or forced air convection | 50/31 | . . Vector control |
| 40/965 | Devices using heat pumps | 50/32 | . . . using natural substances as pesticides or insecticides, for fighting the disease vector |
| 40/966 | Powered by renewable energy sources | 50/321 | characterised by the vector |
| 40/967 | using waste heat, e.g. from an internal combustion engine | | |
| 40/968 | using ice | | |
| 50/00 | in human health protection | | |
| 50/10 | . against extreme weather events | | |
| 50/12 | . . Early warning systems for extreme weather events | | |
| 50/14 | . . Storm shelters or storm cellars | | |
| 50/16 | . . Landslide or mudflow monitoring or protecting systems | | |
| 50/20 | . Air quality improvement or preservation | | |
| 50/21 | . . Mechanical or electrostatic filtering in heating, ventilation or air conditioning [HVAC] | | |

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|--------|-----------|---|--------|-----------|---|
| 50/322 | | Ticks | 50/384 | | of the genus Flavivirus |
| 50/323 | | Insects | 50/385 | | the disease being Dengue |
| 50/324 | | Stink bugs, bed bugs, kissing bugs or triatomine bugs | 50/386 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/325 | | Chigoe or jigger fleas, cat fleas, moorhen fleas or rat fleas | 50/387 | | the disease being Yellow fever, i.e. Ochropyra |
| 50/326 | | Sand flies, black flies or Tsetse flies | 50/388 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/327 | | Mosquitos | 50/389 | | the disease being Japanese encephalitis |
| 50/328 | | Aedes | 50/39 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/329 | | Culex | 50/391 | | the disease being Zika |
| 50/33 | | Anopheles; Culiseta; Mansonia; Psorophora | 50/392 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/331 | | Snails of the genus Biomphalaria, Oncomelania or Bulinus | 50/393 | | the disease being West Nile fever |
| 50/332 | | characterised by the natural substance | 50/394 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/333 | | Substances of botanical origin, e.g. essential oils, waxes, flowers, seeds, leafs or wood | 50/395 | | the disease being Tick-borne encephalitis [TBE] |
| 50/334 | | Plant oils, i.e. vegetable or essential oils | 50/396 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/335 | | Canola oil | 50/397 | | of the genus Nairovirus, i.e. Congo-Crimean haemorrhagic fever or Rift valley fever or Hantaan haemorrhagic fever |
| 50/336 | | Castor oil | 50/398 | | the vector-borne disease being caused by a bacteria |
| 50/337 | | Catnip oil, e.g. nepetalactone | 50/399 | | of the genus Borrelia |
| 50/338 | | Cedar oil | 50/40 | | the bacteria being Borrelia crocidurae, Borrelia duttoni, Borrelia hermsii, Borrelia hispanica, Borrelia miyamotoi, Borrelia parkeri or Borrelia turicatae, i.e. relapsing fever or borreliosis |
| 50/339 | | Cinnamon oil | 50/401 | | the bacteria being Borrelia burgdorferi, i.e. Lyme disease or Lyme borreliosis |
| 50/34 | | Citronella oil | 50/402 | | of the genus Rickettsia, Orientia, Ehrlichia, Neorickettsia, Neoehrlichia or Anaplasma, i.e. Rickettsial diseases, e.g. spotted fever |
| 50/341 | | Cocunut oil | 50/403 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/342 | | Eucalyptus oil | 50/404 | | the bacteria being Francisella tularensis, i.e. Tularaemia |
| 50/343 | | Lemon oil | 50/405 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/344 | | Geranium oil | 50/406 | | the bacteria being Yersinia pestis, i.e. Plague |
| 50/345 | | Mustard oil | 50/407 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/346 | | Neem oil, e.g. Azadirachtin | 50/408 | | the vector-borne disease being caused by a protozoa |
| 50/347 | | Orange oil | 50/409 | | of the genus Leishmania i.e. Leishmaniasis, Sand-fly fever, phlebotomus fever, kala-azar, black fever or Dumdum fever |
| 50/348 | | Soybean oil | 50/41 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/349 | | Camphor | | | |
| 50/35 | | Garlic | | | |
| 50/351 | | Pepper | | | |
| 50/352 | | Rotenone | | | |
| 50/353 | | Tobacco or nicotine | | | |
| 50/354 | | Pyrethrum, e.g. Chrysanthemum cinerariifolium | | | |
| 50/356 | | Fermented microbes, e.g. abermectins or spinosad | | | |
| 50/357 | | Substances of mineral origin | | | |
| 50/358 | | Sulfur | | | |
| 50/359 | | Kaolin; Diatomaceous earth | | | |
| 50/36 | | Natural soaps | | | |
| 50/37 | | Means for catching or killing the vector, e.g. traps or nets | | | |
| 50/371 | | the vector being mosquitos | | | |
| 50/372 | | Impregnated bed nets; Long-lasting insecticidal bed nets [LLINs] | | | |
| 50/373 | | the vector being flies | | | |
| 50/374 | | the vector being stink bugs, kissing bugs, triatomine bugs or fleas | | | |
| 50/375 | | the vector being ticks | | | |
| 50/38 | | Medical treatment of vector-borne diseases characterised by the agent | | | |
| 50/381 | | the vector-borne disease being caused by a virus | | | |
| 50/382 | | of the genus Alphavirus, i.e. Chikungunya | | | |
| 50/383 | | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera | | | |

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| | | | |
|--------|--|--------------|---|
| 50/411 | of the genus Plasmodium, i.e. Malaria | 50/473 | the bacteria being Escherichia coli, i.e. E. coli Infection |
| 50/412 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera | 50/474 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/413 | of the genus Trypanosoma | 50/475 | of the genus Shigella, i.e. Dysentery |
| 50/414 | the protozoa being Trypanosoma cruzi i.e. Chagas disease or American trypanosomiasis | 50/476 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/415 | the protozoa being Trypanosoma brucei gambiense or Trypanosoma brucei rhodesiense, i.e. Human African trypanosomiasis or sleeping sickness | 50/478 | of the genus Legionella, i.e. Legionellosis or Legionnaires' disease |
| 50/416 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera | 50/479 | of the genus Leptospira, i.e. Leptospirosis |
| 50/417 | . . . the vector-borne disease being caused by a helminth, i.e. Helmanthiasis | 50/48 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/418 | of the phylum nematoda | 50/481 | of the genus Salmonella, i.e. Salmonellosis |
| 50/419 | the nematode being Dracunculus medinensis or Guinea worm, i.e. Dracunculiasis | 50/482 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/42 | the nematode being a filarial worm | 50/483 | the bacteria being Salmonella typhi, i.e. Typhoid fever |
| 50/421 | the filarial worm being Wuchereria bancrofti, brugia malayi or Brugia timor, i.e. Lymphatic filariasis | 50/484 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/422 | the filarial worm being Onchocerca volvulus, i.e. Onchocerciasis or river blindness | 50/485 | . . . The waterborne disease being caused by a protozoa |
| 50/423 | the helminth being a trematode flatworm of the genus Schistosoma, i.e. Schistosomiasis or bilharziasis | 50/486 | the protozoan being Entamoeba histolytica, i.e. Amoebiasis |
| 50/45 | . . Means for preventing water-borne diseases | 50/487 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/451 | . . . Genetic or molecular screening of pathogens | 50/488 | the protozoan being Cryptosporidium parvum, i.e. Cryptosporidiosis |
| 50/452 | . . . Non water-based sanitation | 50/489 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera |
| 50/453 | Pit latrines | 50/49 | the protozoan being Cyclospora cayetanensis, i.e. Cyclosporiasis |
| 50/454 | Dry closets e.g. incinerator closets | 50/491 | the protozoan being Giardia lamblia or Giardia intestinalis, i.e. Giardiasis |
| 50/455 | having means for adding powder, e.g. earth | 50/492 | of the phylum Microsporidia, i.e. Microsporidiosis |
| 50/456 | Chemical toilets | 50/50 | . . Chemical or biological analysis of biological material for identifying the disease, e.g. blood or urine testing, rapid diagnostic tests [RTDs] or immunological testing |
| 50/46 | . . Medical treatment of waterborne diseases characterized by the agent | 50/51 | . . . the disease being Chikungunya fever |
| 50/462 | . . . The waterborne disease being caused by a virus | 50/52 | . . . the disease being Cholera |
| 50/463 | the virus being the Hepatitis A virus [HAV] | 50/53 | . . . the disease being Dengue fever |
| 50/464 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera | 50/54 | . . . the disease being Hepatitis A |
| 50/465 | the virus being the poliovirus, i.e. Poliomyelitis or Polio | 50/55 | . . . the disease being Leishmaniasis, Sand-fly fever, phlebotomus fever, kala-azar, black fever or Dumdum fever |
| 50/466 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera | 50/56 | . . . the disease being Leptospirosis |
| 50/467 | of the genus Polyomavirus: JC virus or BK virus, i.e. Polyomavirus infection | 50/57 | . . . the disease being Lyme disease or Lyme borreliosis |
| 50/468 | . . . The waterborne disease being caused by a bacteria | 50/58 | . . . the disease being Malaria |
| 50/469 | the bacteria being clostridium botulinum, i.e. Botulism | 50/59 | . . . the disease being Typhus or typhoid fever |
| 50/47 | the bacteria being Campylobacter jejuni, i.e. Campylobacteriosis | 50/60 | . . . the disease being Yellow fever or Ochropyra |
| 50/471 | the bacteria being Vibrio cholerae, i.e. Cholera | 90/00 | Technologies having an indirect contribution to adaptation to climate change |
| 50/472 | the medicinal preparation containing antigens or antibodies, e.g. vaccines, antisera | 90/10 | . Information and communication technologies [ICT] supporting adaptation to climate change. |

Y02A

- 90/12 . . Specially adapted for meteorology, e.g. weather forecasting, climate modelling
- 90/13 . . . Monitoring or forecasting for establishing the amount of global warming
- 90/14 . . . Real-time meteorological measuring
- 90/15 . . . Weather or climate specific geographic information systems [GIS], databases or models
- 90/16 . . . Climate simulation; Climate scenario development
- 90/17 . . . Weather surveillance systems using the reflection or reradiation of electromagnetic waves
- 90/18 Radar-based
- 90/19 Based on light detection and ranging [LIDAR] systems
- 90/20 . . specially adapted for the handling or processing of medical or healthcare data, relating to climate change
- 90/22 . . . for administrative, organizational or management aspects influenced by climate change adaptation
- 90/24 . . . for detecting, monitoring or modelling of medical or healthcare patterns in geographical or climatic regions, e.g. epidemics or pandemics
- 90/26 . . . for diagnosis or treatment, for medical simulation or for handling medical devices
- 90/30 . Assessment of water resources
- 90/32 . . based on topography, e.g. mapping, location, large scale investigation of water resources or satellite or aerial imagery
- 90/34 . . Hydrogeology; Hydrogeophysics
- 90/342 . . . by measuring electric resistivity
- 90/344 . . . by measuring magnetic field strength
- 90/36 . . Seismic methods or vibration analysis
- 90/40 . Monitoring or fighting invasive species

Annex 2. Selection of technology classes by hazard

| STORMS | | |
|--|---|--------------------------------------|
| TECHNOLOGIES | CPC CODE | Y02A CATEGORY |
| Dykes and dams | Y02A10/13 | COASTAL ZONES - RIVER BASINS |
| Sea walls, surge or tidal barriers | Y02A10/14 | |
| Self contained breakwaters | Y02A10/15 | |
| Revetments of the Shore | Y02A10/16 | |
| Groynes | Y02A10/17 | |
| Jetties or landing bridges | Y02A10/18 | |
| Land claim or beach nourishment | Y02A10/21 | |
| Wetland Restoration or creation | Y02A10/22 | |
| Dune restoration or creation | Y02A10/23 | |
| Cliff stabilization | Y02A10/24 | |
| Artificial reefs | Y02A10/26 | |
| Restoration or protection of coral reefs | Y02A10/27 | |
| Sediment management | Y02A10/28 | |
| Floods prevention | Y02A10/30 | |
| Permanent physical barriers to protect industrial installations from flooding | Y02A10/31 | |
| Temporarily physical barriers to protect industrial installations from flooding | Y02A10/32 | |
| evacuation systems | Y02A10/39 | |
| Planning and monitoring of coastal areas | Y02A10/41 | |
| Disaster preparedness plan | Y02A10/44 | |
| Computerized floods control | Y02A10/46 | |
| insurance | Y02A10/48 | |
| Water pollution control technologies keeping clear the surface of open water from oil spills | Y02A20/204 | WATER MANAGEMENT |
| Saltwater intrusion barriers | Y02A20/404 | INFRASTRUCTURE |
| Extreme weather resilient electric power supply system | Y02A30/14 | |
| Floods resilient equipment | Y02A30/16; Y02A30/17; Y02A30/18; Y02A30/19 | |
| Floating Houses | Y02A30/21 | |
| Elevated Houses | Y02A30/23 | |
| Storm resilient vessels | Y02A30/35 | |
| Active motion dampening system for ports | Y02A30/36 | |
| Climate resilient water supply or treatment infrastructures | Y02A30/40 | |
| Pumping equipment for floods draining | Y02A30/45 | |
| Resilient IT infrastructure | Y02A30/50 | |
| Build windbreaks | Y02A40/225 | AGRICULTURE |
| Control of sand encroachment | Y02A40/227 | |
| Wetlands restoration or protection | Y02A40/228 | |
| Early warning systems for extreme weather events | Y02A50/12 | HEALTH |
| Storm shelters or storm cellars | Y02A50/14 | |
| Weather forecasting, climate modeling | Y02A90/12 | INDIRECT CONTRIBUTION (OTHERS) |
| Real-time meteorological measuring | Y02A90/14 | |
| Weather/climate specific information systems | Y02A90/15 | |
| Weather surveillance systems | Y02A90/17; Y02A90/18; Y02A90/19 | |

