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

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Introduction

Adaptation to climate change will require new technologies (Fankhauser 2017, 2019). Although mitigation technology is intended to slow global warming, adaptation technology helps firms, communities, and governments function in a changing environment. An important role can be played by technologies that increase resilience to climate risks and extremes. These may include better irrigation systems, advanced weather forecasting tools, new drugs to treat changing disease patterns, and drought- and heat-tolerant crops. The extent to which such advanced technologies are developed and become globally available will have a significant impact on countries' ability to deal with the impacts of climate change (Klein and Tol 1997; Miao 2017; GCA 2019).

Although the economic literature on climate change mitigation technologies is abundant (see Popp 2019 for a survey), very little has been written about the development of new adaptation technologies or their diffusion to countries that are experiencing climate shocks. The economy of many developing countries remains highly dependent on agriculture, and

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This paper is based on an earlier report (Dechezleprêtre et al. 2020) commissioned by the World Bank and funded through the bank's Global Facility for Disaster Reduction and Recovery (GFDRR). Fankhauser also acknowledges financial support from the UK Foreign and Development Office (FCDO) through its support for the Climate Compatible Growth (CCG) program. Stoever acknowledges financial support from the BMBF and EU Marie Curie Actions/COFUND through the DAAD PRIME program. The authors thank Stéphane Hallegatte, Kerstin Hötte, Brenden Jongman, Emma Katherine Phillips, Jean-Louis Racine, Jun Rentschler, Sugandha Srivastav, Arame Tall, and Erika Vargas for their comments and feedback. The authors are also grateful to Mary Anderson for editorial assistance. Any remaining errors are ours.

Online enhancement: appendix.

Electronically published July 24, 2023

Review of Environmental Economics and Policy, volume 17, number 2, summer 2023.
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the availability of new climate-resilient crop varieties will be a vital issue. For other countries, protection against floods and storms is the main concern. The need for adaptation technology is thus very heterogeneous. Whether the different adaptation technologies will be made available in the countries that need them most is a crucial question that is largely open.

The aim of this paper is to start building an evidence base 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 explore 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 and technologies for climate change adaptation are urgently needed in the Global South, where many countries are particularly vulnerable to climate shocks (Fankhauser and McDermott 2014).

The analysis relies on 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 nearly all 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.

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 nontechnological forms of innovation and low-tech options. These softer forms of innovation and adjustments to existing technology likely constitute the bulk of current adaptation activity, especially in developing countries (UNEP 2014). One consequence of focusing on patents is therefore that low-income countries are practically absent from the data.[1]

The empirical adaptation literature is focused almost exclusively on the deployment of existing technology rather than development of new technology (Markanday, Galarraga, and Markandya 2019). Examples include irrigation and crop choices in the case of agriculture (Seo and Mendelsohn 2008; Kurukulasuriya, Kala, and Mendelsohn 2011), air-conditioning and building design in the case of heat waves (Deschênes and Greenstone 2011; Rapson 2014; Day et al. 2019), and physical infrastructure for water management (Dessai and Hulme 2007; Kirshen et al. 2015) and flood protection (Linquiti and Vonortas 2012; Ranger, Reeder, and Lowe 2013).

However, as climate change unfolds, adaptation innovation will become increasingly critical. One of the few papers to analyze adaptation innovation is by Hötte and Jee (2022), who use US patent data to study the link between innovation in adaptation and mitigation. They distinguish between science-intensive adaptation technologies (e.g., in agriculture and health) and more engineering-based innovation (e.g., in coastal protection and water management). Conway et al. (2015) focus more narrowly on water-related technologies. Using global patent data, the authors describe innovation in this sector and document international collaboration

[1]When analyzing international technology transfer, we supplement patent data with data on foreign direct investment (FDI)—another widely used measure of cross-border technology diffusion. The results are shown in the appendix (available online).

on innovation and technology diffusion. Miao and Popp (2014), Li (2017), and Hu et al. (2018) also use patent data but from a different perspective. They examine the drivers of adaptation innovation, focusing on the effects of past natural disasters. They find that such events are associated with an increase in the number of subsequent risk-mitigating innovations, at a magnitude that differs across types of disaster and technology. Compared with the existing literature, the scope of our paper is much wider. We provide the first quantitative description of the current dynamics and geography of innovation in the full range of adaptation technologies at a global scale. However, the analysis is mostly descriptive and leaves the identification of the drivers of this innovation for future research.

The rest of the paper proceeds as follows. The next section discusses the role of advanced technology for adaptation to climate change and how patent data can help us understand where we are now. The section on "Invention of Technologies for Climate Change Adaptation" reviews how global innovation activity in adaptation technologies has developed over time and space. This is followed by a discussion on the international transfer of adaptation technologies. The section on "Patenting Activity in Relation to Climate Hazards" examines the relationship between adaptation technology and physical climate risks (and therefore adaptation needs). The final section concludes with implications for policy and further research.

