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From Extreme Events to Extreme Seasons: Financial Stability Risks of Climate Change in Mexico

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WORKING PAPERS

From extreme events to extreme seasons: Financial stability risks of climate change in Mexico

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From extreme events to extreme seasons: Financial stability risks of climate change in Mexico[1]

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Abstract

This paper explores the financial stability implications of acute physical climate change risks using a novel approach that focuses on a severe season associated with a sequence of tropical cyclone and flood events. Our approach was recently applied to study physical risks in the Mexican financial sector, but the framework is applicable to other countries as well. We show that even if the scale of individual climate events may not be material at an aggregate national scale, considering a sequence of events could lead to potentially significant macro-financial impacts in the short term. This could occur even if none of the individual events affect the particular region(s) with highest concentrations of banking sector exposures. Our results indicate potential for even greater effects in the future given the increasing severity and frequency of extreme events from climate change. Thus, this paper highlights the importance of considering sequences of extreme physical risk events driven by climate change, rather than just individual extreme events, to better understand financial stability implications and design effective policies.

[1] This work developed from a joint IMF and World Bank work on climate risk analysis for the 2022 Mexico FSAP. We would like to thank Vikram Haksar (IMF) and Ilias Skamnelos (WB) (FSAP mission chiefs) and FSAP team members for their helpful comments and suggestion. We also thank WB experts Dorra Berraies and Cristina Stefan for their analytical support. We are also grateful to the members of Mexican Financial Authorities for a highly productive engagement, discussions, and feedback.

I. Introduction

The geographical diversification of firms' exposures (relative to the often more localized nature of disasters) is cited as a key factor for only moderate/contained systemwide financial stability impacts of acute physical climate risks[2] in several preliminary climate risk assessments (NGFS, 2022)**.** For large countries, it may indeed be reasonable to expect relatively mild national-level impacts of geographically concentrated individual climate-related extreme events (since an individual event would only impact a subset of total exposures). This is particularly true if exposures are not geographically concentrated in a single location that is subject to such climate-related extreme events. Yet it is important to recognize that extreme events do not always occur in isolation. Rather, it is possible for a sequence of extreme events affecting multiple different parts of a country (or indeed the globe) to occur within a relatively short time window (e.g., over the course of a season).[3]

The concept of sequences or clusters of extreme events is not new: there is an increasingly robust body of scientific literature on the topic, and it is also already embedded in many of the catastrophe modelling approaches used by the (re)insurance industry. Sequences and clusters of extreme events have been studied within the growing field of compound weather and climate events science and statistics (Zscheischler et al., 2018; Towe et al. 2020; Bevacqua et al., 2021). Compound events have been defined as "the combination of multiple drivers and/or hazards that contributes to societal or environmental risk" (Zscheischler et al., 2018). The interaction of such shocks can amplify impacts (with the overall impacts being greater than the sum of the parts; Kopp et al., 2017), potentially exceeding the coping capacity of firms, households, the government, and banks, who might have been able to cope with those events if they had occurred separately. The IPCC Sixth Assessment Report included a discussion of compound events, concluding that there is high confidence that "concurrent extreme events at different locations, but possibly affecting similar sectors in different regions, will become more frequent with increasing global warming, in particular above 2°C of global warming" (IPCC, 2021). Indeed there is already evidence of increasing sequential tropical cyclone hazards in some regions (Xi et al., 2023). In the (re)insurance industry, sequences and clusters of events are captured in catastrophe models that are built using stochastic event sets with multiple events each year. Such models enable the estimation of not only occurrence exceedance probabilities (which look at probabilities of individual event losses – e.g., a 1-in-100-year flood event loss) but also aggregate exceedance probabilities (which consider total aggregated losses from multiple events in a given year – e.g., a 1-in-100-year aggregate loss) (Homer and Ming, 2017). These metrics are important from a portfolio management perspective, and (re)insurers with portfolios across multiple regions are increasingly looking to understand how global-scale correlations of extreme events can impact their risk diversification strategies (Carozza and Boudreault, 2021). The annual exceedance probability metric has

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[2] Physical risks from climate change are typically categorized into acute physical risks (associated with increased frequency and severity of extreme events – e.g., tropical cyclones, floods, and droughts) and chronic physical risks (associated with gradual changes – e.g., rising sea levels). Acute physical risks associated with tropical cyclones and floods are the focus of this paper, whilst noting that other acute physical risks and chronic risks may also be substantial for Mexico.

[3] For example, within an individual tropical cyclone season, a country might be subjected to multiple tropical cyclones, such as those experienced by Mexico in 2010 (Hurricane Alex, Hurricane Karl and Tropical Storm Matthew).

also been used for analyzing general insurance liabilities in the Bank of England's 2021 Biennial Exploratory Scenario for testing resilience to climate change risks (Bank of England, 2021).

In the context of physical climate risk assessments, the implications of spatial or temporal clusters of events could be substantial. Failure to account for the potential for sequences of events, and to recognize that individual extreme events are not spatially and/or temporally independent from one another, could lead to an underestimation of the materiality of acute physical risks (Zscheischler et al., 2018). For individual financial institutions, more widespread or correlated extreme weather events under climate change could undermine the effectiveness of banks' diversification strategies (BIS, 2021; ECB, 2021). For a domestic financial system as a whole, the implications could be substantial if a series of shocks affects a large number of institutions and/or jurisdictions, creating longer-lasting impacts and triggering negative feedback loops between bank lending and the real economy (FSB, 2020).