| FLOODS | | |
|---|--|------------------------------|
| TECHNOLOGIES | CPC CODE | Y02A CATEGORY |
| Reservoirs, Polders | Y02A10/12 | COASTAL ZONES - RIVER BASINS |
| Dykes; Dams | Y02A10/13 | |
| Groynes | Y02A10/17 | |
| Sediment management | Y02A10/28 | |
| Floods prevention; Floods Management | Y02A10/30 | |
| Permanent physical barriers to protect industrial installations from flooding | Y02A10/31 | |
| Temporarily physical barriers to protect industrial installations from flooding | Y02A10/32 | |
| Infiltration of water into the ground | Y02A10/33 | |
| Flood-proof sanitary latrines | Y02A10/34 | |
| Revetment for protection of river banks | Y02A10/35 | |
| Equalizing tanks in the sewage system for regulating the run off | Y02A10/36 | |
| Bioswales | Y02A10/37 | |
| Changing the natural surface of ground to reroute water | Y02A10/38 | |
| Weirs | Y02A10/383 | |
| Locks | Y02A10/386 | |
| Evacuation systems | Y02A10/39 | |
| Curb floodplain development | Y02A10/395 | |
| Improve floods warnings | Y02A10/42 | |
| Disaster preparedness plan | Y02A10/44 | |
| Floods mapping | Y02A10/46 | |
| insurance | Y02A10/48 | |
| Dams or Barriers | Y02A20/12 | WATER MANAGEMENT |
| Water filtration | Y02A20/152;Y02A20/154;Y02A20/156 | |
| Enforce water standards | Y02A20/16 | |
| Water pollution control technologies | Y02A20/20; Y02A20/202; Y02A20/204; Y02A20/206 | |
| Off-grid powered water treatment | Y02A20/208; Y02A20/211; Y02A20/212; Y02A20/214; Y02A20/216 | |
| river restoration | Y02A20/402 | |
| Draining or infiltration of impermeable surface | Y02A20/408 | |
| Extreme weather resilient electric power supply system | Y02A30/14 | INFRASTRUCTURE |
| Floods resilient equipment | Y02A30/16; Y02A30/17; Y02A30/18; Y02A30/19 | |
| Floating Houses | Y02A30/21 | |
| Elevated Buildings | Y02A30/23 | |
| Permeable roads | Y02A30/32 | |
| Climate resilient railways transportation | Y02A30/38 | |
| Pumping equipment for floods draining | Y02A30/45 | |
| Resilient IT infrastructure | Y02A30/50 | |
| Sloping ground terrains in public areas | Y02A30/68 | |
| Aeroponics seed potato production | Y02A40/17 | |
| Change farming practices | Y02A40/282 | |

| | | |
|---|-----------------------------------|--------------------------------|
| Crops rotation | Y02A40/286 | AGRICULTURE |
| Crop diversification, avoiding mono cropping | Y02A40/288 | |
| Terracing | Y02A40/292 | |
| Agroforestry | Y02A40/294 | |
| Early warning systems for extreme weather events | Y02A50/12 | HEALTH |
| Landslide or mudflow monitoring or protecting systems | Y02A50/16 | |
| Weather forecasting, climate modeling | Y02A90/12 | INDIRECT CONTRIBUTION (OTHERS) |
| Real time meteorological measuring | Y02A90/14 | |
| Weather/climate specific information systems | Y02A90/15 | |
| Weather surveillance systems | Y02A90/17; Y02A90/18; Y02A90/19 | |
| Mapping and location of water resources | Y02A90/32 | |
| Hydrogeology; hydrophysics | Y02A90/34; Y02A90/342; Y02A90/344 | |

| DROUGHTS | | |
|--|--|------------------------------|
| TECHNOLOGIES | CPC CODE | Y02A CATEGORY |
| insurance | Y02A10/48 | COASTAL ZONES - RIVER BASINS |
| Tanks | Y02A20/102; Y02A20/104; Y02A20/106 | WATER MANAGEMENT |
| harvest rainwater | Y02A20/108 | |
| Obtaining drinking water | Y02A20/109; Y02A20/112 | |
| Water wells | Y02A20/114; Y0A2 20/116; Y02A20/118; Y0A2 20/119 | |
| Dams or Barriers | Y02A20/12 | |
| Desalinate | Y02A20/124 - Y02A20/144 | |
| Use "grey" water | Y02A20/146; Y02A20/148 | |
| Reduce leakage | Y02A20/15 | |
| Enforce water standards | Y02A20/16 | |
| Solar or wind powered water pumping | Y02A20/18 | |
| Water pollution control technologies | Y02A20/20; Y02A20/202; Y02A20/206 | |
| Water metering with adaptation potential | Y02A20/218 | |
| Water pricing strategies | Y02A20/22 | |
| Industrial water (cooling, production, ...) | Y02A20/30; Y02A20/302; Y02A20/304 | |
| river restoration | Y02A20/402 | |
| Artificial recharge of aquifers | Y02A20/406 | |
| Increase efficiency and recycling | Y02A20/411; Y02A20/412; Y02A20/414 | |
| Precision agriculture | Y02A40/12 | AGRICULTURE |
| Abiotic stress | Y02A40/13 | |
| Crops tolerant to droughts | Y02A40/132 | |
| Symbiotic seeds | Y02A40/15 | |
| Pest or insect control | Y02A40/16; Y02A40/162; Y02A40/164; Y02A40/166; Y02A40/168 | |
| Aeroponics seed potato production | Y02A40/17 | |
| Fertilizer Management | Y02A40/18; Y02A40/19; Y02A40/20; Y02A40/201; Y02A40/202; Y02A40/203; Y02A40/204; Y02A40/205; Y02A40/206; Y02A40/207; Y02A40/208; Y02A40/209; Y02A40/21; Y02A40/211; Y02A40/212; Y02A40/213; Y02A40/214; Y02A40/215; Y02A40/216 | |
| Change land topography to improve water uptake | Y02A40/221; Y02A40/222; Y02A40/223; Y02A40/224 | |
| Control of sand encroachment | Y02A40/227 | |
| Wetlands restoration or protection | Y02A40/228 | |
| Biochar technology | Y02A40/229 | |
| Improve soil conservation | Y02A40/232; Y02A40/233; Y02A40/234 | |

| | | |
|---|--|--------------------------------|
| irrigation efficiency | Y02A40/235; Y02A40/236; Y02A40/237; Y02A40/238; Y02A40/239; Y02A40/24; Y02A40/241 | |
| Limiting deforestation; reforestation | Y02A40/242; Y02A40/243 | |
| Change farming practices | Y02A40/282 | |
| Mulch Stubble or Straw | Y02A40/284 | |
| Crops rotation | Y02A40/286 | |
| Crops diversification | Y02A40/288 | |
| Use lower planting densities | Y02A40/29 | |
| Terracing | Y02A40/292 | |
| Agroforestry | Y02A40/294 | |
| Bushfire and forest fire prevention and control | Y02A40/296; Y02A40/298 | |
| Timing of farming operations | Y02A40/30; Y02A40/302 | |
| Evapotranspiration | Y02A40/50 | |
| Ecological corridors or buffer zones | Y02A40/60 | |
| Additional fodder during the dry season | Y02A40/73 | |
| Optimizing pasture management | Y02A40/74 | |
| Technologies to reduce water consumption in Food processing | Y02A40/922 | |
| Means for preventing water-borne disease | Y02A50/45 | |
| Use non-water-based sanitation | Y02A50/452; Y02A50/453; Y02A50/454; Y02A50/455; Y02A50/456 | HEALTH |
| Weather forecasting, climate modeling | Y02A90/12 | |
| Weather/climate specific information systems | Y02A90/15 | |
| Mapping and location of water resources | Y02A90/32 | |
| Hydrogeology; hydrophysics | Y02A90/34; Y02A90/342; Y02A90/344 | INDIRECT CONTRIBUTION (OTHERS) |

| HEATWAVES | | |
|--|---|--------------------------------|
| TECHNOLOGIES | CPC CODE | Y02A CATEGORY |
| River restoration | Y02A20/402 | WATER MANAGEMENT |
| Weather forecasting for energy supply management | Y02A30/12 | INFRASTRUCTURE |
| Rotary buildings | Y02A30/22 | |
| Technologies to improve thermal insulation | Y02A30/24 - Y02A30/249; Y02A30/25 - Y02A30/257; | |
| Passive climatisation | Y02A30/259; Y02A30/26; Y02A30/261 | |
| Air conditioning technologies | Y02A30/27 - Y02A30/278 | |
| Resilient IT infrastructures | Y02A30/50 | |
| urban green infrastructure and heat control | Y02A30/62; Y02A30/64 | |
| Abiotic stress | Y02A40/13 | |
| Crops tolerant to heat | Y02A40/138 | |
| Pest or insect control | Y02A40/16; Y02A40/162; Y02A40/164; Y02A40/166; Y02A40/168 | |
| Greenhouse Technology | Y02A40/258; Y02A40/26; Y02A40/262; Y02A40/264; Y02A40/266; Y02A40/268 | |
| Crops rotation | Y02A40/286 | |
| Agroforestry | Y02A40/294 | |
| Timing of farming operations | Y02A40/30 | |
| Advance sowing dates to offset moisture stress during warm periods | Y02A40/302 | |
| Evapotranspiration | Y02A40/50 | |
| Ecological corridors or buffer zones | Y02A40/60 | |
| Climate tolerant animal varieties | Y02A40/72 | |
| Optimizing pasture management | Y02A40/74 | |
| Temperature management in livestock housing | Y02A40/75; Y02A40/76 | |
| Mechanical or electrostatic filtering in ventilation or air conditioning | Y02A50/21 | HEALTH |
| Weather forecasting, climate modeling | Y02A90/12 | INDIRECT CONTRIBUTION (OTHERS) |
| Real time meteorological measuring | Y02A90/14 | |
| Weather/climate specific information systems | Y02A90/15 | |
| Weather surveillance systems | Y02A90/17; Y02A90/18; Y02A90/19 | |
| Medical information relating to climate change | Y02A90/20; Y02A90/22; Y02A90/24; Y02A90/26 | |
| Monitoring or fighting invasive species | Y02A90/40 | |

| SEA LEVEL RISE | | |
|---|-----------------------|--------------------------------------|
| TECHNOLOGIES | CPC CODE | Y02A CATEGORY |
| Reservoirs, Polders | Y02A10/12 | COASTAL ZONES - RIVER BASINS |
| Dykes and dams | Y02A10/13 | |
| Sea walls, surge or tidal barriers | Y02A10/14 | |
| Self contained breakwaters | Y02A10/15 | |
| Groynes | Y02A10/17 | |
| Jetties or landing bridges | Y02A10/18 | |
| Land claim or beach nourishment | Y02A10/21 | |
| Wetland Restoration or creation | Y02A10/22 | |
| Dune restoration or creation | Y02A10/23 | |
| Cliff stabilisation | Y02A10/24 | |
| Artificial seaweed | Y02A10/25 | |
| Artificial reefs | Y02A10/26 | |
| Restoration or protection of coral reefs | Y02A10/27 | |
| Sediment management | Y02A10/28 | |
| Permanent physical barriers to protect industrial installations from flooding | Y02A10/31 | |
| Infiltration of water into the ground | Y02A10/33 | |
| Curb floodplain development | Y02A10/395 | |
| Planning and monitoring of coastal areas | Y02A10/41 | |
| Water quality or standards enforcement | Y02A20/16 | WATER MANAGEMENT |
| Water pollution control technologies | Y02A20/20; Y02A20/206 | |
| Saltwater intrusion barriers | Y02A20/404 | INFRASTRUCTURE |
| Elevated Houses | Y02A30/23 | |
| Plant tolerant to salinity | Y02A40/135 | AGRICULTURE |
| Floating agriculture | Y02A40/226 | |
| Wetlands restoration or protection | Y02A40/228 | INDIRECT CONTRIBUTION (OTHERS) |
| Weather forecasting, climate modelling | Y02A90/12 | |
| Monitoring/forecasting the amount of global warming | Y02A90/13 | |
| Weather/climate specific information systems | Y02A90/15 | |
| Climate simulation, Climate scenario development | Y02A90/16 | |
| Assessment of water resources based on topography | Y02A90/32 | |

Annex 3. Selection of FDI deals related with adaptation to climate change

To challenge the patent-based results, we extract information on FDI deals for the period 1995–2015 from the Zephyr database provided by Brussels-based business publisher Bureau Van Dijk.⁴⁸ The objective is to identify foreign investments that could lead to adaptation technology transfers. To target these deals, we adapt the methodology used in Dussaux, Dechezleprêtre, and Glachant (2018) and apply it to adaptation technologies. We define FDI ‘adaptation’ deals as deals where both the acquiring firms have filed at least one adaptation patent in the residence country of the target firm, and the activity of the target firm is linked with adaptation to climate change, as follows:

We first select acquiring firms that have patented at least one adaptation patent in the country where the target firm is located. Using the Y02A PATSTAT classification, we could identify every firm that filed an adaptation patent in a country. We extract all observations with pairs (applicant firm, application country) specific to adaptation patents and matched these adaptation pairs with the Zephyr database. By doing so, we only retain deals where the acquiring firm have filed at least one adaptation patent in the target country.

Second, we use information on target firms’ industrial activity. Using the NACE Rev. 2 classification,⁴⁹ we identify activities with a potential link to adaptation technologies. We match the selection of NACE codes linked with technologies for climate change adaptation with the industrial activity NACE code of the target firm to only retain target firms in adaptation-related sectors. To identify transfers across countries, we restrict our database to foreign deals, defined as deals where the acquirer and the target country are different.

⁴⁸ For more information on the Zephyr database, see the Bureau Van Dijk website: <https://www.bvdinfo.com/en-gb/our-products/data/specialist/zephyr>.