The Role of Technologies for Climate Change Adaptation

The Importance of Innovation in Climate Adaptation

Homo sapiens has managed to thrive in nearly all currently observed climate conditions. We have developed technologies and skills to adapt buildings, infrastructure, agriculture, and economic activity to multiple environments and climate risks. Over the centuries, we have generated a stock of knowledge that equips us with considerable adaptation capabilities.

However, that knowledge base may be insufficient in the face of unprecedented climate change. Although the Fifth Intergovernmental Panel on Climate Change Assessment Report (IPCC 2014) acknowledges the importance of nontechnological solutions and traditional knowledge to ensure human adaptation to future conditions, it also identifies technology as one of the three areas that can reduce the current and future climate change adaptation gap.

Looking at specific sectors and climate extremes can help us understand why new technologies are important. Take the example of sea-level rise and related hazards in coastal zones (Klein et al. 2001). Adaptation first involves describing and assessing 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 cheaper, more effective dikes, levees, salt intrusion barriers using resistant materials, and detached breakwaters. Last, the impacts can be reduced by early warning systems, saline-resistant crops, new aquaculture solutions, desalination equipment, and better drainage systems. Most of these solutions can be made more effective by using advanced technologies. The United Nations Development Programme (UNDP) cites the example of early warning systems that helped prevent fatalities in Bangladesh in 2007 (UNDP 2018). The United Nations' estimate is a benefit–cost ratio of up to 500:1. Air cooling offers another illustration; the diffusion of air conditioners has been estimated to be

responsible for almost the entire reduction in heat wave–induced fatalities observed in the United States during the twentieth century (Barreca et al. 2016).

The Diffusion of Adaptation Technology

Although the UNEP Adaptation Gap Report (UNEP 2014) highlights an increasing need for advanced technologies, it also observes that needs are less likely to translate into demand in developing economies. This issue is not specific to adaptation. In all technological areas, the limited availability of scientists and engineers, low number of past innovations, and low research and development (R&D) expenditure (Fagerberg 1994; Keller 1996; Griffith et al. 2004; Kneller and Stevens 2006) reduce the ability of countries to use new knowledge.

These limited capacities pose a particular challenge to adaptation, as many low-technology countries are highly affected by climate change (IPCC 2021) and traditional knowledge is likely to be insufficient given the scale of the problem. As an illustration, a report of technology needs by 25 middle-income and low-income countries indicates that around 75 percent of the gaps concern modern technologies,[2] especially for infrastructure, health, water management, disaster risk management, and coastal zones protection (UNEP 2014).[3] Combining traditional knowledge with modern scientific and technological tools can pay particularly high dividends—for example, when Inuit hunters combine their knowledge of wildlife and sea ice with weather station and GPS data to adapt to changing conditions.

Adaptation Patents

There is only patchy knowledge of the geography of supply and demand for these advanced adaptation technologies. One way of quantifying the growth and spread of adaptation innovation is by using patent data. Patent data provide a useful tool to draw a systematic landscape of the past and current patterns and trends of innovative activity in all regions of the world.[4] In the rest of this article, we rely on the PATSTAT database, which contains patents (corresponding to 19 million distinct inventions patented across several jurisdictions) filed between 1995 and 2015 in nearly all world patent offices.

Put simply, the patenting process involves two stages. An inventor first files a patent to protect an invention, most often in the home country patent office. The inventor may then extend this protection by filing additional patents in other countries where commercial opportunities can be expected. The set of 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 and avoids double-counting inventions protected in several countries. Counting the number of patents filed in country Y by

[2]More information about the Technology Needs Assessment is available at https://unfccc.int/ttclear/tna.

[3]Low absorptive capacities mean domestic economic actors are less able to imitate an imported technology. In this context, intellectual property rights are less useful in securing innovation returns and thus in providing technology owners with incentives to transfer.

[4]Note that patents protect the results of "applicable" research leading to ready-to-use technologies that 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 technologies and rely on patent protection. In the data used in this article, around 15 percent of adaptation patents are filed by universities or nonprofit organizations.

Table 1 Technology fields of Y02A patents included in the study

Category	Description	Examples
Coastal and river protection	Technologies for adaptation to climate change in coastal zones and river basins	Dikes, dams, artificial reefs, groins, real-time flood 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 adaption to climate change in agriculture, forestry, livestock, or agrifood production	Windbreaks; greenhouse technologies; irrigation systems; plants tolerant to drought, heat, and salinity
Health	Technologies for adaptation to climate change in human health protection	Air quality improvement, catalytic converters, treatment of mosquito-borne diseases
Indirect adaptation	Technologies that make an indirect contribution to climate change adaptation	Climate simulation, radar-based weather surveillance, real-time meteorological measurement

Source: Technologies for Adaptation to Climate Change.