Against this background, we developed an analysis of acute physical climate risks, focusing on a sequence of extreme events affecting different parts of the country within a single season. The analysis takes Mexico as an example. Mexico is exposed to a wide range of acute physical climate risks, including tropical cyclones, floods, droughts, and heatwaves. The analysis focuses specifically on tropical cyclones and floods, given the substantial impact of these events historically. The consideration of a series of extreme events consisting of tropical cyclones and floods is particularly pertinent to Mexico. This is largely due to the concentration of banking sector credit exposures in a few geographical regions relative to the hazard distribution of tropical cyclones and floods. In particular, banking sector credit to firms is highly concentrated in Mexico City (which historically has not experienced tropical cyclones and widespread floods to the same extent as other parts of the country). Outside of Mexico City, exposures are distributed amongst several regions that are not geographically proximate due to the large size of the country. These less geographically concentrated exposures are less likely to be impacted by a single tropical cyclone or flood event, due to the comparatively localized nature of these perils (for example, relative to perils such as drought which can impact the entire country in a single event – see Stahle et al., 2016).

The modelling approach used in our analysis builds upon recent methodologies developed jointly by the IMF and the World Bank in the context of the Financial Sector Assessment Program (FSAP). A set of disaster scenarios are analyzed for current climate conditions and potential future conditions considering climate change. The risks from these scenarios are analyzed using a combination of a model of direct damages (based on catastrophe risk modelling approaches), a macroeconomic model for generating macro-financial scenarios, and a financial sector impact model to analyze the impact on the financial sector (based on the standard IMF solvency stress testing method used in FSAPs). The damage estimates from the extreme season scenarios were used as input in generating scenario-dependent macro-financial paths. These scenarios are further translated into impact on the financial sector. Additionally, to account for other indirect effects that could potentially compound the effects of initial direct damages, we also considered three additional channels via shocks to total factor productivity (TFP), higher unemployment, and effects from financial markets. A similar approach was also used for modelling the impacts of typhoon risks to the Philippines (Hallegatte et al., 2022a). The novel aspect of the Mexico analysis is to extend this approach to consider a sequence of disaster events occurring during a season, rather than looking at individual events. Consequently, this paper also contributes to the growing literature on climate-related disasters and crises (Wolbers and others, 2021), their macroeconomic impacts (Hallegatte, 2015), and the analysis of their impacts on the financial system (see Ranger and others, 2022 and Adrian et al. (2022) for more details along with discussion of climate related policy works by central banks and policy institutions around the world), and ongoing efforts by the Network for Greening the Financial System to strengthen methodologies for the assessment of physical climate risks.

To date, most analyses of acute physical risks have adopted one of two approaches. They have either: (i) considered scenarios of individual events (e.g., the two individual flood scenarios considered in the analysis of climate-related risks for the Dutch financial sector (Regelink et al., 2017), and the individual typhoon and flood scenarios considered in the analysis of climate-related risks in Japan (Bank of Japan, 2022)); or (ii) taken an approach that is based on hazard maps that show the potential severity of a given peril at a given location for a specific return period[4] without considering potential plausible scenarios of individual events or sequences of events (rather, they essentially assume that all locations are affected simultaneously, even for very large countries) (e.g., analysis of exposures to flood risk in Denmark (Danmarks Nationalbank, 2021) and Norway (Haug et al., 2021)). In the second approach, the lack of consideration of potential scenarios may limit the interpretability of the analyses and their application in scenario-based stress-testing exercises. In the first approach, the focus on individual events whilst ignoring potential sequences of events may risk underestimation of the potential materiality of risk.

The contribution of our work is the extension of the event-based approach to consider sequences of events where we highlight their importance in understanding the potential materiality of possible climate scenarios on financial stability. The approach challenges previous studies (e.g., Bos and others, 2018) that make a case for focusing on large-scale disasters only. Even if the scale of individual events may not be material at an aggregate national scale, by considering a sequence of events we demonstrate that it is possible to have a substantial macro-financial impact. This could occur even if none of the individual events affect the region(s) with highest concentrations of banking credit and other financial exposures (e.g., Mexico City in our application). Whilst the approach used in our analysis does not explicitly capture the potential for non-linear amplifications often characteristic of compound events (Dunz and others, 2021; Ranger and others, 2021), such amplifications would only serve to potentially further increase the materiality of the modelled scenarios.

In particular, the application of our approach to the Mexican economy shows that the impact of extreme seasons involving floods and tropical cyclones could be material in the short-term following these disaster events, as highlighted by the modeled effects on key macro-financial variables. For example, within the first year following a sequence of extreme events occurring under end-of-century climate conditions in a high-emissions climate scenario in Mexico, the country's gross domestic product (GDP) could decline by up to 2 percent (relative to the baseline without climate-related extreme events). And, while the short-term system-wide aggregate impacts on the Mexican banking system appear relatively modest, the results indicate that some individual financial institutions could face material risks. For example, while the aggregate capital adequacy ratio (CAR) depletion is about 1.2 percent under the high-emissions climate change scenario, it declines by over 4 percentage points at some banks. Thus, vulnerabilities exist in the financial system. These effects indicate potential for severe

[4] A return period is a measure of the frequency of an event, and is defined as the expected time (usually expressed in years) between events exceeding a particular extreme threshold.

effects in the future given the potential increasing severity and frequency of extreme events due from climate change.