⁴⁹ “NACE Rev. 2” refers to Statistical Classification of Economic Activities in the European Community (NACE, for the French “nomenclature statistique des activités économiques dans la Communauté européenne”). It is the industry standard classification system used in the European Union. The current version is revision 2.

Annex 4. Construction of the Five Hazard Indicators

The sea level rise indicator is the original University of Notre Dame Global Adaptation Index (ND-GAIN) indicator whose definition is provided in Table 7. Importantly, it corresponds to projections by the end of the century.

Temperature and floods indicators rely on [Climdex \(https://www.climdex.org/\)](https://www.climdex.org/) simulations for the period 2040–70 under the IPCC’s RCP4.5 scenario.⁵⁰ The final score for both indicators is the average of the resulting indicator computed in 20 climate models as part of the CMIP5 program.⁵¹

The droughts indicator is the projected change in annual runoff under the RCP4.5 scenario from the [Aqueduct water stress database of the World Resources Institute](#). For each country, we compute the mean of the basin level’s score for the water supply indicator under the RCP4.5 scenario for the years 2020, 2030, and 2040.

We then average these four indicators at the country level.

Last, the storms indicator only includes past events because we could not find any relevant projections. It is the country’s average annual number of storms per capita for the period 1900–2015. The historical number of storms per country for the period 1900–2015 is extracted from the Centre for Research on the Epidemiology of Disasters (CRED) Emergency Events Database ([EM-DAT](#)). The assumption here is that past events are strongly positively correlated with future threats.

Finally, we normalize each these five indicators so that they range from 0 to 1, where 0 represents the minimum threat faced by countries, and 1 the maximum.

⁵⁰ A Representative Concentration Pathway (RCP) scenario refers to a greenhouse gas concentration trajectory adopted by the IPCC. Four pathways were used for climate modelling and research for the IPCC Fifth Assessment Report in 2014. RCP4.5 is a stabilization scenario (stabilizing radiative forcing at 4.5 W m⁻² in the year 2100 without ever exceeding that value) that assumes the imposition of emissions mitigation policies.

⁵¹ The Climate Model Intercomparison Project, Phase 5 (CMIP5) refers to a standard experimental protocol for studying the output of coupled atmosphere-ocean general circulation models (AOGCMs). It includes 35 climate model experiments to evaluate the relevance of such models in simulating the recent past climate, to produce projections of future climate conditions, and to analyze the factors leading to differences among the models’ projections. For more information about CMIP5, see the Program for Climate Model Diagnosis & Intercomparison website: <https://pcmdi.llnl.gov/mips/cmip5/>.

Annex 5. Convert monetary values to Purchase Power Parity (PPP) constant

2005 international\$

Because the assets exposure indicator provided in TCE-DAT is reported in PPP (constant 2005 international\$), we need to be consistent and express both GDP per capita and storms induced damages reported by EM-DAT in the same unit.

Compute GDP per capita in PPP (constant 2005 international\$)

Due to data availability issues, we have to compute GDP per capita PPP constant (Power Purchase Parity) 2005 international\$ from GDP per capita constant local currency and GDP per capita current PPP using the following formula:

$$\begin{aligned} & GDP \text{ per capita } (y)_{constant \text{ PPP } 2005} \\ &= \frac{GDP \text{ per capita } (y)_{constant \text{ LCU}}}{GDP \text{ per capita } (2005)_{constant \text{ LCU}}} * GDP \text{ per capita } (2005)_{current \text{ PPP}} \end{aligned}$$

Where:

- $GDP \text{ per capita } (y)_{constant \text{ PPP } 2005}$: GDP per capita at year y in PPP constant 2005 international\$
- $GDP \text{ per capita } (y)_{constant \text{ LCU}}$: GDP per capita at year y in constant LCU
- $GDP \text{ per capita } (2005)_{constant \text{ LCU}}$: GDP per capita in 2005 in constant LCU
- $GDP \text{ per capita } (2005)_{current \text{ PPP}}$: GDP per capita in 2005 in current PPP international\$

Convert EM-DAT damages in PPP (constant 2005 international\$)

EM-DAT data on damages are expressed in current US\$. To convert the amount of damages into PPP constant 2005 international\$, we compute a conversion index between GDP per capita in US\$ and the GDP per capita in PPP constant 2005 international\$ computed above.

$$Index_CurrUS_to_PPPcons(y) = \frac{GDP \text{ per capita } (y)_{constant \text{ PPP } 2005}}{GDP \text{ per capita } (y)_{current \text{ US\$}}}$$

and so

$$Damages(s)_{constant \text{ PPP } 2005} = Index_CurrUS_to_PPPcons(y) * Damages(s)_{current \text{ US\$}}$$

where:

- $Damages(s)_{constant\ PPP\ 2005}$: Damages induced by the storms s in PPP constant 2005 international\$
- $Damages(s)_{current\ US\$}$: Damages induced by the storms s in current US\$, as reported in the EM-DAT database
- $GDP\ per\ capita\ (y)_{constant\ PPP\ 2005}$: GDP per capita at year y in PPP constant 2005 international\$
- $GDP\ per\ capita\ (y)_{current\ US\$}$: GDP per capita at year y in current US\$

Annex 6. Detailed description of climate indicator building

Droughts indicator

The droughts indicator we used is the Global Precipitation Climatology Centre Drought Index (GPCC-DI), a water supply anomaly indicator. It is the combination of both a precipitation accumulation index, the Standardized Precipitation Index from Deutscher Wetterdienst (SPI-DWD), and an evapotranspiration index, the Standardized Precipitation Evapotranspiration Index (SPEI) (for more detailed information, see Ziese et al. 2014). The GPCC-DI is a monthly indicator, available for the period 1952-2016. We built a yearly-location level index by computing the average of this indicator within a year by location. We chose this indicator because it takes into account not only precipitation, but also temperature, whose role in meteorological droughts is crucial (Dai et al. 2018). GPCC-DI is available for several accumulation periods. We kept the 6 months accumulation period indicator, because it is well suited to analyze groundwater droughts impacts, affecting mainly freshwater availability for human consumption and agriculture (Rhee et al. 2010; Spinoni et al. 2019).

Taking a range of values from -4 to 4, this indicator identifies wet as well as droughts areas. Positive values represent an excess of precipitation compared to the normal and/or evapotranspiration below normal and correspond to a wet environment, whereas negative values indicate a deficit of precipitation (or an excess of evapotranspiration), and correspond to a drought. Based on an adapted classification from Lloyd-Hughes and Saunders (2002), we considered that an area is affected by a droughts event when the value of the indicator falls below -1.00, and that this event is an extreme one when the indicator is above -1.50 (see Table 13 in the paper above). It corresponds to all areas affected by either a severe or an extreme drought.

Extreme precipitation indicator

The extreme precipitation index is built on a precipitation indicator called Rx5day. This indicator, reporting the annual maximum consecutive 5-day precipitation, is widely used as a proxy for flash floods or landslides, as illustrated by several studies compiled in Tabari (2019). Moreover, the Rx5day indicator is highly correlated with flash floods or landslide damages (Ávila et al. 2016; Wu & Huang 2015). We extract data for the period 1970-2016 from the PANGEA databases (Mistry 2019). This Rx5day indicator represents the absolute amount of maximum precipitation per year and location. We first calculate the average value of this indicator per location for the period 1970-2015 and its local standard deviation. We then compute a precipitation anomaly as the difference between the yearly value of the Rx5day indicator and its average local long-term value, divided by the within location standard

deviation (see equation below). It allows us to identify excess of precipitation compared with long run statistics, controlling for the usual variation in this area.

$$\text{Precipitation anomaly}_{it} = \frac{Rx5day_{it} - \text{Mean_Rx5day}_i}{\text{Std_Dev_Rx5day}_i}$$

We define a moderate excess of precipitation if the precipitation anomaly ranges from 1 to 2, and extreme if it exceeds 2. We prefer to use the anomaly rather than absolute thresholds because of the high correlation between deviation in extreme precipitation and floods (Pielke & Downton 2000).

Because floods and landslide hazards are also function of specific local conditions (basin's topography, presence of a large river, ...) (Kunkel et al. 1999), we also used a floods country level physical exposure indicator from Index for Risk Management (infoRM) database⁵² (De Groeve et al. 2014). This physical exposure indicator, managed by the European Commission⁵³, evaluates people physical exposure to floods by taking into account local density of people and topography characteristics (but not the existing infrastructure). It is a combination of the (annual) frequency of floods (UNEP Global Risk Data Platform (GRID) 2009⁵⁴) and the total population living in the area affected by the event (Oak Ridge National Laboratory 2012)⁵⁵. It allows us to restrict our analysis to countries where population are expected to be exposed to flash floods events.

Heatwaves indicator

The heatwaves indicator is based on the Excess Heat Factor (EHF). We choose this heatwaves indicator as it is particularly well suited to analyze heatwaves impact on human health (Nairn et al. 2018). A heatwave is defined as at least three consecutive days where the Excess Heat Factor (EHF) is positive. We build our heatwaves indicator in two steps. First, we identify areas affected by at least one heatwave within a year. To do so, we selected areas where the Heatwaves Number (HWN) indicator is non-zero. This index counts the number of heatwaves per year occurring during the summer and allows us to target the 'hottest' heatwaves. Because our heatwaves proof adaptation technologies are designed to copy with high temperature, we need to exclude 'cold' places from our analysis. We target 'hot places' as those where the maximum temperature reached within a year is at least 38°C, using the TXx indicator. Finally, we evaluate the intensity of all heatwaves events using the Heatwaves Magnitude (HWM)

⁵² <https://drmkc.jrc.ec.europa.eu/inform-index/INFORM-Risk>

⁵³ The Index for Risk Management – infoRM – database is available here: <https://ec.europa.eu/jrc/en/publication/index-risk-management-inform>.

⁵⁴ For information on the UNEP Global Risk Data Platform: <http://preview.grid.unep.ch>

⁵⁵ For information on the Oak Ridge National Laboratory: <http://www.ornl.gov/sci/landscan/>

indicator. It is based on the temperature average of all heatwaves identified by the HWN indicator. Moderate heatwaves correspond to HWM above zero and below or equal to 3, and extreme ones to HWM equal or above 6. The final indicator represents the percentage of the country affected by at least one heatwave, in areas where the annual maximum temperature is equal or above 38°C, and the heatwaves magnitude is above 0 and below 3 (moderate) or above 3 (extreme).

OTHER GRIDDED DATA

Population data

Population data come from the publicly available History Database of the Global Environment (HYDE version 3.2) (Klein Goldewijk et al. 2017). We extracted gridded count population data for the years 1980, 1990, 2000, 2010 & 2015⁵⁶. These data are available at 5 arc minutes resolution. Because climate data are available at either 0,25° or 1° resolution, we rescaled the population data by summing the grid-cells population count at an higher scale. We use simple linearity assumption to create a yearly value at each location for our entire period. We compute the total population of a country in a given year by summing the number of people living in all locations in this country by year, and then obtain the share of country's population living at each location

Agricultural data

Land use data come from the History Database of the Global Environment (HYDE version 3.2) (Klein Goldewijk et al. 2017). We extract gridded land use data for two types of agricultural activities (cropland and pasture) for the years 1980, 1990, 2000, 2010 & 2015⁵⁷. The database contains the area (in hectare) covered by intense agricultural activity (cropland or pasture) by location, at a 5 arc minutes resolution. We limit our analysis to these two types of land use, as they are the most intense in term of human labor and capital, but also the most productive areas. We are interested in the surface covered by agricultural activity without distinguishing between cropland and pasture. We so compute the area covered by both activities summing the surface they covered within a cell. As for the population data, we rescaled the land use data and obtained yearly values by linearity. We compute the total area covered by intensive agricultural activity for a country in a given year by summing the area used for agriculture in all

⁵⁶ Data from HYDE version 3.2 are available here: <https://dataportaal.pbl.nl/downloads/HYDE/HYDE3.2/>

⁵⁷ Data from HYDE version 3.2 are available here: <https://dataportaal.pbl.nl/downloads/HYDE/HYDE3.2/>

locations within this country by year, and then obtain the share of country's agricultural area at each location.

Then, we construct a variant of the pure climatic indexes described in the previous section by interacting agricultural or population data described above with our climate data at the gridded level. Similarly to the previous section, we computed the share of country's agricultural area or population affected by each intensity of climate events.

Annex 7. Computation of the cumulative effect variable

In order to measure the long-term effect of climate extremes on the invention (or imports) of adaptation technologies, we report the cumulative effect of the extreme events variables. The cumulative effect equals the sum of all coefficients reported in our estimation.

To illustrate the computation of this effect, we will use the results of the effect of extreme droughts events affecting population on the invention of adaptation technologies as an example. As reported in Table A 14 the average effect of droughts extreme events ($Event_{D,c,y}$) on the invention of adaptation technologies is given by:

$$Inv_{D,c,t} = \beta_1 Event_{D,c,t-1} + \beta_2 Event_{D,c,t-2} + \dots + \beta_9 Event_{D,c,t-9} + \beta_{10} Event_{D,c,t-10} + \mu_{e,c,t} \quad (A.1)$$

Where $\mu_{e,c,t} = \delta X_{c,t} + \varepsilon_{D,c,t}$

We want to estimate the cumulative effect $Cumul$ define as: $Cumul = \beta_1 + \beta_2 + \dots + \beta_9 + \beta_{10}$

To do so, we transform equation A.1 as follow:

$$Inv_{D,c,t} = Cumul * Event_{D,c,t-1} + \beta_2 [Event_{D,c,t-2} - Event_{D,c,t-1}] + \beta_3 [Event_{D,c,t-3} - Event_{D,c,t-1}] + \dots + \beta_{10} [Event_{D,c,t-10} - Event_{D,c,t-1}] + \mu_{e,c,t} \quad (A.2)$$

Finally, we estimate equation A.2 to get the effect and the statistical significance of the long-term cumulative effect $Cumul$.