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 (Eaton and Kortum 1996; Dechezleprêtre et al. 2011).

In April 2018, the EPO introduced a new classification for patents related to "technologies for adaptation to climate change" (the Y02A category in the Cooperative Patent Classification), which allows analysts to identify relevant inventions among 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,"[5] which corresponds closely to the United Nations Framework Convention on Climate Change (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 patent titles and abstracts, ensuring full coverage across space and time. We conservatively use 2015 as the last reliable year of data, because it takes 4–5 years for the various members of a patent family to be comprehensively included in PATSTAT.[6]

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 categories, which cover the main fields of adaptation activities and technologies (table 1). The technologies are categorized into coastal and river protection, water management,

[5]Technologies for Adaptation to Climate Change. Cooperative Patent Classification Subclass Y02A, Espacenet website, European Patent Office. https://worldwide.espacenet.com/classification?locale=en_EP#!/CPC=Y02A.

[6]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 4 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.

infrastructure, agriculture, health, and indirect adaptation (see table 1 for the definition of these categories and some examples). As an example, the second category, "water management," groups all patents protecting "technologies for adaptation to climate change related to water conservation; efficient water supply; and efficient water use." Each category is further divided into multiple items. For instance, the water management subcategory comprises 52 items, including rainwater harvesting, saltwater intrusion barriers, and water desalination. The former item includes promising technologies to tackle freshwater shortages during droughts. The health category includes solutions to address health issues exacerbated by climate change, such as air pollution and waterborne diseases. This category covers not only medical treatment but also, for instance, nonwater sanitation technologies, scrubbers, and air-conditioning filters.

Using Patents to Study Innovation

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(s) and applicant(s). Second, patent data measure the *output* of the innovation process, whereas 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, they are filed only in countries where there is a 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, Nelson, and Walsh 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 that are most vulnerable to climate change also weakly enforce IP rights. The data reveal that few patents are filed in low-income countries. Whether this indicates a measurement problem or low access to technology is difficult to establish, although complementary indicators suggest the latter (such as limited graduate-level education, which is a proxy for scientific knowledge production capacity).

We address 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 among sectors (Cohen, Nelson, and Walsh 2000). Therefore, we primarily discuss time trends, which are immune to this problem if heterogeneity in patenting propensity across sectors varies only weakly over time.

Finally, the value of individual patents is heterogeneous across patent offices and in other respects. For example, inventions filed at the Chinese Patent Office are known to have a lower economic value than inventions filed at the EPO or at the US Patent and Trademark Office (Boeing and Mueller 2015, 2016). As a result, the vast majority of these patents are not filed abroad, indicating that inventors anticipate 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).

Invention of Technologies for Climate Change Adaptation

The Growth of Innovation in Climate Adaptation

We first use the data to study the global growth 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 upward trend in patenting could be partly driven by a general increase in patenting propensity rather than by a genuine increase in innovation. To control for this factor, figure 1 shows the number of patented inventions in all technology fields and in climate change mitigation technologies. The pace of innovation for adaptation appears to be comparable to the 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.

The trend for climate change mitigation stands in sharp contrast with adaptation (figure 1). Although its decoupling from the average trend started earlier and more powerfully, patented innovation suddenly fell around 2013. This decrease over the end of the period has been documented in previous studies and has been linked to the simultaneous decrease of oil prices (Probst et al. 2021). The same cause likely explains the lower, later decrease in adaptation-related