The implication is sharp: climate risks could have significant financial stability risks. This potentially holds not just for Mexico but for other countries as well. Even if a country may not face systematic risk due to any single climate-related extreme event (e.g., an individual tropical cyclone or flood) due to large/diverse geography (such as Mexico, United States), there is a possibility that a sequence of events occurring within a short timeframe (e.g., over the course of a season) could negatively affect the entire economic and financial systems. Whilst smaller countries may be less likely to be affected by multiple events in a short timeframe than some larger countries, this possibility remains. Given that just a single event can already be devastating to the economy (e.g., Hurricane Maria in 2017 led to estimated losses equivalent to 226 percent of the Dominican Republic's GDP; IMF, 2021), a sequence of multiple events could generate even greater economic impacts.

The insight from this paper is relevant for informing climate-related policy. Despite covering only limited channel of risks and data limitations, our study was able to detect potential for material risks from climate-related extreme events. Whilst the results give insights into the potential impacts of acute physical risks from tropical cyclones and flooding on the Mexican financial system, the analysis is regarded as exploratory, and more work is needed to refine the model before it can be used for regulatory applications. Further extension to other climate-related risks faced by Mexico (e.g., drought) could help to uncover the potential scale of physical risks to the Mexican economy. In addition, application of our approach to other countries with additional data, and further exploration of non-linear compounding effects that may arise from sequences of events in these countries and potentially across borders, could help to deepen our understanding of the nature of compounding physical climate risks. Such a risk assessment could eventually help develop better policy frameworks.

The remainder of this paper is structured as follows: Section II provides an overview of climate-related disasters in Mexico. Section III presents the scenarios that are considered in this paper. Section IV describes the methodology for each of the modelling components – the direct damages model, the macroeconomic model, and the financial sector impact model, respectively. Section V presents the results, and Section VI discusses these findings, including uncertainties and limitations, and concludes.

II. Climate-related disasters in Mexico

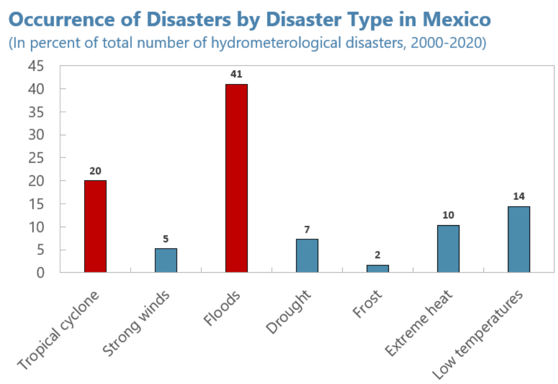
Mexico is highly exposed to a range of disasters associated with acute physical climate change risks, including tropical cyclones and floods. During the last two decades, floods and tropical cyclones have constituted a substantial hazard burden among hydrometeorological disasters (Figure 1), both in terms of frequency of occurrence and the number of people impacted. These perils are the focus of this analysis. However, other acute risks, including drought and heatwaves, as well as chronic risks, may nonetheless be substantial[5], along with non-climate-related risks, including earthquakes. Past tropical

[5] For example, for heatwaves there is evidence of a relationship between extreme heat and credit performance in Mexico (Aguilar-Gomez and others, 2022). For droughts, although direct impacts of droughts on the banking sector may be limited, for example due to low credit exposures to agriculture, they can nonetheless have substantial impacts on communities and the economy. For example, 80 percent of farmers in Mexico are smallholder farmers,

cyclone events have included cases where some federal states were hit twice in a very short period (e.g., Hurricane Karl and Tropical Storm Matthew in Veracruz in 2010, which caused 25 billion MXN of economic losses and affected more than 500,000 people) or the storm had two landfalls (e.g., Hurricane Alex in 2010, which caused 25 billion MXN of economic losses and affected 650,000 people), significantly exacerbating financial losses and the impact on populations. Amongst the most impactful recent flood events is the October 2007 floods in Tabasco and surrounding states, which resulted in economic losses of more than 35 billion MXN and affected more than 2 million people. The frequency and severity of floods and tropical cyclones in Mexico is likely to be impacted by climate change, though there are substantial uncertainties in projected changes (as discussed further in Appendix I).

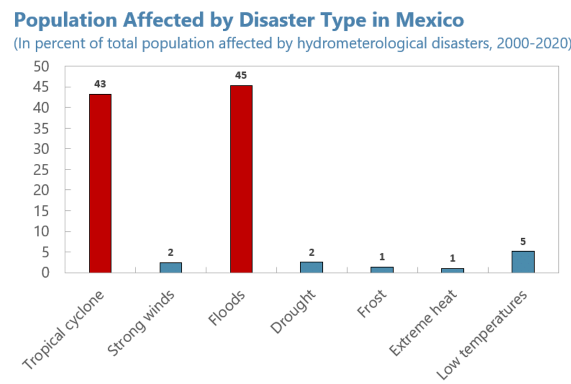
Figure 1. Hydrometeorological Disasters in Mexico

Floods and tropical cyclones are the most frequent hydrometeorological disasters in Mexico…



Sources: WB staff calculations based on CENAPRED data.