In our example, we see that $Cumul = 0.046 = 0.004 + 0.008 + 0.004 + 0.006 + 0.008 + 0.005 + 0.002 + 0.002 + 0.001 + 0.005$

TABLES (Appendix)

List of tables in the appendix

Table A 1. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths (restricted to 1995-2015)..... 191

Table A 2. Efficiency of Storm Related Technology in Reducing Storm Induced Damages (restricted to 1995-2015)..... 191

Table A 3. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths, Controlling for People Exposed Multiple Times (1990-2015) 192

Table A 4. Efficiency of Storm Related Technology in Reducing Storm Induced Damages, Controlling for Assets Exposed Multiple Times (1990-2015)..... 192

Table A 5. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths for People Living Near the Coast (1990-2015)..... 193

Table A 6. Efficiency of Storm Related Technology in Reducing Storm Induced Damages for Assets Located Near the Coast (1990-2015) 193

Table A 7. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths: Country & Time Fixed Effects (1990-2015) 194

Table A 8. Efficiency of Storm Related Technology in Reducing Storm Induced Damages: Country & Time Fixed Effects (1990-2015) 194

Table A 9. Impact of Storm Technologies on Deaths, Sensitivity to Stock Discount Rates (1990-2015)..... 195

Table A 10. Impact of Storm Technologies on Damages, Sensitivity to Stock Discount Rates (1990-2015)..... 196

| | |
|--|-----|
| Table A 11. Storms Related Technology Efficiency in Reducing Storms Induced Deaths (Stock Exposure Various Wind Speeds)..... | 197 |
| Table A 12. Storms Related Technology Efficiency in Reducing Storms Induced Deaths (Stock Exposure Various Wind Speeds)..... | 198 |
| Table A 13. Patents and Extreme Event Statistics by Countries | 199 |
| Table A 14. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015..... | 202 |
| Table A 15. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015..... | 203 |
| Table A 16. Effect of Extreme Weather Events on the Share of Adaptation Inventions in All Technologies Invented, 1995-2015..... | 204 |
| Table A 17. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015 (Poisson)..... | 205 |
| Table A 18. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015 (Poisson)..... | 206 |
| Table A 19. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015 (Zero Inflated Negative Binomial) | 207 |
| Table A 20. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015 (Zero Inflated Negative Binomial) | 208 |
| Table A 21. Number of Firms Inventing at Least One Adaptation Patent, By Country (1995-2015)..... | 209 |
| Table A 22. Effect of Foreign and Local Extreme Weather Events on the Filing of Adaptation Patents, 1995-2015..... | 210 |

| | |
|---|-----|
| Table A 23: Differentiated Effect of Local and Foreign Extreme Weather Events on Adaptation Patent Filing, 1995-2015 | 211 |
| Table A 24. Effect of Extreme Weather Events on the Co-Invention of Adaptation Technologies, 1995-2015..... | 212 |
| Table A 25. Effect of Foreign and Extreme Weather Events on the Filing of Adaptation Patents (Droughts Agriculture), 1995-2015..... | 213 |
| Table A 26. Differentiated Effect of Local and Foreign Extreme Weather Events on Adaptation Patent Filing (Droughts Agriculture), 1995-2015 | 214 |
| Table A 27. Effect of Extreme Weather Events on the Co-Invention of Adaptation Technologies (Droughts Agriculture), 1995-2015..... | 215 |

Table A 1. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths (restricted to 1995-2015)

| DEATHS (1995-2015) | | | |
|---|-----------------------|------------------------|------------------------|
| | Storms patents | | All patents |
| | Negative Binomial | OLS | Negative Binomial |
| Stock of HVI technologies at t-1 (hundreds) | -0.769*** (0.0792) | -0.422*** (0.0534) | 1.18e-05 (5.54e-05) |
| Population exposed to storms | 34knots to 96knots | 0.0125*** (0.00173) | 0.0152*** (0.00290) |
| | Over 96knots | 0.0987 (0.0961) | 0.0948* (0.0505) |
| | | | 0.0972 (0.106) |
| Stock of people exposed to past storms over 96knots (t-1) | 0.0377 (0.0330) | 0.0412 (0.0245) | 0.0462 (0.0401) |
| Log GDP per capita (PPP constant 2005 international\$) | -0.0271 (0.164) | -0.549** (0.226) | -0.833** (0.422) |
| Log country's population (millions) | -8.726*** (2.479) | -6.875*** (1.476) | -9.247*** (2.342) |
| Time trend | X | X | X |
| Country FE | X | X | X |
| Observations | 122 | 122 | 122 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 2. Efficiency of Storm Related Technology in Reducing Storm Induced Damages (restricted to 1995-2015)

| DAMAGES (1995-2015) | | | |
|---|--------------------|---------------------|----------------------------|
| | Storms patents | | All patents |
| | OLS | Negative Binomial | OLS |
| Stock of HVI technologies at t-1 (hundreds) | -0.457 (0.271) | -0.361 (0.321) | -0.000118*** (3.05e-05) |
| Assets exposed to storms | 34knots to 96knots | 0.187** (0.0664) | 0.192** (0.0696) |
| | Over 96knots | 1.163 (1.344) | 1.073 (1.293) |
| | | | 1.839 (1.454) |
| Stock of assets exposed to past storms over 96knots (t-1) | -0.299 (0.320) | 0.306* (0.161) | -0.351 (0.293) |
| Log GDP per capita (PPP constant 2005 international\$) | 1.411** (0.509) | 0.826* (0.498) | 1.603*** (0.401) |
| Log country's population (millions) | 22.04** (9.357) | 9.967*** (2.220) | 22.33** (8.897) |
| Time trend | X | X | X |
| Country FE | X | X | X |
| Observations | 112 | 112 | 112 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 3. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths, Controlling for People Exposed Multiple Times (1990-2015)

| DEATHS (1990-2015) | | | | |
|--|--------------------|------------------------|------------------------|------------------------|
| | | Storms technologies | | All technologies |
| | | Negative Binomial | OLS | Negative Binomial |
| Stock of HVI technologies at t-1 (hundreds) | | -0.592*** (0.159) | -0.330*** (0.0622) | 4.71e-05 (3.99e-05) |
| Population exposed to storms | 34knots to 96knots | 0.0189*** (0.00357) | 0.0222*** (0.00675) | 0.0171*** (0.00272) |
| | Over 96knots | 0.162 (0.126) | 0.113* (0.0563) | 0.174 (0.127) |
| Stock of people exposed to past storms over 96 knots (t-1) | | 0.0110 (0.0327) | 0.00684 (0.0304) | 0.0217 (0.0385) |
| Log GDP per capita (PPP constant 2005 international\$) | | -0.704*** (0.140) | -0.890*** (0.169) | -1.397*** (0.256) |
| Log country's population (millions) | | -2.735 (1.684) | -2.077 (2.112) | -2.468 (2.587) |
| Time trend | | X | X | X |
| Country FE | | X | X | X |
| Observations | | 144 | 144 | 144 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 4. Efficiency of Storm Related Technology in Reducing Storm Induced Damages, Controlling for Assets Exposed Multiple Times (1990-2015)

| DAMAGES (1990-2015) | | | | |
|--|--------------------|----------------------|----------------------|----------------------------|
| | | Storms technologies | | All technologies |
| | | Negative Binomial | OLS | OLS |
| Stock of HVI technologies at t-1 (hundreds) | | -0.676*** (0.223) | -0.577** (0.227) | -0.000132*** (3.70e-05) |
| Assets exposed to storms | 34knots to 96knots | 0.216** (0.0979) | 0.339*** (0.0630) | 0.360*** (0.0727) |
| | Over 96knots | 2.360* (1.238) | 1.980 (1.310) | 1.849 (1.228) |
| Stock of assets exposed to past storms over 96 knots (t-1) | | 0.417** (0.171) | 0.153 (0.158) | 0.152 (0.129) |
| Log GDP per capita (PPP constant 2005 international\$) | | 1.138*** (0.232) | 1.025** (0.384) | 1.119** (0.360) |
| Log country's population (millions) | | 7.832*** (2.826) | 10.32 (6.325) | 10.12 (6.401) |
| Time trend | | X | X | X |
| Country FE | | X | X | X |
| Observations | | 131 | 131 | 131 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 5. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths for People Living Near the Coast (1990-2015)

| DEATHS (1990-2015) | | |
|---|------------------------|-----------------------|
| | Storms patents | |
| | Negative Binomial | OLS |
| Stock of HVI technologies at t-1 (hundreds) | -0.601*** (0.168) | -0.346*** (0.0604) |
| Population exposed to storms living within 5 km from the coasts | 0.0370*** (0.00814) | 0.0652*** (0.0143) |
| | 0.404*** (0.142) | 0.278** (0.0923) |
| Stock of people exposed to past storms over 96knots (t-1) | 0.00584 (0.0333) | 0.0106 (0.0244) |
| Log GDP per capita (PPP constant 2005 international\$) | -0.487* (0.272) | -1.086*** (0.159) |
| Log country's population (millions) | -3.719 (2.455) | -1.894 (2.069) |
| | 0.0395** (0.0196) | 0.0258 (0.0161) |
| Time trend | X | X |
| Country FE | X | X |
| Observations | 144 | 144 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 6. Efficiency of Storm Related Technology in Reducing Storm Induced Damages for Assets Located Near the Coast (1990-2015)

| DAMAGES (1990-2015) | | |
|---|---------------------|----------------------|
| | Storms patents | |
| | OLS | Negative Binomial |
| Stock of HVI technologies at t-1 (hundreds) | -0.618** (0.240) | -0.504 (0.309) |
| Assets exposed to storms living within 5 km from the coasts | 0.852*** (0.128) | 0.433** (0.209) |
| | 6.589 (4.421) | 6.608 (5.130) |
| Stock of assets exposed to past storms over 96knots (t-1) | 0.00965 (0.156) | 0.139*** (0.0303) |
| Log GDP per capita (PPP constant 2005 international\$) | 1.151** (0.394) | 1.019*** (0.357) |
| Log country's population (millions) | 10.47* (5.389) | 8.918*** (2.048) |
| Time trend | X | X |
| Country FE | X | X |
| Observations | 131 | 131 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 7. Efficiency of Storm Related Technology in Reducing Storm Induced Deaths: Country & Time Fixed Effects (1990-2015)

| DEATHS (1990-2015) | | | | |
|---|--------------------|----------------------|------------------------|-------------------------|
| | | Storms patents | All patents | |
| | | Negative Binomial | Negative Binomial | |
| | | OLS | OLS | |
| Stock of HVI technologies at t-1 (hundreds) | | -0.244 (0.183) | -0.279** (0.0988) | -9.67e-06 (4.45e-05) |
| Population exposed to storms | 34knots to 96knots | 0.00730 (0.00483) | 0.00996** (0.00351) | 0.00739 (0.00499) |
| | Over 96knots | 0.158*** (0.0279) | 0.139*** (0.0357) | 0.148*** (0.0281) |
| Stock of people exposed to past storms over 96knots (t-1) | | -0.00275 (0.0167) | 0.00480 (0.0222) | -0.00330 (0.0182) |
| Log GDP per capita (PPP constant 2005 international\$) | | -0.618*** (0.228) | -0.571*** (0.133) | -0.679*** (0.250) |
| Log country's population (millions) | | 0.497*** (0.135) | 0.486*** (0.0831) | 0.512*** (0.142) |
| | Time FE | X | X | X |
| | Country FE | X | X | X |
| | Observations | 144 | 144 | 144 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 8. Efficiency of Storm Related Technology in Reducing Storm Induced Damages: Country & Time Fixed Effects (1990-2015)

| DAMAGES (1990-2015) | | | | |
|---|--------------------|--------------------|---------------------|----------------------------|
| | | Storms patents | All patents | |
| | | OLS | OLS | |
| | | Negative Binomial | Negative Binomial | |
| Stock of HVI technologies at t-1 (hundreds) | | -0.829 (0.462) | -0.443 (0.481) | -0.000237*** (6.20e-05) |
| Assets exposed to storms | 34knots to 96knots | 0.119 (0.0753) | 0.121 (0.0897) | 0.136 (0.0822) |
| | Over 96knots | 2.947** (1.257) | 3.029*** (0.962) | 2.896** (1.099) |
| Stock of assets exposed to past storms over 96knots (t-1) | | 0.364 (0.464) | 0.660*** (0.218) | 0.384 (0.429) |
| Log GDP per capita (PPP constant 2005 international\$) | | 0.102 (0.828) | 0.247 (0.494) | -0.000623 (0.663) |
| Log country's population (millions) | | 0.809 (0.543) | 0.624** (0.265) | 0.811 (0.452) |
| | Time FE | X | X | X |
| | Country FE | X | X | X |
| | Observations | 131 | 131 | 131 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 9. Impact of Storm Technologies on Deaths, Sensitivity to Stock Discount Rates (1990-2015)