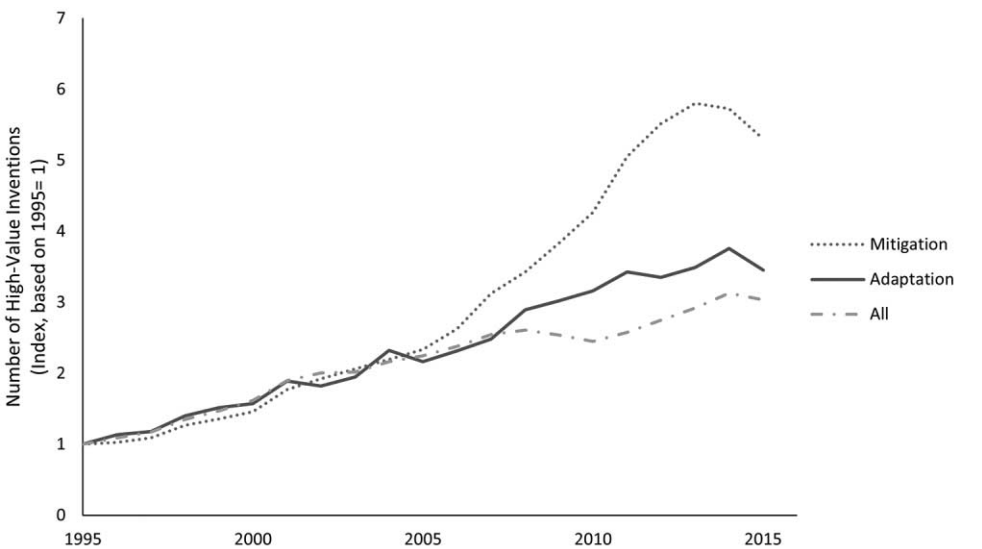


Figure 1 Evolution of climate change adaptation, mitigation, and all technologies, as measured by high-value patents, 1995–2015. Authors' calculations based on the World Patent Statistical Database (PATSTAT) data. "High-value" inventions are patented inventions filed in at least two patent offices. A color version of this figure is available online.

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 technological 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

Note: Calculations based on World Patent Statistical Database (PATSTAT) data. We built a technological benchmark for each Y02A category in two steps. We first selected all International Patent Classification (IPC) codes corresponding to Y02A patents, by adaptation category. Next, we extracted the first four characters of each IPC code, and those with the largest number of observations, until we covered at least 70 percent of the patents in that field, and then retained all patents with four matching characters in their IPC codes. "High-value" patented inventions are filed in at least two patent offices.

innovation, as around one-quarter of adaptation-related inventions also reduce carbon emissions (e.g., desalination systems powered with solar panels or thermal insulation technologies).[7]

How then should we interpret the long-term trend, and in particular the fact that adaptation-related innovation activity has followed the average trend since 1995? A first response could be that countries exposed to climate change do not need new technologies in this area but rather the dissemination of existing solutions and knowledge. We have already challenged this claim earlier. It is hard to believe that we do not need to accelerate adaptation technology. This is a key message from the IPCC report on the physical basis of climate change, released in August 2021. It also holds true for developing countries, as suggested by the Technology Needs Assessments reported to the UNFCCC by their governments (UNFCCC 2018).

What about the fact that, over the same 2005–2015 period, innovation in climate change mitigation grew twice as fast? The difference is impressive, but so is the gap between adaptation and mitigation funding needs. UNEP (2016) estimates the annual cost of adaptation to be around US$140–$300 billion by 2030. By contrast, global investments needed to successfully mitigate carbon emissions are estimated at between US$1.5 and $3.5 trillion a year by the IPCC (2018). It is also true the bulk of climate risks, and thereby adaptation needs, is still to come. The fact that current demand is weak but will grow in the near future may imply that more public investment is needed to prepare for future adaptation needs. This seems to be happening; 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.[8]

Another way of interpreting the pace of adaptation-related innovation is to look at similar technologies. Table 2 compares the growth rate of innovation aimed at reducing the impact

[7]Removing inventions that relate to both adaptation and mitigation produces a stable percentage (around 0.3 percent of global inventions) throughout the study period (see figure A1).

[8]Many of these technologies are also public goods (e.g., infrastructure, flood protection). Again, this may call for more public investment.

Table 3 Average technology transfer rates, by technology field, 2010–2015

	Share of technology transferred	
Technology	**Adaptation (%)**	**Technological benchmark (%)**
Agriculture	10	13
Coastal and river protection	10	34
Health	24	23
Indirect adaptation	27	32
Infrastructure	16	30
Water management	18	25
Mean	17	26

Note: Calculations based on World Patent Statistical Database (PATSTAT) data. The technology transfer rate is the percentage of invention patents filed in more than one country.

of climate change (column 2) with that of innovation in the same technological domain but not related to adaptation (column 3). As in previous work, the domains are delineated using the patent classification system (Benner and Waldfogel 2008; Nemet 2012). After a patent application is filed, a patent examiner assigns patents to one or more patent classification subgroups. The International Patent Classification (IPC) consists of around 60,000 subgroups. These subgroups are combined in about 400 higher-level groups, which are then aggregated further. As in previous work, we use these groupings to identify six technological domains corresponding to our six adaptation categories. Details on the methodology are provided in the note below the table.

Table 2 shows that, in relative terms, for any Y02A category, adaptation-related innovation has grown faster than the corresponding technological benchmark. Each domain has thus seen a shift of R&D efforts toward adaptation. Differences with the technological benchmark are often large; for instance, the growth rate is twice as high for adaptation-related water management as for water management in general. This is much less true for agriculture or infrastructure. For the first sector, a possible interpretation is a more limited applicability of agricultural inventions due to geographic differences. Table 3, which we will discuss later, shows less international diffusion of agricultural adaptation than of other adaptation technologies. At the same time, this sector is less important for industrialized countries with a high technological capacity than for middle- and low-income countries; this reduces the overall incentives for innovation.