…and affect the highest number of people.



Sources: WB staff calculations based on CENAPRED data.

Note: The estimates presented in Figure 1 are based on data from CENAPRED. Different methodologies for defining events and for estimating the affected population may result in different estimates of these variables, potentially resulting in higher estimates for some disaster types. The time period of the analysis (2000-2020) does not include the recent severe drought and heatwave events occurring in 2021 and 2022. Furthermore, Figure 1 does not include an estimate of the direct and indirect damages and economic losses associated with different hazard types and does not consider chronic risk.

Due to the relatively localized nature of floods and tropical cyclone events, the impacts of these perils on the macroeconomy and financial system are dependent on the geographic distribution of economic and banking sector exposures relative to that of physical hazards. Both GDP and credit exposure in Mexico are heavily concentrated in a few states. In 2020, six states contributed collectively to around 50 percent of the national GDP: Mexico City (17.51 percent), Mexico State (9.15 percent), Nuevo León (7.74 percent), Jalisco (6.92 percent), Veracruz (4.53 percent), and Guanajuato (4.00 percent) (Figure 2). Credit exposure in Mexico is also heavily concentrated geographically in a few

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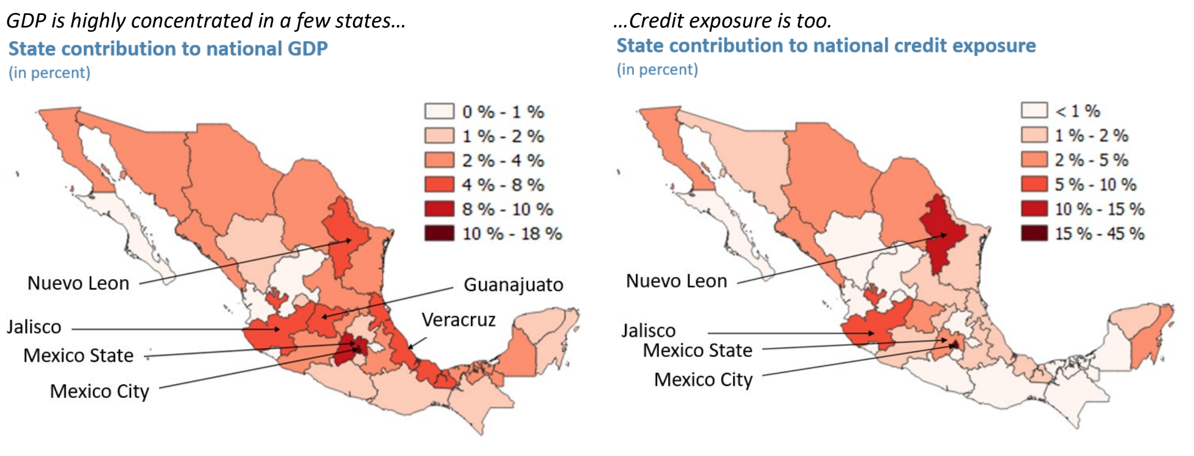
with limited access to credit and insurance, and a reliance on rainfed production – hence high vulnerability to drought risk. Recent drought and heatwave conditions in Mexico have highlighted the importance of these risks. For chronic risks such as sea level rise, modeling suggests the potential for substantial economic losses, for example due to loss of coastal ecosystem services (Fernández-Díaz and others, 2022). It is also important to acknowledge that other nature-related risks, including biodiversity-related risks, may interact with climate physical risks. Whilst an analysis of nature-related risks more broadly is beyond the scope of this paper, an initial analysis of exposures to biodiversity loss has been completed by Banco de Mexico (Martínez-Jaramillo and Montanez-Enriquez, 2021).

states, broadly reflecting the geographic distribution of GDP. More than 44 percent (1,513 billion MXN) of total credit (3,434 billion MXN) is recorded in Mexico City which is aligned with its contribution to GDP. Other federal states that account for a relatively high reported credit exposure are Nuevo Léon, Jalisco, State of Mexico, and Sinaloa which contribute respectively 13 percent, 6.4 percent, 4.9 percent, and 3.2 percent of total credit. The remaining 27 federal states account for only 28 percent of total credit exposure. The concentration of exposures in Mexico City is important when considering the physical risk profile of Mexico, particularly since the tropical cyclone and flood hazard profile of Mexico City is relatively mild compared with other parts of the country (see Appendix I for further details). This informs the selection of scenarios modelled as part of our analysis, as outlined in Section III. However, it is important to note that the low concentration of credit exposure in several federal states known for their active economic activity may in part be due to the recording of credit at the domicile of a firm's headquarters (often in Mexico City), even though the operations financed by the credit may be located elsewhere in the country. Bressan and others (2023) have recently started developing a methodology to examine credit on an asset level for a sample of listed firms in Mexico (taking into account the location of individual industrial plants rather than relying solely on headquarter location), an approach which, data-permitting, could be further explored in future.