| DEATHS (1990-2015) | | | | | | | | | | | | |
|--|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| Stock of storms technologies at t-1 (thousands) | No Discount | -0.0233 (0.0761) | -0.0201 (0.0747) | -0.0143 (0.0716) | | | | | | | | |
| | Discount rate = 10% | | | | -0.338 (0.209) | -0.335 (0.205) | -0.329 (0.201) | | | | | |
| | Discount rate = 15% | | | | | | | -0.510*** (0.195) | -0.508*** (0.189) | -0.503*** (0.184) | | |
| | Discount rate = 25% | | | | | | | | | | -0.744*** (0.198) | -0.740*** (0.188) |
| Population exposed to storm between 34 & 96 knots | 0.00875*** (0.00126) | 0.00885*** (0.00124) | 0.00907*** (0.00137) | 0.00908*** (0.00131) | 0.00916*** (0.00136) | 0.00938*** (0.00158) | 0.00916*** (0.00138) | 0.00923*** (0.00147) | 0.00945*** (0.00171) | 0.00923*** (0.00143) | 0.00929*** (0.00154) | 0.00951*** (0.00180) |
| Population exposed to storm wind over 96 knots | 0.151 (0.128) | 0.148 (0.127) | 0.144 (0.128) | 0.144 (0.120) | 0.141 (0.120) | 0.138 (0.122) | 0.145 (0.115) | 0.143 (0.115) | 0.140 (0.118) | 0.146 (0.113) | 0.145 (0.113) | 0.143 (0.116) |
| Stock of people exposed to past storms (t-1) | Discount rate = 10% | 0.0135 (0.0306) | | | 0.0102 (0.0286) | | | 0.00884 (0.0282) | | 0.00677 (0.0283) | | |
| | Discount rate = 15% | | 0.0170 (0.0395) | | | 0.0132 (0.0360) | | | 0.0124 (0.0353) | | 0.0107 (0.0351) | |
| | Discount rate = 25% | | | 0.0315 (0.0617) | | | 0.0270 (0.0554) | | | 0.0269 (0.0542) | | 0.0259 (0.0537) |
| Log GDP per capita (PPP constant 2005 international\$) | -0.982*** (0.236) | -0.951*** (0.207) | -0.913*** (0.216) | -0.666*** (0.227) | -0.641*** (0.201) | -0.611*** (0.219) | -0.592*** (0.196) | -0.573*** (0.171) | -0.545*** (0.195) | -0.566*** (0.190) | -0.557*** (0.164) | -0.534*** (0.188) |
| Log country's population (millions) | -3.162** (1.520) | -3.388** (1.717) | -3.817* (1.973) | -3.038** (1.388) | -3.241** (1.583) | -3.706** (1.833) | -2.976** (1.473) | -3.196* (1.653) | -3.699** (1.871) | -3.042* (1.600) | -3.269* (1.775) | -3.811* (1.966) |
| Observations | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 | 144 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 10. Impact of Storm Technologies on Damages, Sensitivity to Stock Discount Rates (1990-2015)

| DAMAGES (1990-2015) | | | | | | | | | | | | | |
|--|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| | No Discount | -0.108 (0.0678) | -0.109 (0.0684) | -0.109 (0.0697) | | | | | | | | | |
| Stock of storms technologies at t-1 (thousands) | Discount rate = 10% | | | | -0.378* (0.177) | -0.378* (0.176) | -0.378* (0.177) | | | | | | |
| | Discount rate = 15% | | | | | | | -0.502* (0.233) | -0.502* (0.232) | -0.503* (0.231) | | | |
| | Discount rate = 25% | | | | | | | | | | -0.698* (0.327) | -0.698* (0.328) | -0.699* (0.328) |
| Assets exposed to storm between 34 & 96 knots | | 0.197** (0.0650) | 0.197** (0.0639) | 0.197** (0.0631) | 0.193** (0.0613) | 0.193** (0.0601) | 0.193** (0.0593) | 0.191** (0.0603) | 0.191** (0.0589) | 0.191** (0.0581) | 0.188** (0.0593) | 0.188** (0.0580) | 0.189** (0.0571) |
| Assets exposed to storm wind over 96 knots | | 1.446 (1.195) | 1.438 (1.131) | 1.448 (1.091) | 1.551 (1.280) | 1.549 (1.209) | 1.555 (1.159) | 1.583 (1.312) | 1.586 (1.242) | 1.595 (1.191) | 1.599 (1.333) | 1.609 (1.267) | 1.624 (1.218) |
| Stock of assets exposed to past storms (t-1) | Discount rate = 10% | -0.0173 (0.216) | | | 0.0206 (0.227) | | | 0.0165 (0.229) | | | -0.00257 (0.225) | | |
| | Discount rate = 15% | | -0.0406 (0.186) | | | 0.0247 (0.170) | | | 0.0300 (0.171) | | | 0.0170 (0.171) | |
| | Discount rate = 25% | | | -0.0327 (0.235) | | | 0.0647 (0.189) | | | 0.0833 (0.187) | | | 0.0814 (0.190) |
| Log GDP per capita (PPP constant 2005 international\$) | | 0.839** (0.325) | 0.844** (0.333) | 0.840** (0.342) | 1.027** (0.345) | 1.027** (0.357) | 1.024** (0.369) | 1.051** (0.349) | 1.049** (0.364) | 1.045** (0.377) | 1.052** (0.352) | 1.048** (0.370) | 1.041** (0.384) |
| Log country's population (millions) | | 10.59 (6.454) | 10.71 (6.455) | 10.68 (6.314) | 10.66 (6.042) | 10.62 (6.128) | 10.45 (6.039) | 10.49 (6.007) | 10.41 (6.128) | 10.18 (6.089) | 10.21 (6.102) | 10.12 (6.245) | 9.850 (6.267) |
| Observations | | 131 | 131 | 131 | 131 | 131 | 131 | 131 | 131 | 131 | 131 | 131 | 131 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 11. Storms Related Technology Efficiency in Reducing Storms Induced Deaths (Stock Exposure Various Wind Speeds) (1990-2015)

| | | DEATHS | | |
|--|--------------------|-----------------------|------------|------------|
| | | <i>Storms patents</i> | | |
| | | Negative Binomial | | |
| Stock of HVI technologies at t-1 | | -0.508*** | -0.498*** | -0.520*** |
| | (hundreds) | (0.189) | (0.178) | (0.196) |
| Population | 34knots to 96knots | 0.00923*** | 0.00932*** | 0.00928*** |
| exposed to storms | | (0.00147) | (0.00164) | (0.00159) |
| | Over 96knots | 0.143 | 0.140 | 0.138 |
| | | (0.115) | (0.120) | (0.124) |
| | over 96knots (t-1) | 0.0124 | | |
| | | (0.0353) | | |
| Stock of people | | | 0.00256 | |
| exposed to past | over 64knots (t-1) | | (0.00365) | |
| storms (t-1) | | | | 0.000224 |
| | over 34knots (t-1) | | | (0.00165) |
| Log GDP per capita (PPP constant 2005 international\$) | | -0.573*** | -0.631*** | -0.534*** |
| | | (0.171) | (0.191) | (0.200) |
| Log country's population (millions) | | -3.196* | -3.293** | -2.813 |
| | | (1.653) | (1.355) | (1.756) |
| | Time trend | X | X | X |
| | Country FE | X | X | X |
| | Observations | 144 | 144 | 144 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 12. Storms Related Technology Efficiency in Reducing Storms Induced Deaths (Stock Exposure Various Wind Speeds) (1990-2015)

| DAMAGES | | <i>Storms patents</i> | | |
|--|--------------------|-----------------------|----------|----------|
| | | Negative Binomial | | |
| Stock of HVI technologies at t-1 (hundreds) | | -0.502* | -0.560* | -0.471* |
| | | (0.232) | (0.259) | (0.245) |
| Assets exposed to storms | 34knots to 96knots | 0.191** | 0.196*** | 0.190** |
| | | (0.0589) | (0.0566) | (0.0584) |
| | Over 96knots | 1.586 | 1.699 | 1.551 |
| | | (1.242) | (1.223) | (1.249) |
| Stock of assets exposed to past storms (t-1) | Over 96knots | 0.0300 | | |
| | | (0.171) | | |
| | Over 64knots | | 0.0749 | |
| | | | (0.0459) | |
| | Over 34knots | | | -0.00826 |
| | | | | (0.0181) |
| Log GDP per capita (PPP constant 2005 international\$) | | 1.049** | 0.985** | 1.086** |
| | | (0.364) | (0.348) | (0.350) |
| Log country's population (millions) | | 10.41 | 9.523 | 10.93* |
| | | (6.128) | (6.826) | (5.759) |
| | Time trend | X | X | X |
| | Country FE | X | X | X |
| | Observations | 131 | 131 | 131 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 13. Patents and Extreme Event Statistics by Countries

| Country | Droughts | | | | Floods | | | Heatwaves | | |
|------------------------|---------------------------------------|--|-----------------------------|--------------------------|---------------------------------------|-----------------------------|--------------------------|---------------------------------------|-----------------------------|--------------------------|
| | Average country's population affected | Average country's agricultural area affected | Total adaptation inventions | Total adaptation imports | Average country's population affected | Total adaptation inventions | Total adaptation imports | Average country's population affected | Total adaptation inventions | Total adaptation imports |
| Algeria | 9% | 8% | 0 | 11 | 5% | 1 | 6 | | | |
| Argentina | 7% | 8% | 17 | 240 | 4% | 11 | 70 | 16% | 7 | 238 |
| Belarus | 3% | 3% | 2 | 0 | 5% | 6 | 0 | | 3 | |
| Belgium | 4% | 3% | 64 | 204 | 5% | 40 | 141 | 0% | 90 | 397 |
| Bosnia and Herzegovina | | | | | 6% | 2 | 0 | | 1 | |
| Brazil | 6% | 7% | 229 | 734 | 5% | 64 | 399 | 1% | 54 | 712 |
| Bulgaria | 6% | 6% | 10 | 38 | 6% | 8 | 23 | 7% | 12 | 48 |
| Canada | 7% | 7% | 312 | 1250 | 5% | 213 | 851 | 0% | 288 | 2083 |
| China | 7% | 7% | 8846 | 1618 | 4% | 4272 | 905 | 11% | 6685 | 2397 |
| Colombia | 7% | 7% | 14 | 43 | 4% | 4 | 32 | 0% | 8 | 34 |
| Costa Rica | 6% | 7% | 0 | 15 | 7% | 0 | 13 | 0% | | 19 |
| Croatia | 8% | 8% | 6 | 17 | 7% | 9 | 21 | 7% | 7 | 37 |
| Cyprus | 7% | 7% | 5 | 81 | 2% | 0 | 20 | 36% | 1 | 39 |
| Czech Republic | 5% | 2% | 33 | 103 | 5% | 35 | 78 | 0% | 23 | 107 |
| Denmark | 6% | 6% | 49 | 193 | 2% | 56 | 160 | 0% | 80 | 348 |
| Dominican Republic | | | | | | | | 0% | | 2 |
| Ecuador | 0 | 0 | 2 | 8 | 4% | 4 | 5 | 0% | 4 | 8 |
| Egypt | | | | | 2% | 10 | 41 | 34% | 7 | 10 |
| El Salvador | | | | | 8% | 0 | 0 | 0% | | 2 |
| Estonia | 7% | 7% | 3 | 22 | 4% | 1 | 17 | 0% | 1 | 39 |
| Finland | 6% | 5% | 42 | 88 | 5% | 79 | 117 | 0% | 78 | 204 |
| France | 4% | 4% | 407 | 661 | 4% | 334 | 559 | 2% | 548 | 1300 |
| Georgia | 5% | 6% | 2 | 4 | 3% | 1 | 1 | 4% | 3 | 2 |
| Germany | 4% | 4% | 995 | 804 | 4% | 773 | 697 | 0% | 1450 | 1525 |
| Greece | 0 | 0 | 66 | 147 | 0 | 38 | 61 | 26% | 41 | 128 |
| Honduras | | | | | | | | 0% | | 2 |
| Hungary | 7% | 7% | 26 | 71 | 6% | 19 | 45 | 4% | 16 | 109 |
| Ireland | 4% | 4% | 45 | 176 | 5% | 11 | 110 | 0% | 10 | 288 |
| Israel | | | | | 4% | 48 | 100 | 32% | 74 | 319 |
| Italy | 7% | 7% | 159 | 423 | 4% | 83 | 275 | 7% | 151 | 718 |
| Japan | 0 | 0 | 5381 | 787 | 4% | 3457 | 548 | 0% | 8297 | 1955 |
| Jordan | | | | | 5% | 3 | 8 | | 1 | |
| Kazakhstan | | | | | 4% | 3 | 0 | | | |
| Kenya | | | | | 6% | 0 | 0 | | | |
| Latvia | 5% | 6% | 7 | 12 | 4% | 2 | 19 | 0% | 5 | 36 |
| Lithuania | 5% | 5% | 0 | 15 | 7% | 1 | 33 | 0% | | 41 |
| Luxembourg | 4% | 5% | 4 | 70 | 9% | 1 | 29 | 0% | 8 | 146 |
| Malaysia | 0 | 0 | 22 | 81 | 5% | 7 | 67 | 0% | 10 | 65 |
| Malta | | | | | 0% | 3 | 7 | 0% | | 14 |
| Mexico | 9% | 8% | 89 | 558 | 5% | 41 | 266 | 3% | 27 | 577 |
| Moldova | 5% | 5% | 8 | 0 | 2% | 7 | 2 | | 13 | |
| Morocco | 9% | 9% | 14 | 97 | 8% | 5 | 30 | 51% | 1 | 24 |
| Netherlands | 5% | 5% | 224 | 666 | 5% | 118 | 458 | 0% | 414 | 1096 |
| New Zealand | 5% | 5% | 67 | 207 | 4% | 21 | 87 | 0% | 37 | 213 |
| Norway | 4% | 4% | 73 | 245 | 6% | 88 | 245 | 0% | 29 | 158 |
| Panama | 4% | 5% | 6 | 4 | 8% | 7 | 1 | 0% | 2 | 5 |
| Peru | 6% | 6% | 6 | 41 | 4% | 2 | 20 | 0% | 1 | 18 |
| Poland | 4% | 4% | 84 | 148 | 7% | 40 | 101 | 0% | 48 | 297 |
| Portugal | 9% | 9% | 15 | 159 | 4% | 3 | 65 | 12% | 14 | 150 |
| Romania | 6% | 6% | 23 | 34 | 5% | 26 | 29 | 6% | 25 | 60 |
| Russia | 5% | 6% | 831 | 673 | 4% | 677 | 534 | 3% | 664 | 930 |
| Saudi Arabia | 8% | 0 | 68 | 25 | 5% | 41 | 9 | 11% | 21 | 10 |
| Singapore | 8% | | 56 | 200 | 5% | 13 | 51 | 0% | 35 | 139 |
| Slovakia | 5% | 5% | 11 | 35 | 7% | 9 | 38 | 0% | 3 | 67 |
| Slovenia | 9% | 9% | 3 | 31 | 3% | 6 | 22 | 1% | 12 | 61 |
| South Africa | 7% | 7% | 52 | 359 | 5% | 9 | 121 | 6% | 15 | 229 |
| South Korea | 5% | 5% | 3133 | 1018 | 3% | 1498 | 492 | 0% | 3668 | 2002 |
| Spain | 9% | 8% | 279 | 528 | 3% | 114 | 257 | 17% | 99 | 675 |
| Sweden | 5% | 5% | 116 | 150 | 6% | 99 | 134 | 0% | 81 | 346 |
| Switzerland | 0 | 0 | 127 | 212 | 4% | 68 | 139 | 0% | 147 | 528 |
| Tajikistan | | | | | 4% | 0 | 0 | | | |
| Tunisia | | | | | 5% | 2 | 18 | 62% | 1 | 11 |
| Turkey | 6% | 6% | 14 | 167 | 5% | 6 | 86 | 14% | 10 | 202 |
| Ukraine | 4% | 4% | 49 | 41 | 4% | 70 | 12 | 2% | 76 | 34 |

| | | | | | | | | | | |
|--------------------------|----|----|------|------|----|------|------|-----|------|------|
| United Kingdom | 7% | 6% | 495 | 2159 | 6% | 327 | 2015 | 0% | 394 | 3755 |
| United States of America | 0 | 0 | 2431 | 4186 | 4% | 2016 | 2896 | 13% | 3466 | 4804 |