In any case, this conveys a key general message. The overall growth of innovation in adaptation is slower than in mitigation because it occurs in technology fields—agriculture, health, water management, infrastructure—where innovation is growing less than the average technology.

Geographic Concentration of Climate Change Adaptation

Adaptation innovation is highly concentrated, with the top five inventor countries (China, Germany, Japan, South Korea, and the United States) accounting for more than 60 percent of the world's innovation activity (table 4). This share is, however, lower than in other technological areas, as the same top five countries represent around three-quarters of both the

Table 4 Top 10 inventor countries in climate change adaptation technologies, 2010–2015

Rank	Country	Share of world's high-value adaptation inventions (%)[a]	Top three technology fields	Specialization index[b]
1	United States	23.6	Indirect adaptation, agriculture, water management	1.02
2	Japan	15.8	Health, water management, infrastructure	0.67
3	Germany	10.8	Health, infrastructure, water management	1.01
4	South Korea	7.0	Coastal zones, water management, agriculture	0.88
5	China	6.5	Coastal zones, agriculture, infrastructure	0.74
6	France	5.8	Health, infrastructure, indirect adaptation	1.59
7	United Kingdom	3.8	Water management, infrastructure, indirect adaptation	1.31
8	Sweden	2.1	Health, infrastructure, indirect adaptation	2.05
9	Canada	2.1	Coastal zones, agriculture, water management	1.23
10	Netherlands	2.1	Agriculture, infrastructure, coastal zones	1.78

Note: 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.

[b]The specialization index is the ratio of the country's share of global innovation in adaptation technologies to the country's share of global innovation in all technologies.

world's total patented inventions in all technologies and global climate mitigation innovations. The contribution of Japan is the reason for this lower concentration. Although the country leads the innovation race both in general and for climate change mitigation (Probst et al. 2021), it is clearly overtaken by the United States for adaptation-related technologies, which account for nearly a quarter of high-value inventions developed between 2010 and 2015 (table 4). The position of Japan seems to be primarily determined by a lower specialization in this technology area (see the specialization index in table 4); this is ultimately driven by a lower relative performance in technologies mitigating impacts on agriculture.

China's ranking at fifth place in table 4 may be lower than expected when looking at raw patent data. The indicator used here is the number of *high-value* inventions, which excludes inventions patented in a single country. As explained earlier, this allows us to control for cross-country heterogeneity in the individual quality of patented inventions. If we consider instead all inventions, including those protected in a single country, China becomes by far the most active inventor in the field, filing nearly half of all adaptation patents in the world. This does not reflect the weight of China in the development of advanced technologies. It is well established that China's patenting behavior is an outlier, in that domestic inventors file patents of lower average quality than in other countries (Prud'homme and Zhang 2017; Boeing and Mueller 2019).[9]

[9]The lower quality of Chinese patents is mainly explained by the implementation of policies in China that aim to incentivize Chinese inventors to file patent applications. As an example, the Chinese government subsidizes patent filing, leading to a decrease in the cost of patenting and the patenting of technologies of lower economic value.

International Technology Transfer

Cross-Border Technology Transfers

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

A first indicator of 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 2 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 lower than the average for all technologies (24 percent) and about half that of mitigation technologies (31 percent).

Table 3 compares the transfer rate in each adaptation category with that of their category-specific benchmarks. It shows that the low rate of international transfer is not driven by the characteristics of the technological domain in which adaptive technologies are developed; in all but one field, they diffuse less than their nonadaptation variants.

This low diffusion could be explained by three sets of nonexclusive factors: (*a*) high barriers to technology transfer (such as tariffs or lax enforcement of IP rights), (*b*) limited technological