Figure 2. Geographic Distribution of GDP and Credit Exposure in Mexico



Sources: author calculation using GDP data from statistica.com and credit data from Banco de Mexico (end of 2021)

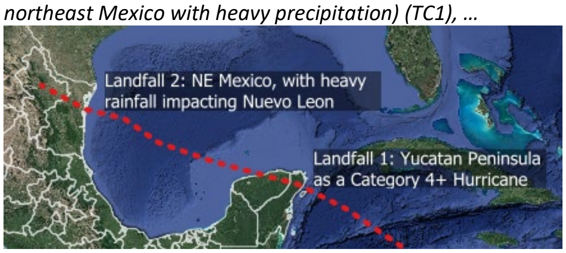
III. Scenarios

The relative geographical distributions of hazard and exposure in Mexico suggests that an individual severe tropical cyclone or flood event is unlikely to cause material impacts at an aggregate national scale, unless it impacts Mexico City with sufficient intensity (which is relatively unlikely based on the hazard profile of the city). However, it is possible that a sequence of events impacting different parts of the country within a relatively short time period (i.e., within a single tropical cyclone/flood season), could result in a large combined impact. There is existing evidence for the occurrence of such clustering of events in the region. For example, Atlantic tropical cyclones counts have been shown to be temporally clustered, with periods of high activity interspersed with periods of relatively low activity, in part linked to large-scale patterns, such as those of sea surface temperatures (Villarini et al., 2010; Mumby et al., 2011; Dominguez et al. 2021).

To analyze the potential scale of impacts from a sequence of events, five scenarios are included in the analysis. Scenarios TC1, TC2 and TC3 are individual tropical cyclone events, Scenario F1 is an individual flood event, and Scenario ES1 is an extreme season comprised of a sequence of several extreme events (i.e., TC1, TC2, TC3, and F1 all occurring within a few months of each other during one season) (Figure 3). Each of the scenarios is an extreme (but plausible) event and is estimated to result in direct damages with a return period greater than 50 years at a national scale. Each of the individual event scenarios is based either on similar events that have occurred historically or on events drawn from catalogs of synthetic events (generated using statistical resampling algorithms). The scenarios were selected to cover a range of different flood and tropical cyclone-prone regions with financial sector exposures.

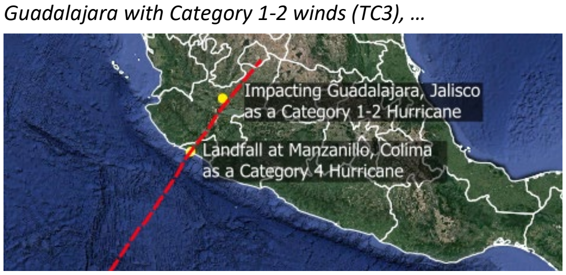
Figure 3. Tropical Cyclone and Flood Scenarios

The scenarios analyzed are a tropical cyclone with two landfalls (Yucatan Peninsula as Category 4 hurricane and northeast Mexico with heavy precipitation) (TC1), …

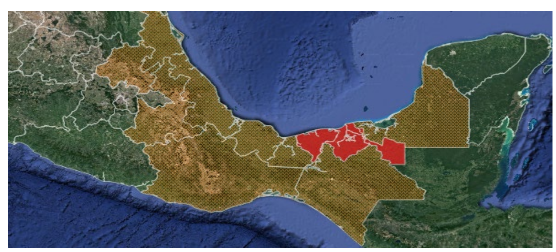


…two tropical cyclones impacting Veracruz within approximately 10 days (TC2), …

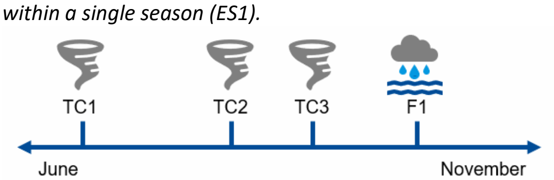
…a tropical cyclone making landfall in Colima impacting Guadalajara with Category 1-2 winds (TC3), …



…a river flood in Tabasco and surrounding states (F1), …



…and an extreme season scenario combining all these events within a single season (ES1).



Source: author illustration.

To analyze the impacts of climate change on the severity of these scenarios, two versions of each scenario have been defined. The first has been defined based on the estimated distribution of extreme events under historical/current climate conditions ("historical conditions"; Scenarios TC1-hist, TC2-hist, TC3-hist, F1-hist, and ES1-hist). The second has been defined based on the estimated distribution of extreme events under future climate change conditions corresponding to RCP8.5[6] by the middle of the century and the end of the century ("climate change conditions"; Scenarios TC1-cc, TC2-cc, TC3-cc, F1-cc, and ES1-cc).[7] The modelling of these scenarios considers potential future increases in hazard severity associated with climate change (i.e., increased windspeed and precipitation for tropical cyclone scenarios and increased streamflow for flood scenario), but assumes constant vulnerability and exposure (i.e., potential future growth of capital stock is not considered). Each scenario is intended to have the same frequency of occurrence (return period) for the historical and climate change conditions, with the climate change adjustment applied to the hazard severity only (keeping the frequency fixed).[8] A more detailed description of the scenarios is available in Appendix II.

IV. Methods

To estimate the financial sector impacts for each of the defined scenarios, the direct damages and economic losses are first estimated (Figure 4). The direct damage estimates, expressed as the percentage of physical capital stock that is damaged for a given scenario, are used as an input to the macroeconomic impact modelling, the output of which is then used to estimate financial sector impacts.