Table A 14. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015

| Inventions | | Droughts | | Floods | Heatwaves |
|---|------|---------------------|--------------------|--------------------|-------------------|
| | | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| Percentage of the country's population/agricultural area affected by an extreme event | t-1 | 0.004 (0.004) | -0.000 (0.005) | 0.005 (0.004) | 0.007* (0.004) |
| | t-2 | 0.008*** (0.003) | 0.003 (0.004) | 0.001 (0.005) | 0.005 (0.005) |
| | t-3 | 0.004 (0.004) | 0.003 (0.004) | 0.005 (0.005) | 0.009* (0.005) |
| | t-4 | 0.006* (0.004) | 0.002 (0.004) | 0.002 (0.005) | 0.008 (0.005) |
| | t-5 | 0.008** (0.004) | 0.007* (0.004) | 0.001 (0.006) | 0.008 (0.005) |
| | t-6 | 0.005** (0.003) | 0.002 (0.003) | 0.004 (0.006) | 0.007 (0.006) |
| | t-7 | 0.002 (0.003) | 0.001 (0.004) | 0.004 (0.006) | 0.002 (0.005) |
| | t-8 | 0.002 (0.003) | 0.001 (0.003) | 0.011** (0.005) | 0.009* (0.005) |
| | t-9 | 0.001 (0.002) | -0.000 (0.003) | 0.004 (0.005) | 0.004 (0.005) |
| | t-10 | 0.005 (0.003) | 0.002 (0.004) | 0.001 (0.004) | 0.006 (0.005) |
| Protection of Property Rights | | 0.144 (0.104) | 0.134 (0.109) | 0.167 (0.134) | 0.117 (0.105) |
| Long-term cumulative effect | | 0.046** (0.023) | 0.021 (0.028) | 0.024 (0.030) | 0.065 (0.045) |
| Period | | 1995-2015 | | | |
| Observations | | 1,040 | 1,019 | 1,019 | 1,143 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 15. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015

| Imports | | Droughts | | Floods | Heatwaves |
|---|------|---------------------|---------------------|---------------------|---------------------|
| | | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| Percentage of the country's population/agricultural area affected by an extreme event | t-1 | 0.005** (0.002) | 0.005* (0.003) | -0.000 (0.003) | 0.001 (0.002) |
| | t-2 | 0.003 (0.002) | 0.003 (0.002) | 0.002 (0.002) | 0.002 (0.003) |
| | t-3 | 0.005** (0.002) | 0.005** (0.002) | 0.000 (0.003) | 0.004 (0.003) |
| | t-4 | 0.007*** (0.002) | 0.008*** (0.002) | 0.001 (0.003) | 0.003 (0.003) |
| | t-5 | 0.002 (0.002) | 0.002 (0.002) | -0.003 (0.003) | 0.006*** (0.002) |
| | t-6 | 0.001 (0.002) | 0.003 (0.002) | 0.001 (0.003) | -0.000 (0.002) |
| | t-7 | -0.002 (0.002) | -0.001 (0.002) | 0.001 (0.003) | 0.001 (0.002) |
| | t-8 | 0.000 (0.002) | 0.003 (0.002) | 0.006* (0.003) | -0.002 (0.002) |
| | t-9 | 0.002 (0.002) | 0.003* (0.002) | 0.005** (0.002) | 0.001 (0.002) |
| | t-10 | 0.001 (0.003) | 0.003 (0.003) | 0.000 (0.004) | -0.001 (0.002) |
| Protection of Property Rights | | 0.069 (0.053) | 0.049 (0.048) | 0.045 (0.047) | 0.048 (0.038) |
| Freedom to trade | | 0.159*** (0.060) | 0.171*** (0.060) | 0.272*** (0.058) | 0.189*** (0.060) |
| Long-term cumulative effect | | 0.025* (0.014) | 0.035** (0.015) | -0.009 (0.018) | 0.014 (0.015) |
| Period | | 1995-2015 | | | |
| Observations | | 1,059 | 1,038 | 944 | 1,184 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 16. Effect of Extreme Weather Events on the Share of Adaptation Inventions in All Technologies Invented, 1995-2015

| Share adaptation inventions | | Droughts | | Floods | Heatwaves |
|---|------|--------------------|--------------------|---------------------|-------------------|
| | | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| Percentage of the country's population/agricultural area affected by an extreme event | t-1 | 0.000 (0.006) | -0.002 (0.008) | 0.009 (0.007) | -0.000 (0.004) |
| | t-2 | 0.013** (0.005) | 0.011* (0.006) | -0.001 (0.007) | 0.000 (0.006) |
| | t-3 | -0.006 (0.004) | -0.007 (0.005) | 0.005 (0.011) | 0.009 (0.006) |
| | t-4 | 0.001 (0.004) | -0.001 (0.006) | 0.009 (0.008) | 0.007 (0.007) |
| | t-5 | -0.002 (0.006) | -0.003 (0.006) | 0.003 (0.009) | 0.007 (0.006) |
| | t-6 | -0.002 (0.006) | -0.004 (0.005) | -0.004 (0.010) | -0.000 (0.011) |
| | t-7 | -0.001 (0.007) | -0.002 (0.008) | -0.030** (0.012) | -0.006 (0.005) |
| | t-8 | -0.004 (0.007) | -0.004 (0.008) | 0.007 (0.009) | 0.001 (0.006) |
| | t-9 | -0.005 (0.005) | -0.007 (0.007) | 0.004 (0.009) | 0.001 (0.007) |
| | t-10 | 0.004 (0.005) | 0.000 (0.005) | -0.006 (0.008) | -0.008 (0.006) |
| Protection of Property Rights | | 0.043 (0.111) | 0.047 (0.114) | 0.055 (0.122) | -0.012 (0.165) |
| Period | | 1995-2015 | | | |
| Observations | | 1,040 | 1,019 | 1,019 | 1,143 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 17. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015
(Poisson)

| Inventions (Poisson) | | Droughts | | Floods | Heatwaves |
|---|------|--------------------|--------------------|---------------------|---------------------|
| | | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| Percentage of the country's population/agricultural area affected by an extreme event | t-1 | 0.011 (0.008) | -0.003 (0.009) | -0.001 (0.011) | 0.010* (0.005) |
| | t-2 | 0.013** (0.007) | -0.002 (0.006) | 0.008 (0.009) | 0.011 (0.007) |
| | t-3 | 0.022* (0.012) | 0.008 (0.009) | 0.005 (0.010) | -0.001 (0.009) |
| | t-4 | 0.027** (0.013) | 0.010 (0.011) | 0.004 (0.012) | 0.023*** (0.009) |
| | t-5 | 0.019* (0.010) | 0.004 (0.008) | 0.010 (0.010) | 0.012* (0.007) |
| | t-6 | 0.009 (0.008) | -0.004 (0.007) | 0.020*** (0.007) | 0.025** (0.010) |
| | t-7 | 0.004 (0.008) | -0.010 (0.006) | 0.014 (0.010) | 0.022* (0.012) |
| | t-8 | 0.011 (0.009) | 0.007 (0.008) | 0.011 (0.012) | 0.033** (0.015) |
| | t-9 | 0.009 (0.008) | 0.004 (0.009) | -0.003 (0.014) | 0.031*** (0.011) |
| | t-10 | 0.003 (0.006) | 0.001 (0.008) | -0.002 (0.016) | 0.027*** (0.009) |
| Protection of Property Rights | | 0.239** (0.098) | 0.209 (0.127) | 0.229* (0.129) | 0.024 (0.071) |
| Period | | 1995-2015 | | | |
| Observations | | 1,040 | 1,019 | 1,019 | 1,143 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 18. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015
(Poisson)

| Imports (Poisson) | Droughts | Floods | Heatwaves | | |
|---|-------------------|---------------------|---------------------|-------------------|---------------------|
| | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> | |
| | t-1 | 0.004** (0.002) | 0.006** (0.003) | -0.004 (0.003) | 0.001 (0.002) |
| | t-2 | 0.004** (0.002) | 0.006** (0.003) | 0.002 (0.002) | 0.004* (0.002) |
| | t-3 | 0.005** (0.002) | 0.007** (0.003) | 0.000 (0.004) | 0.009** (0.003) |
| | t-4 | 0.006*** (0.002) | 0.007*** (0.003) | 0.000 (0.003) | 0.008** (0.004) |
| Percentage of the country's population/agricultural area affected by an extreme event | t-5 | 0.004** (0.002) | 0.004** (0.002) | -0.003 (0.003) | 0.008*** (0.003) |
| | t-6 | 0.004** (0.002) | 0.006*** (0.002) | -0.002 (0.003) | 0.004** (0.002) |
| | t-7 | 0.002 (0.002) | 0.002 (0.002) | -0.003 (0.005) | 0.005** (0.002) |
| | t-8 | 0.005** (0.002) | 0.006** (0.002) | 0.001 (0.005) | 0.003 (0.002) |
| | t-9 | 0.003** (0.001) | 0.004*** (0.002) | 0.005 (0.003) | 0.006* (0.003) |
| | t-10 | 0.002 (0.001) | 0.003** (0.002) | 0.001 (0.003) | -0.000 (0.003) |
| Protection of Property Rights | | 0.022 (0.044) | 0.023 (0.036) | -0.034 (0.061) | 0.001 (0.023) |
| Freedom to trade | | 0.151* (0.089) | 0.157* (0.087) | 0.203* (0.113) | 0.198*** (0.049) |
| Period | | 1995-2015 | | | |
| Observations | | 1,059 | 1,038 | 944 | 1,184 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 19. Adaptation Technologies Inventions Following Extreme Weather Events, 1995-2015 (Zero Inflated Negative Binomial)

| Inventions (Zero inflated Negative Binomial) | | Droughts | | Floods | Heatwaves |
|---|------|--------------------|--------------------|--------------------|--------------------|
| | | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| Percentage of the country's population/agricultural area affected by an extreme event | t-1 | 0.003 (0.004) | -0.000 (0.004) | 0.004 (0.004) | 0.008* (0.004) |
| | t-2 | 0.007** (0.003) | 0.002 (0.004) | 0.001 (0.006) | 0.004 (0.005) |
| | t-3 | 0.004 (0.003) | 0.003 (0.004) | 0.005 (0.005) | 0.009* (0.005) |
| | t-4 | 0.005 (0.004) | 0.001 (0.004) | 0.002 (0.005) | 0.008 (0.006) |
| | t-5 | 0.008** (0.003) | 0.007 (0.004) | 0.001 (0.006) | 0.008 (0.005) |
| | t-6 | 0.005* (0.003) | 0.002 (0.003) | 0.004 (0.006) | 0.009 (0.007) |
| | t-7 | 0.002 (0.003) | 0.000 (0.004) | 0.005 (0.006) | 0.003 (0.006) |
| | t-8 | 0.002 (0.003) | 0.001 (0.003) | 0.011** (0.006) | 0.010** (0.005) |
| | t-9 | 0.001 (0.002) | -0.001 (0.003) | 0.004 (0.005) | 0.005 (0.005) |
| | t-10 | 0.005 (0.003) | 0.002 (0.004) | 0.002 (0.004) | 0.006 (0.005) |
| Protection of Property Rights | | 0.146 (0.100) | 0.136 (0.106) | 0.171 (0.132) | 0.113 (0.105) |
| Period | | 1995-2015 | | | |
| Observations | | 1,040 | 1,019 | 1,019 | 1,143 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 20. Imports of Adaptation Technologies Following Extreme Weather Events, 1995-2015 (Zero Inflated Negative Binomial)

| Imports (Zero inflated Negative Binomial) | | Droughts | | Floods | Heatwaves |
|---|------|---------------------|---------------------|---------------------|---------------------|
| | | <i>Population</i> | <i>Agriculture</i> | <i>Population</i> | <i>Population</i> |
| Percentage of the country's population/agricultural area affected by an extreme event | t-1 | 0.005** (0.002) | 0.005** (0.002) | -0.001 (0.003) | 0.000 (0.002) |
| | t-2 | 0.002 (0.002) | 0.002 (0.002) | 0.001 (0.002) | 0.001 (0.003) |
| | t-3 | 0.005** (0.002) | 0.006** (0.002) | -0.001 (0.003) | 0.004 (0.003) |
| | t-4 | 0.005** (0.002) | 0.006*** (0.002) | -0.000 (0.003) | 0.002 (0.003) |
| | t-5 | 0.003 (0.002) | 0.002 (0.002) | -0.005* (0.003) | 0.005** (0.002) |
| | t-6 | 0.001 (0.002) | 0.003 (0.002) | -0.001 (0.003) | -0.000 (0.002) |
| | t-7 | -0.000 (0.002) | 0.000 (0.002) | -0.000 (0.002) | 0.001 (0.002) |
| | t-8 | 0.001 (0.002) | 0.003 (0.002) | 0.005 (0.003) | -0.002 (0.002) |
| | t-9 | 0.002 (0.002) | 0.004** (0.002) | 0.004** (0.002) | 0.001 (0.002) |
| | t-10 | 0.001 (0.002) | 0.003 (0.003) | -0.001 (0.003) | -0.002 (0.002) |
| Protection of Property Rights | | 0.046 (0.052) | 0.033 (0.049) | 0.021 (0.047) | 0.031 (0.037) |
| Freedom to trade | | 0.189*** (0.056) | 0.193*** (0.057) | 0.263*** (0.054) | 0.159*** (0.046) |
| Period | | 1995-2015 | | | |
| Observations | | 1,059 | 1,038 | 944 | 1,184 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the country level in parenthesis