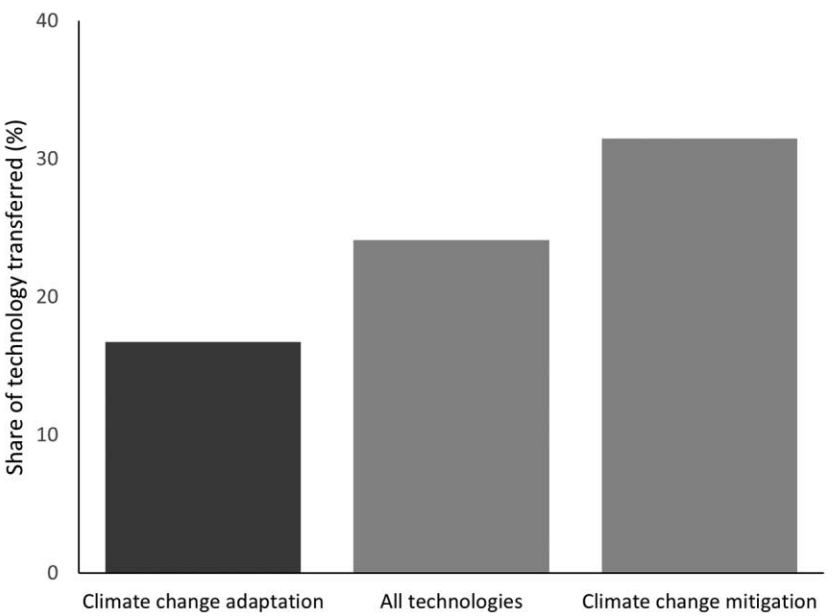


Figure 2 Global average technology transfer rates, 2010–2015. Calculations based on World Patent Statistical Database (PATSTAT) data. The technology transfer rate is the share of a country's technology patents that are also filed in at least one other country. A color version of this figure is available online.

capabilities in potential recipient countries, and (*c*) unsuitability of individual innovations to different contexts. Statistics in table 3 lend support to the third hypothesis. The technological capacities of recipient countries, IP enforcement, and trade barriers are unlikely to vary much within a technological domain. This could have important implications for the allocation of policy efforts between supporting domestic innovation that targets local needs, on the one hand, and stimulating international technology diffusion, on the other. The former may need to be given priority.

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 transfer as a benchmark (in parentheses).

A first notable fact is the overwhelming dominance of high-income countries; 93 percent of all exported technologies for climate change adaptation originate in these countries, which also receive 71 percent of all exported inventions. In contrast, low-income countries receive virtually no foreign-patented technologies. It could be that foreign inventors use other tools to protect these technologies in low-income countries, in particular industrial secrecy, or that they do not feel the need to protect their IP there, as the risk of counterfeiting is limited by low imitation capacity.

Middle-income countries receive 28 percent of all adaptation transfers, the vast majority of which come from high-income countries, with China receiving half of these transfers. Patent flows to middle-income countries 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 in parentheses), except for the slightly larger role of middle-income countries as technology recipients; this is mostly due to China's particularly strong role as a destination for adaptation patents. To test the robustness of the patent-based results, we also study technology transfers through foreign direct investment (FDI). Results are similar (see the appendix).

Table 5 Distribution between country income groups of patented inventions of technologies for climate change adaptation, 2010–2015 (%)

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

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

Patenting Activity in Relation to Climate Hazards

The landscape drawn from the previous statistics features a world where adaptation-related technologies are confined in the Global North and China. This suggests a geographical mismatch between the availability of the technologies and countries' adaptation needs. Let us now relate the patterns of innovation described in the previous two sections to countries' exposure to climate risks.

Measuring Climate Risks

The 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, 36). 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 people and assets 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 (e.g., technologies may help people relocate away from the most exposed areas) and faces 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 6). 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 equal to 0 means no exposure to hazard, whereas 1 corresponds to the maximum hazard exposure among countries. Hazards are classified into five threats, similar to the hazard typology of the IPCC (2014) but with some modifications to facilitate correspondence with the patent classification. They are summarized in table 6. Four of the five indexes are based on

Table 6 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 5-day calendar window; projected for 2040–2070 under the RCP4.5 scenario	Climdex
Floods	RX5DAY: monthly maximum precipitation over 5 consecutive days (mean per year); projected for 2040–2070 under the RCP4.5 scenario	Climdex
Droughts	Change in annual runoff from the baseline projection to the future projection; projected for 2020–2040 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}.