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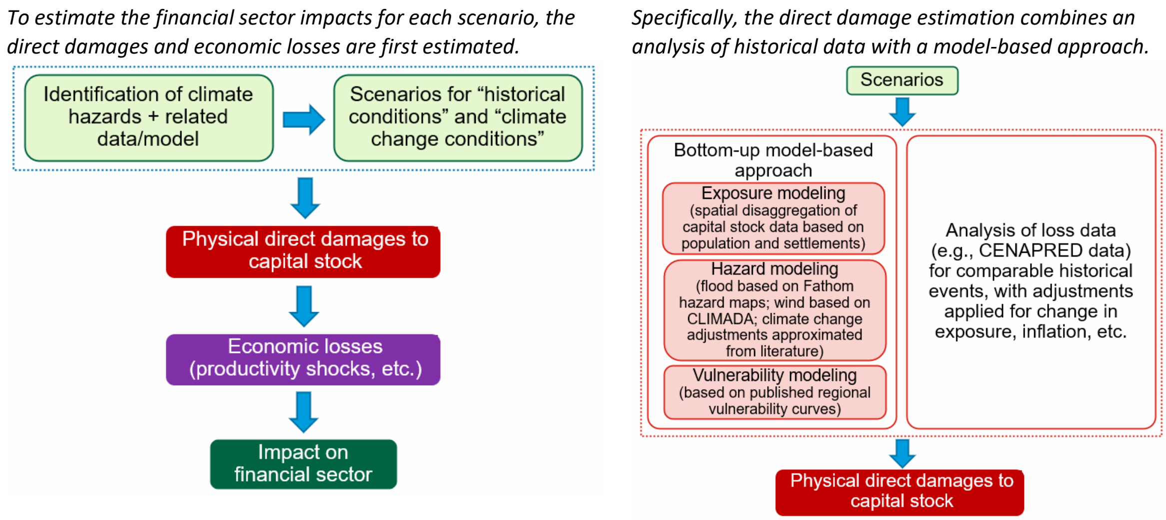
[6] Representative concentration pathway (RCP) 8.5 represents an extreme climate change scenario, corresponding to 8.5W/m2 of total radiative forcing (a cumulative measure of greenhouse gas emissions from all sources) by 2100.

[7] We also analyzed some scenarios using RCP4.5 but these results are not included in this paper. The estimated direct damages for these scenarios fell between those of the "historical conditions" scenarios and the RCP8.5 scenarios.

[8] Analyses of climate change impacts can consider the change in frequency for an event (or series of events) of a given magnitude/severity, and/or the change in the magnitude/severity for an event (or series of events) of fixed frequency. The two approaches are related due to the relationship between the frequency and severity of extreme events, and the decision regarding which approach to use should be tailored based on the specific application. For this analysis, the frequency was kept fixed to explore the potential impacts of climate change on the magnitude/severity of extreme events.

Figure 4. Method for Direct Damages, Economic Impact, and Financial Sector Impact Modelling



Source: author illustration.

Direct damages model

The methodology used to estimate direct damages[9] for each scenario combines: (i) an analysis of historical loss data for comparable events; and (ii) a model-based approach using exposure, hazard and vulnerability data (Figure 4). The results of the analysis of historical loss data are used to inform and validate the model-based approach, with the final direct damage estimates for each scenario based on a combination of the results of these two approaches.

For the analysis of historical CENAPRED[10] loss data, historical losses for events comparable to each scenario (where available) are scaled to a 2020 loss estimate based on exposure growth and inflation assumptions. Historical loss data were extracted from detailed CENAPRED reports for events similar to the defined scenarios. CENAPRED provides economic loss data divided into direct damages and indirect losses by state. In cases where the split between direct and indirect impacts is unavailable, this is estimated using the average ratio for other events of the same peril type (flood or tropical cyclone). These data were then scaled to estimated "as-if" 2020 losses, using estimates of exposure growth and inflation. These government data are considered a reliable historical loss dataset, and were also compared with other historical loss databases, including EMDAT.

The model-based approach combines three modules: (i) an exposure module, which characterizes the spatial distribution of capital stock; (ii) a hazard module, which characterizes the flood depths and/or windspeeds associated with a scenario; and (iii) a vulnerability module, which estimates

[9] Direct damages (first-round effect) refer to the physical damage to assets caused directly by an event, with the losses occurring at the time of the disaster or shortly thereafter. Examples of direct physical damages include the destruction of residences, productive capital, infrastructure, and crops.

[10] Centro Nacional de Prevención de Desastres

the damage for a given flood depth and/or windspeed for the exposure at risk. A comparison of the results from the approach based on historical loss data and the model-based approach was conducted, to further tune the parameters of the model-based approach, and to determine the final loss estimates.

To estimate the direct damages for the extreme season scenario (Scenario ES1), the results of the direct damage estimation methodology for individual events are summed. Note that a simple addition is plausible in the case of the direct damages for ES1 since the spatial extents of the direct damages of the constituent scenarios (Scenarios TC1, TC2, TC3 and F1) do not overlap[11]. However, for indirect economic impacts, compounding effects may be expected to occur due to transmission channels that can result in impacts beyond the original spatial extent of the area directly affected by an event. Yet, as explained further below, in this analysis compounding effects are only captured as an economic general equilibrium effect to the extent that the direct effects of damages generate consequent endogenous effects on TFP, unemployment and financial markets channels via the macro model. This is the extent to which compounding can be captured in the model given modelling and data limitations.