Table A 21. Number of Firms Inventing at Least One Adaptation Patent, By Country (1995-2015)

| Country | Droughts | Floods |
|----------------|-----------------|---------------|
| Canada | 28 | 24 |
| China | 403 | 325 |
| Germany | 199 | 182 |
| France | 81 | 87 |
| United Kingdom | 104 | 107 |
| Japan | 687 | 627 |
| South Korea | 358 | 278 |
| Netherlands | 51 | 34 |
| Sweden | 16 | 15 |
| USA | 469 | 414 |

Source: Authors' calculations based on World Patent Statistical Database (PATSTAT) data.

Table A 22. Effect of Foreign and Local Extreme Weather Events on the Filing of Adaptation Patents, 1995-2015

| Logit | | Droughts | | Floods | |
|--|---|---------------------|---------------------|----------------------|---------------------|
| | | (A) | (B) | (A) | (B) |
| Share of country's population affected by the extreme events | At t-1 | 0.011*** (0.002) | 0.009*** (0.002) | -0.000 (0.004) | -0.001 (0.004) |
| | At t-2 | 0.004* (0.002) | 0.002 (0.002) | -0.001 (0.003) | -0.002 (0.003) |
| | At t-3 | 0.007*** (0.002) | 0.005** (0.002) | 0.003 (0.003) | 0.003 (0.003) |
| | At t-4 | 0.011*** (0.002) | 0.010*** (0.002) | 0.006* (0.003) | 0.005 (0.003) |
| | At t-5 | 0.008*** (0.002) | 0.006*** (0.002) | 0.006** (0.003) | 0.005 (0.003) |
| | At t-6 | 0.008*** (0.002) | 0.007*** (0.002) | 0.003 (0.003) | 0.002 (0.003) |
| | At t-7 | 0.002 (0.002) | 0.002 (0.002) | 0.007** (0.003) | 0.006* (0.003) |
| | At t-8 | 0.007*** (0.002) | 0.006*** (0.002) | 0.009*** (0.003) | 0.008** (0.003) |
| | At t-9 | 0.005** (0.002) | 0.004** (0.002) | 0.007** (0.003) | 0.007** (0.003) |
| | At t-10 | 0.007*** (0.002) | 0.006*** (0.002) | 0.008*** (0.003) | 0.008*** (0.003) |
| Recipient Country Control variables | Protection of Property Rights | -0.005 (0.030) | 0.022 (0.031) | -0.108*** (0.032) | -0.066** (0.033) |
| | Freedom to trade | 0.237*** (0.063) | 0.244*** (0.063) | 0.236*** (0.073) | 0.253*** (0.075) |
| | Year FE | X | X | X | X |
| | Pair Inventor firm/Recipient Country FE | X | X | X | X |
| | Inventor country specific time trend | | X | | X |
| | Observations | 57,333 | 57,333 | 43,899 | 43,899 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the pair level in parenthesis

Table A 23: Differentiated Effect of Local and Foreign Extreme Weather Events on Adaptation Patent Filing, 1995-2015

| Logit | | Droughts (A) | Floods (A) | |
|--|---|---------------------|---------------------|---------------------|
| Share of country's population affected by the extreme events | At t-1 | 0.019*** (0.003) | -0.001 (0.006) | |
| | At t-2 | 0.009** (0.004) | 0.004 (0.006) | |
| | At t-3 | 0.009*** (0.003) | 0.007 (0.006) | |
| | At t-4 | 0.019*** (0.003) | 0.018*** (0.005) | |
| | Local weather events | At t-5 | 0.020*** (0.004) | 0.017*** (0.005) |
| | At t-6 | 0.012*** (0.004) | 0.016*** (0.005) | |
| | At t-7 | 0.002 (0.004) | 0.021*** (0.006) | |
| | At t-8 | 0.014*** (0.003) | 0.017*** (0.005) | |
| | At t-9 | 0.006* (0.003) | 0.017*** (0.005) | |
| | At t-10 | 0.007** (0.003) | 0.019*** (0.005) | |
| Foreign weather events | At t-1 | 0.006** (0.003) | 0.000 (0.004) | |
| | At t-2 | 0.000 (0.003) | -0.005 (0.004) | |
| | At t-3 | 0.004 (0.003) | 0.002 (0.004) | |
| | At t-4 | 0.008*** (0.003) | 0.000 (0.005) | |
| | At t-5 | 0.002 (0.003) | 0.003 (0.004) | |
| | At t-6 | 0.005* (0.003) | -0.005 (0.005) | |
| | At t-7 | 0.002 (0.003) | -0.000 (0.004) | |
| | At t-8 | 0.004 (0.003) | 0.005 (0.004) | |
| | At t-9 | 0.005* (0.003) | 0.001 (0.005) | |
| | At t-10 | 0.005* (0.003) | 0.001 (0.004) | |
| Recipient Country Control variables | Protection of Property Rights | 0.012 (0.032) | -0.070** (0.033) | |
| | Freedom to trade | 0.198*** (0.067) | 0.258*** (0.075) | |
| | Year FE | X | X | |
| | Pair Inventor firm/Recipient Country FE | X | X | |
| | Inventor country specific time trend | | | |
| | Observations | 57,333 | 43,899 | |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the pair level in parenthesis

Table A 24. Effect of Extreme Weather Events on the Co-Invention of Adaptation Technologies, 1995-2015

| Logit | Droughts | | Floods | | |
|--|-------------------------------|--------------------|--------------------|-------------------|-------------------|
| | (A) | (B) | (A) | (B) | |
| Share of country's population affected by the extreme events | At t-1 | 0.033 (0.020) | 0.034* (0.020) | -0.062 (0.044) | -0.055 (0.044) |
| | At t-2 | -0.001 (0.022) | -0.001 (0.022) | -0.003 (0.028) | 0.002 (0.027) |
| | At t-3 | 0.017 (0.016) | 0.018 (0.016) | -0.031 (0.040) | -0.021 (0.039) |
| | At t-4 | 0.001 (0.021) | 0.001 (0.021) | 0.004 (0.024) | 0.012 (0.025) |
| | At t-5 | 0.037** (0.017) | 0.038** (0.017) | -0.026 (0.026) | -0.022 (0.026) |
| | At t-6 | -0.007 (0.020) | -0.008 (0.020) | 0.041 (0.029) | 0.043 (0.030) |
| | At t-7 | 0.031** (0.015) | 0.031** (0.014) | -0.021 (0.027) | -0.020 (0.031) |
| | At t-8 | 0.015 (0.013) | 0.015 (0.013) | 0.004 (0.030) | 0.002 (0.033) |
| | At t-9 | 0.011 (0.015) | 0.012 (0.015) | 0.004 (0.039) | -0.001 (0.040) |
| | At t-10 | 0.028* (0.017) | 0.028* (0.017) | -0.069 (0.045) | -0.066 (0.044) |
| Recipient Country Control variables | Protection of Property Rights | 0.103 (0.176) | 0.125 (0.181) | 0.324 (0.198) | 0.353 (0.233) |
| | Freedom to trade | 1.308** (0.570) | 1.471** (0.647) | 1.369 (0.909) | 0.698 (0.929) |
| Year FE | X | X | X | X | |
| Pair Inventor firm/Recipient Country FE | X | X | X | X | |
| Inventor country specific time trend | | X | | X | |
| Observations | 1,784 | 1,784 | 1,007 | 1,007 | |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the pair level in parenthesis

Table A 25. Effect of Foreign and Extreme Weather Events on the Filing of Adaptation Patents (Droughts Agriculture), 1995-2015

| Logit | | Droughts | |
|---|---|---------------------|---------------------|
| | | (A) | (B) |
| Share of country's agricultural area affected by the extreme events | At t-1 | 0.010*** (0.002) | 0.008*** (0.002) |
| | At t-2 | 0.004* (0.002) | 0.003 (0.003) |
| | At t-3 | 0.006** (0.002) | 0.004 (0.002) |
| | At t-4 | 0.009*** (0.002) | 0.007*** (0.002) |
| | At t-5 | 0.007*** (0.002) | 0.006** (0.002) |
| | At t-6 | 0.008*** (0.002) | 0.007*** (0.002) |
| | At t-7 | 0.002 (0.002) | 0.001 (0.002) |
| | At t-8 | 0.007*** (0.002) | 0.006*** (0.002) |
| | At t-9 | 0.004 (0.002) | 0.003 (0.002) |
| | At t-10 | 0.009*** (0.002) | 0.008*** (0.002) |
| Recipient Country Control variables | Protection of Property Rights | -0.032 (0.030) | 0.007 (0.031) |
| | Freedom to trade | 0.262*** (0.064) | 0.267*** (0.064) |
| | Year FE | X | X |
| | Pair Inventor firm/Recipient Country FE | X | X |
| | Inventor country specific time trend | | X |
| Observations | | 57,434 | 57,434 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the pair level in parenthesis

Table A 26. Differentiated Effect of Local and Foreign Extreme Weather Events on Adaptation Patent Filing (Droughts Agriculture), 1995-2015

| Logit | Droughts (Agriculture) (A) |
|---|-------------------------------|
| | 0.018*** (0.004) |
| | 0.016*** (0.004) |
| | 0.013*** (0.004) |
| | 0.022*** (0.004) |
| | 0.023*** (0.004) |
| Local weather events | 0.020*** (0.005) |
| | 0.008* (0.004) |
| | 0.017*** (0.004) |
| | 0.007* (0.004) |
| | 0.016*** (0.004) |
| Share of country's agricultural area affected by the extreme events | 0.008** (0.003) |
| | -0.001 (0.003) |
| | 0.003 (0.003) |
| | 0.004 (0.003) |
| | 0.002 (0.003) |
| Foreign weather events | 0.005* (0.003) |
| | 0.001 (0.003) |
| | 0.003 (0.003) |
| | 0.004 (0.003) |
| | 0.006** (0.003) |
| Recipient Country Control variables | 0.012 (0.032) |
| | 0.198*** (0.067) |
| Year FE | X |
| Pair Inventor firm/Recipient Country FE | X |
| Inventor country specific time trend | X |
| Observations | 56,976 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the pair level in parenthesis

Table A 27. Effect of Extreme Weather Events on the Co-Invention of Adaptation Technologies (Droughts Agriculture), 1995-2015

| Logit | | Droughts (Agriculture) | |
|---|---|------------------------|--------------------|
| | | (A) | (B) |
| Share of country's agricultural area affected by the extreme events | At t-1 | 0.011 (0.022) | 0.010 (0.022) |
| | At t-2 | -0.005 (0.022) | -0.007 (0.022) |
| | At t-3 | 0.010 (0.019) | 0.010 (0.018) |
| | At t-4 | -0.011 (0.023) | -0.011 (0.024) |
| | At t-5 | 0.040** (0.016) | 0.040** (0.016) |
| | At t-6 | -0.011 (0.022) | -0.012 (0.022) |
| | At t-7 | 0.028* (0.016) | 0.028* (0.016) |
| | At t-8 | 0.008 (0.015) | 0.008 (0.015) |
| | At t-9 | 0.002 (0.017) | 0.004 (0.017) |
| | At t-10 | 0.026 (0.018) | 0.026 (0.018) |
| Recipient Country Control variables | Protection of Property Rights | 0.094 (0.178) | 0.121 (0.182) |
| | Freedom to trade | 1.247** (0.549) | 1.392** (0.610) |
| | Year FE | X | X |
| | Pair Inventor firm/Recipient Country FE | X | X |
| | Inventor country specific time trend | | X |
| Observations | | 1,784 | 1,784 |

Notes: * p < 0:10, ** p < 0:05, *** p < 0:01. Standard errors clustered at the pair level in parenthesis

FIGURES (Appendix)

List of figures in the appendix

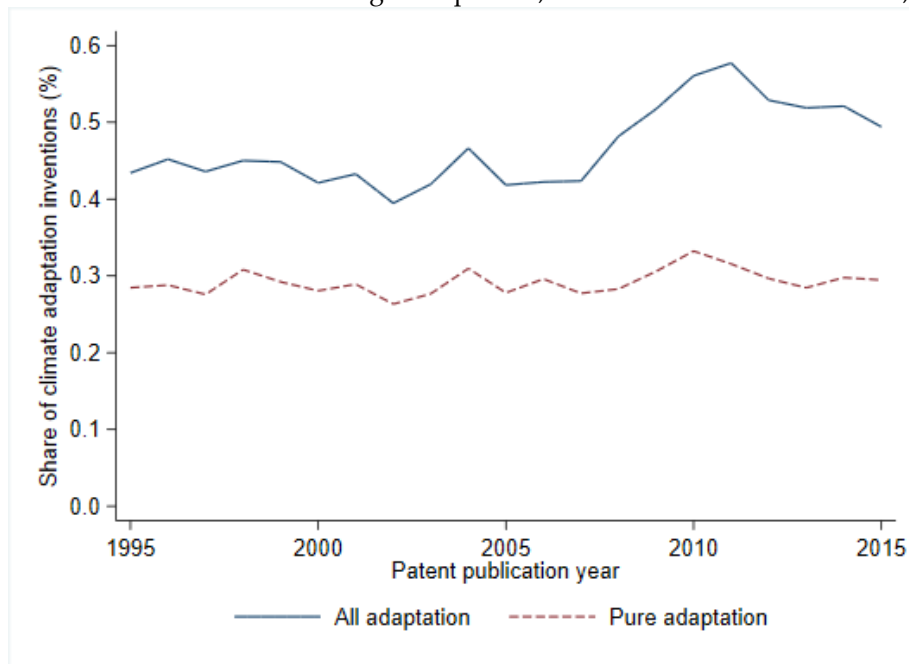
Figure A 1. Innovation for Climate Change Adaptation, as a Share of Total Innovation, 1995–2015..... 218

Figure A 2: Area Affected by Storms Over the Period: Australia 218

Figure A 3: Evolution of the Number of Droughts Related Technologies Invented per Year (1995-2015)..... 219

Figure A 4: Evolution of the Number of Floods Related Technologies Invented per Year (1995-2015)..... 220

Figure A 1. Innovation for Climate Change Adaptation, as a Share of Total Innovation, 1995–2015



Source: Calculations, based on World Patent Statistical Database (PATSTAT) data.