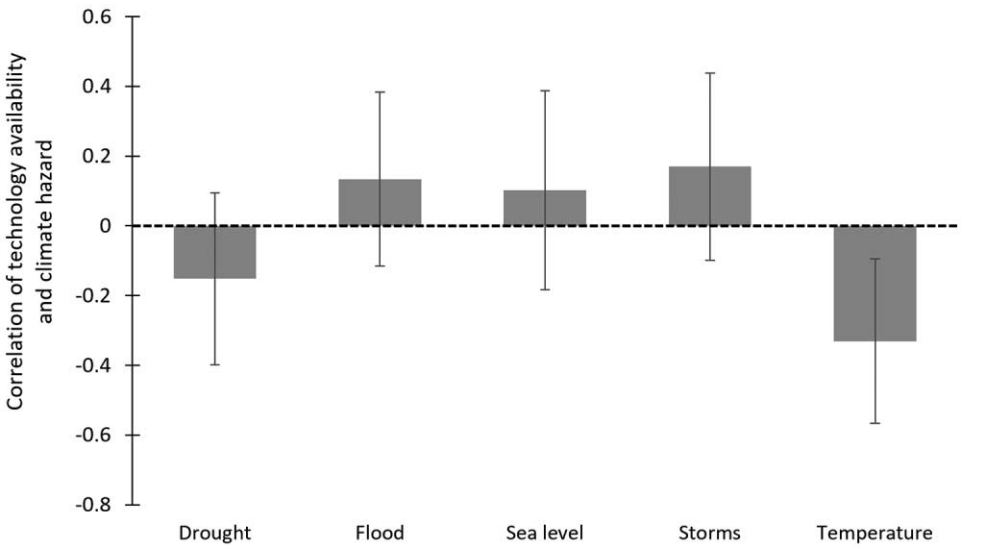


Figure 3 Correlation between availability of advanced adaptation technologies and climate hazard levels in high- and middle-income countries, 2010–2015. Calculations based on World Patent Statistical Database (PATSTAT) and hazard indicators (see table 6). The technology variables are averages for the period 2010–2015. "Technology availability" is the sum of high-value adaptation inventions (i.e., 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. A correlation is −1 in the case of perfect negative correlation and +1 in the case of perfect positive correlation. A color version of this figure is available online.

projections of future climatic change.[10] The only exception is storm risk, which is based on historical events, for data reasons. The implicit assumption is that historic storms are positively correlated with future ones.

Availability of Advanced Adaptation Technology and Climate Hazard Type

For each of the five hazard types, figure 3 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.

The graph confirms the poor correlation between technology availability and hazard levels. Most correlation coefficients are not significantly different from zero. The correlation is even significantly negative for temperature extremes. The interpretation of this negative sign provides an indication of what probably occurs in the other fields: industrialized countries with strong innovation in this domain (such as China, South Korea, Japan, western European countries, and the United States) are less exposed to heat waves than many middle-income countries.

Availability of Adaptation Technology by Country Income Level

Let us further explore the origin of this mismatch by comparing the middle-income country group, with lower technological capabilities, and the high-income country group.

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

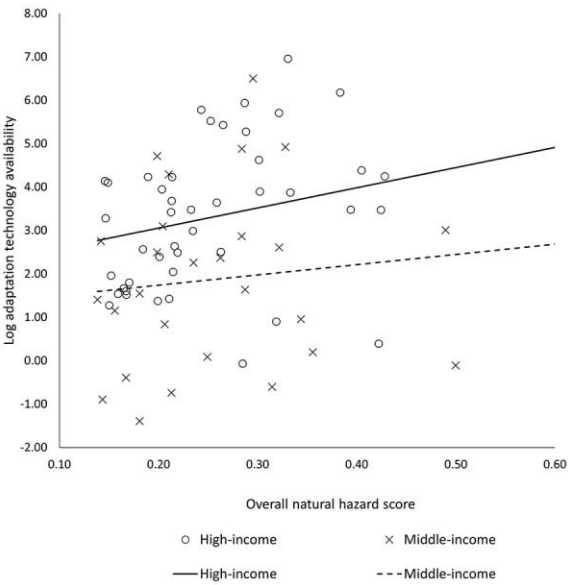


Figure 4 Relationship between the local availability of adaptation-related invention and climate hazards in high- and middle-income countries, 2010–2015. Calculations based on World Patent Statistical Database (PATSTAT) and hazard indicators (see table 6). Each point describes an individual country, and the lines show linear regressions for the two country groups. Country income categories use World Bank–defined classifications. Low-income countries are excluded for lack of sufficient patent data. The "log adaptation technology availability" is the log of the 2010–2015 annual average number of adaptation patents filed in the country. The hazard index is the arithmetic mean of the five hazard indicators listed in table 6, each being normalized to range from 0 to 1. Choosing an arithmetic mean is conventional. Using a more sophisticated weighting rule would require more data and be less transparent.

Figure 4 shows a slightly positive relationship between a country's level of patented technology availability (*y*-axis) and its average hazard index (*x*-axis) for both groups, with nearly parallel regression lines. The two groups primarily differ in terms of technology availability. This is particularly true for countries with the highest hazard scores; almost all middle-income countries in this group produce little innovation, whereas high-income countries such as Australia, Japan, South Korea, and the United States exhibit strong innovation outputs.

In contrast, table 7 suggests a similar average overall hazard score, although the heterogeneity within each group is high. This observation does not contradict the adaptation literature, which has documented a wide adaptation gap between these two groups of countries (Fankhauser and McDermott 2014; Barbier and Hochard 2018; Tol 2018). Our indicators express risks in physical terms, not adaptation capacities.[11] Also bear in mind that figure 3 hides significant disparities across hazard categories, with high-income countries being more exposed to storms, whereas middle-income countries are more likely to experience heat waves.