Whilst several commercial catastrophe models are available for Mexico, the simplified approach developed for our analysis is less resource intensive and can be implemented when outputs from more sophisticated models are not available (as is often the case in many emerging markets and developing economies, where locally validated catastrophe models may not be available). The catastrophe models that are available for Mexico (e.g., those developed by Universidad Nacional Autónoma de México, Evaluación de Riesgos Naturales, Verisk, RMS and other commercial vendors) are widely used in the insurance industry and for regulatory purposes. We did not have access to these models for this analysis, and it is important to note that the loss estimates could potentially be substantially improved using such a model. As outlined below, there are limitations and uncertainties associated with each of the modules of the model. The model results are sensitive to each of these model components and should thus be interpreted with full recognition of the limitations of the analysis. Further analysis based on more granular exposure information and leveraging latest climate science and catastrophe modelling expertise in Mexico would allow damage estimates to be refined.

Exposure module

The exposure module involves two steps: (i) the scaling of total physical capital stock data by state to an estimate of 2020 exposure; and (ii) the spatial disaggregation of this data. This process was used to generate a map of exposures that can subsequently be overlaid with hazard maps.

The scaling of physical capital stock data utilized variables from the World Development Indicators database to adjust the 2013 capital stock data from the Instituto Nacional de Estadística y Geografía (INEGI) to estimates for 2020. INEGI capital stock dataset for 2013 (INEGI, 2013) includes both

[11] Were the individual event scenarios to overlap spatially, it is possible that the direct damages of the extreme season scenario would not be equal to the sum of the direct damages of the individual events. For example, there might be overlapping destruction between climate events (e.g., the same building being destroyed by two events separately), making the damage sub-linear. Or, on the contrary, a scenario could weaken some infrastructure that is then destroyed by a subsequent event, potentially resulting in super-additive damages.

public and private capital stock, including fixed assets (e.g., real estate, infrastructure), and movable assets (e.g., machinery and equipment), reported at a state level. From the dataset, the ratio between total capital stock and annual GDP was extracted. Data from the World Development Indicators database (WB, 2022), including data regarding inflation in Mexico between 2000-2020 as well as the nominal GDP values for the period 2000 -2020 and the gross fixed capital formation, was then used to estimate the value of the capital stock in 2020.

State-level exposure estimates for 2020 were spatially disaggregated to a resolution of approximately 100m, and split into agricultural and built-up (industrial, commercial and residential) classes. The spatial disaggregation utilizes the Global Human Settlement Layer – Population (GHS_POP; Schiavina and others, 2019) and the Settlement Model Grid (GHS_SMOD; Pesaresi and others, 2019), which provide population and built-up area densities. The rationale is that capital stock (e.g., machinery and equipment) is more likely to be in populated or built-up areas. The maximum of the two normalized GHS_POP and GHS_SMOD densities per pixel is used to estimate capital stock density. The capital stock density map is then classified into two sectors using agriculture and built-up land cover classes identified from the Copernicus Global Land Service Land Cover data set (Buchhorn and others, 2020). Finally, the capital stock data is distributed by means of its density. Whilst this methodology provides a useful method for disaggregating the available capital stock data to a more granular geographic dataset, it is important to note the limitations of this approach. For example, the spatial population distribution in Mexico City may not be reflective of the spatial distribution of capital stock (e.g., due to inequalities and the non-homogenous spatial distribution of wealth and poverty).

Hazard module

The approach used to model hazard is based on the perils considered in each scenario, namely wind and/or flood. For some tropical cyclone scenarios, wind is considered to be the main driver of losses, whereas for others, the wind hazard is considered negligible, with most of the losses driven by flooding caused by heavy precipitation associated with the tropical cyclone. Depending on the nature of the scenario, the modelling approach was adjusted accordingly (i.e., for some tropical cyclones, wind was modelled, whilst for others, only flood was modelled). Storm surge is not modelled.

For the "historical conditions" tropical cyclone scenarios, the approach used to generate a windspeed map to model the wind hazard differed between scenarios:

- For Scenario TC1-hist, the wind component of tropical cyclone scenarios was modelled based on historical IBTrACS track data for similar historical events, with wind fields calculated from the track data using CLIMADA's (Aznar-Siguan and Bresch, 2019) implementation of Holland's (2008) method. Whilst several historical wind fields were modelled, it was decided to use the Hurricane Wilma 2005 track as a reference event for Scenario TC1-hist, since its landfall path and intensity is considered representative of the scenario's first landfall, which is associated with the wind-driven loss component of the scenario.
- The wind component of Scenario TC2-hist is negligible, with most damages driven by flooding caused by precipitation associated with the tropical cyclone. Hence, the wind hazard was not modelled in detail for this scenario.

- For Scenario TC3-hist, for which there is no similar historical event, a similar track was selected from the STORM stochastic track dataset (Bloemendaal and others, 2020), with wind fields subsequently simulated using the CLIMADA implementation of Holland's (2008) method.

In the case of the "climate change conditions" scenarios, for the wind hazard, an intensity adjustment is applied using CLIMADA, based on the Knutson and others (2015) intensity adjustments. Since the intensity adjustment factor from Knutson and others (4.5 percent increase in intensity for North Atlantic basin) is only available for one RCP and time horizon (RCP4.5 late 21st Century), the CLIMADA implementation scales this adjustment factor for RCP8.5 and other time horizons by interpolating them according to their relative radiative forcing. It is important to note that tropical cyclone projections for future climates are subject to substantial uncertainty, and different studies at basin or sub-basin scales have varied in their findings, as outlined in Section II.