Note: “Pure adaptation” refers to technologies for climate change adaptation that are not simultaneously classified as mitigation technologies.

Figure A 2: Area Affected by Storms Over the Period: Australia

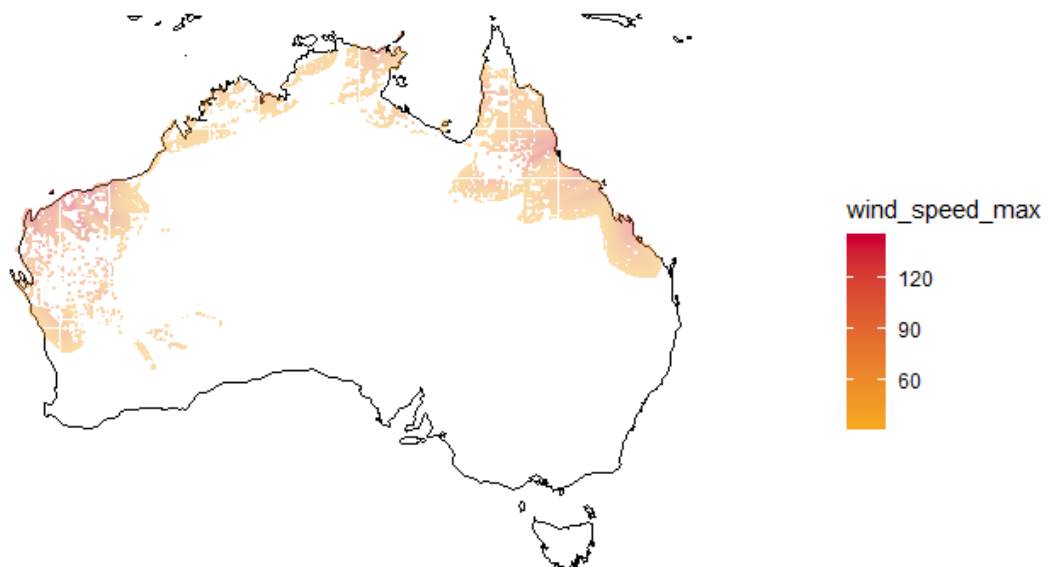
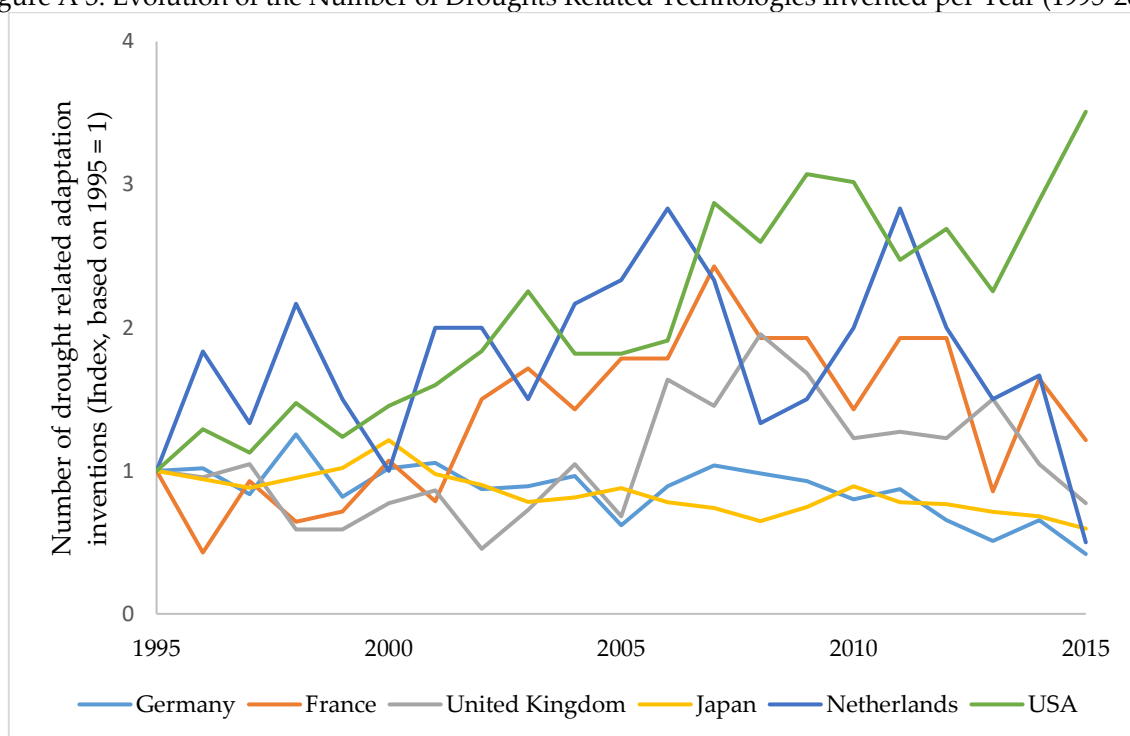
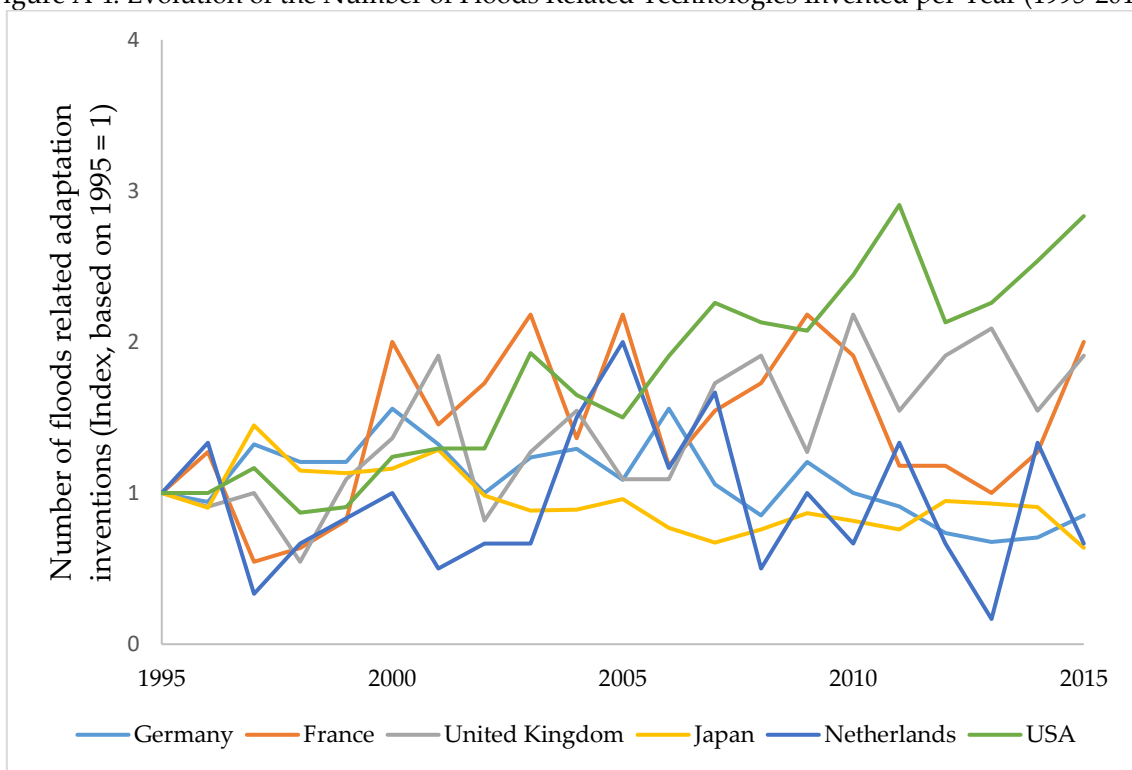


Figure A 3: Evolution of the Number of Droughts Related Technologies Invented per Year (1995-2015)



Source: Authors' calculations based on World Patent Statistical Database (PATSTAT) data.

Figure A 4: Evolution of the Number of Floods Related Technologies Invented per Year (1995-2015)



Source: Authors' calculations based on World Patent Statistical Database (PATSTAT) data.

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RÉSUMÉ

Alors qu'une augmentation d'au moins deux degrés de la température mondiale semble inévitable, la résilience au changement climatique est devenue une préoccupation majeure. Alors que les technologies peuvent jouer un rôle déterminant dans l'adaptation au changement climatique, on sait peu de choses sur le développement et la diffusion des technologies d'adaptation. Cette thèse, composée de quatre chapitres présentant des études descriptives et économétriques, utilise une base de données de brevets unique pour examiner le comportement d'innovation des pays et des entreprises en lien avec les technologies d'adaptation. Le premier chapitre montre que les pays ne dirigent pas spécifiquement leur effort d'innovation vers les technologies d'adaptation. Ces innovations sont très concentrées au sein de quelques pays et très peu diffusées internationalement, causant une inadéquation entre les besoins d'adaptation des pays et leur accès aux technologies. Dans le second chapitre, j'évalue l'efficacité des technologies comme outil de protection contre les dommages économiques et humains induits par les cyclones tropicaux. Ce chapitre prouve que ces technologies permettent de réduire le nombre de morts et les dégâts économiques induits par ces événements, et légitime l'intérêt porté aux technologies comme solution pour l'adaptation au changement climatique. Les deux derniers chapitres détaillent la dynamique de l'innovation dans les technologies d'adaptation à la suite d'événements climatiques extrêmes. Ces deux études, à l'échelle des pays puis des entreprises, montrent que les innovateurs réagissent faiblement à ces extrêmes météorologiques, et qu'ils transfèrent peu leurs brevets aux pays affectés par ces aléas. De plus, ces chapitres confirment que les événements extrêmes n'induisent pas d'efforts supplémentaires des innovateurs vers les technologies d'innovation, ni la mise en place d'innovation commune à plusieurs pays. Ce constat préoccupant plaide pour la mise en place de politiques locales, nationales et internationales ambitieuses afin de pallier le manque d'innovation et d'accès aux technologies d'adaptation, et ainsi induire une réelle transition de l'innovation vers ces technologies.

MOTS CLÉS

Adaptation au Changement Climatique, Economie, Technologies

ABSTRACT

Whilst a 2 or 3 degrees rise on earth appears inevitable, country's resilience to climate change has become a crucial issue. Whereas technologies may play a major role in the global effort to adapt to climate change, little is known about the development and diffusion of adaptation technologies. This thesis, made of four chapters presenting descriptive and econometric studies, attempts to fill this gap by analyzing both countries and firms innovation behavior in adaptation technologies over the last 30 years, relying on a unique patent database targeting adaptation technologies. The first chapter provides the first descriptive study of the global invention and transfer of adaptation technologies. The observations indicate that countries did not specifically direct their innovation efforts towards adaptation technologies over the last 25 years. These innovations are highly concentrated within a few countries and I find very limited international technology diffusion. Consequently, I highlight a mismatch between countries' adaptation needs and their access to technologies. In the second chapter, I assess the effectiveness of technologies as a tool to mitigate economic and human damages induced by tropical cyclones. This chapter shows that these technologies can reduce the number of deaths and economic damage induced by these events, and legitimizes the interest in technologies as a solution for climate change adaptation. The last two chapters detail the dynamics of the innovation in adaptation technologies following extreme weather events. These two studies, at the country level and then at the firm level, show innovators weakly react to these weather extremes, and they do not transfer their patents to countries affected by these hazards. Moreover, these chapters confirm that extreme events do not induce additional efforts of innovators towards innovation technologies, nor the implementation of innovation common to several countries. This worrying observation calls for the implementation of ambitious local, national and international policies in order to overcome the lack of innovation and access to adaptation technologies, and thus induce a real transition in innovation toward these technologies.

KEYWORDS

Climate Change Adaptation, Economics, Technology