We might then ask whether the innovation gap between the two groups of countries is specific to adaptation-related technologies or whether it is a generic technological weakness of

[11]Note that the average overall hazard exposure score of the low-income country groups is comparable (mean = 0.24, standard deviation = 0.06).

Table 7 Local availability of adaptation technology, share of adaptation innovation in the country's total innovation, and climate hazard exposure in high- and middle-income countries, 2010–2015

Variable	Country group	Mean	Standard deviation	Number of countries
Log number of locally protected inventions (technology availability)	High income	3.33	1.65	45
	Middle income	1.87	2.05	27
Number of patented adaptation high-value inventions as a share of the total number of high-value inventions filed in the country (%)	High income	0.81	0.58	45
	Middle income	0.85	0.47	27
Overall hazard exposure score	High income	0.26	0.10	45
	Middle income	0.26	0.09	27

Note: The sample includes 45 high-income and 27 middle-income countries. See the list in the appendix. "High-value" patented inventions are defined as patents filed in more than one patent office.

middle-income countries. Table 7 supports the latter hypothesis, as the gap disappears as soon as technology availability for adaptation is expressed as a share of total patents. Thus, the figure shows that middle-income countries are less innovative and import fewer technologies in general.

Conclusions

This article provides a global snapshot of innovation in technologies for adaptation to climate change and their international diffusion. Relying on patent data, the analysis focuses on solutions at the technological frontier. Frontline innovation and its international diffusion remain the preserve of a small handful of mostly high-income countries, with virtually no adaptation innovation in low-income countries or transfer of the relevant patented knowledge to these countries. To the extent that there is domestic innovation or technology import into these countries, it appears to occur outside the patent system. This pattern is not specific to adaptation technologies. Low-income countries often rely on low-tech solutions and organizational innovations.

The analysis yields three major findings on the situation of middle- and high-income countries. The first is that adaptation innovation did not grow faster than the average for all technologies between 1995 and 2015. This may reflect the fact that adaptation innovation occurs in technological areas—agriculture, health, water management, infrastructure—where innovation increases at a slower pace than average. However, when we compare innovation within each domain, we observe a shift in patenting outputs toward adaptation.

Second, 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 could in principle be compensated by international technology transfer from innovating countries to vulnerable countries. However, this is not the case. The data reveal limited international technology diffusion through either the patent system or FDI. This also holds true when comparing adaptation-related technologies to their relevant benchmark categories. Less adaptation technology is transferred, compared with technology that is comparable but not related to adaptation. This could either be because of adaptation-specific diffusion barriers or

because (advanced) adaptation technologies are less applicable outside the innovating country than other technologies.

Third, a country's exposure to climate risks is not positively correlated with the local availability of patented adaptation inventions. Middle-income countries (like low-income countries) have fewer adaptation innovations at their disposal than high-income countries, but this is not matched by a similar differential in climate risks. High- and middle-income countries are similarly exposed to climate risks—the mean of our risk indicators is similar between the two country groups—and low-income countries face higher risks. In this respect, adaptation is different from mitigation. The availability of mitigation technologies is also lower in the Global South (except China), but so is the need to reduce emissions, insofar as these countries release less carbon than high-income countries and China.

Two important policy implications follow from these observations. First, technological capacity building is an essential ingredient of climate change adaptation, although it is of course not a need that is specific to adaptation technologies. The context-specific nature of adaptation inventions implies a greater need for domestic innovation. Countries cannot rely purely on international adaptation technology diffusion but need to build their own capabilities.

Second, the mismatch between climate risk exposure and the local availability of technology suggests that economic forces fail to transform local adaptation needs into market demand for these technologies, in both low-income and middle-income countries. Solving this problem requires a better understanding of the market failures that hinder demand, as a precondition for designing corrective policies (e.g., through public investment, subsidies, and other policy tools). It also suggests a broader need for international adaptation finance. Although public international funding to date has understandably focused on highly vulnerable low-income countries, the need for more domestic innovation may also justify a higher share of funding for middle-income countries.

The quantitative analysis of global innovation in climate change adaptation is still a new field, and consequently there are several avenues for future research. The first and most important 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 how these technologies contribute to climate change adaptation in the Global South. How crucial are such frontier innovations? How do they relate to low-tech solutions, technology adoption, and other forms of innovation? How do economic incentives shape technology adoption? Third, the data used in this study contain very disaggregated information that could be used to better identify which patents are relevant in a given sector or national context. Combined with country-level technology needs assessments, this research could be exploited to prioritize the transfer of the most useful technologies and support local innovation. A rich research agenda exists to increase the contribution of technical progress to climate change adaptation.

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