For flood, the hazard module is based on the Fathom hazard maps (Sampson and others, 2015), available for a range of return periods. The riverine (defended) hazard maps are used to model flood risk in Scenarios TC1, TC2 and F1, based on a literature review highlighting that riverine flooding was the main driver of flood-related losses for similar historical events. It is important to note that the hazard maps are a global product and may not have been locally calibrated for Mexico. The use of different flood hazard maps can result in large differences in risk estimates. To define the flood hazard for a given scenario event, it was necessary to select a hazard map with an appropriate return period, and to delineate the area in which this hazard map is to be applied. Here, return periods for spatial units were defined as river catchments within a state. The approach to define the appropriate return period for each state/river basin varies between the scenarios, based on a combination of historical flood footprints for similar historical events, event descriptions, precipitation maps for similar historical events, precipitation and streamflow return period analyses available in the literature, and a calibration based on the comparative analysis outlined below.

In the case of "climate change conditions" scenarios for tropical cyclone-driven flooding, a change in rainfall is estimated from Knutson and others (2015). The estimate from Knutson and others (17.3 percent increase in rainfall rate) is only available for one RCP and time horizon (RCP4.5 late 21st Century). To derive factors for RCP8.5 and other time horizons, the adjustment factor is scaled according to relative radiative forcing estimates, based on the methodology implemented in CLIMADA for wind adjustment factors. The rainfall adjustments are then translated to an estimated change in streamflow, based on an assumption that the precipitation-streamflow elasticity for extreme events approaches unity (Breinl and others, 2021). Finally, the change in streamflow is converted to an estimate of the change in return period based on published streamflow return period estimates for rivers in Mexico (Isela and Zarco, 2014, Neri-Flores and others, 2019). This approach uses several simplifying assumptions, and the results should be interpreted recognizing the limitations. For example, the results are highly dependent on the elasticity assumption, which has not been locally proven for Mexican rivers. In addition, published streamflow return periods are only available for some gauges along the rivers and may not be representative of the flood frequency relationships elsewhere in a catchment.

In the case of "climate change conditions" scenarios for non-tropical cyclone-driven flooding, a change in streamflow for a 1-in-100-year is estimated using Di Sante and others (2020). The change in streamflow is converted to an estimate of the change in return period based on published streamflow return period estimates (Mora and others, 2008). This approach is subject to similar limitations to those outlined above for the tropical cyclone-relating flooding climate change adjustments.

Whilst the approaches for climate change adjustments outlined above result in increases in flood risk, it is important to note that several papers indicate that the risk may decrease for some rivers in Mexico (see, for example, Haer and others, 2018, Hirabayashi and others, 2013, Hirabayashi and others, 2021). This may be a result of potentially drier antecedent conditions in the river catchments due to the influence of climate change on other hydrologically important climate variables (e.g., increased temperature and evaporation). Thus, the climate change scenario damage estimates presented in this analysis may be more representative of a "bad case" change in flood risk, yet potentially not the "worst case" given that some model projections show even more severe increases in rainfall and/or streamflow with climate change than the increases assumed in this analysis.

Vulnerability module

To calculate the damage for a given hazard severity for the modelled exposures, published vulnerability curves were used. The European Commission Joint Research Centre vulnerability curves (Huizinga and others, 2017) were used for flood damage estimates, and the Eberenz and others (2021) regional tropical cyclone impact functions were used for wind damage estimates. The flood vulnerability curves relate flood depth to damage. The tropical cyclone vulnerability curves relate wind speed to damage. Where available, separate curves were used for agriculture and built-up (combination of residential, commercial and industrial) exposures. It is important to note that there are other vulnerability curves available for Mexico (e.g., CENAPRED, 2006), and that model results are sensitive to selection of vulnerability curve.

There is substantial uncertainty associated with modelling vulnerability (Kaczmarska and others, 2018). This includes uncertainty in both: (i) the development of the vulnerability model, including aleatory uncertainty (due to randomness of the processes governing the relationships between hazard severity and damage) and epistemic uncertainty (due to a lack of knowledge or data); and (ii) the use of the vulnerability model when modelling a given scenario (Trendafiloski and others, 2017). In this analysis, vulnerability has been modeled as a deterministic function of wind speed or flood depth. However, it is important to note that other methods may be better able to capture uncertainty. For example, vulnerability may be modelled by sampling the damage ratio for each asset from a statistical distribution. Due to an inability to differentiate between exposure data, the same vulnerability curves have been used for all exposures within a given class (built-up or agriculture), rather than differentiating between individual assets based on factors such as their construction type, age, number of stories, and occupancy. The use of a different vulnerability curve, adjustments based on modifiers related to detailed characteristics of the exposed assets, or a probabilistic sampling method for modelling vulnerability may substantially impact the results of the analysis.

Macroeconomic impact

The estimates of direct damages and destruction to the physical capital from physical hazards constitutes the key link between climate driven risks and macro-financial outcomes that can be further translated into impact on the financial sector. The key outcome from the above analysis on climate scenarios that connects the impact of climate related physical hazards to the economic and financial system is the estimate of damages. These damages are first approximated at regional level and then aggregated up to generate the damage at the national level. As such, the estimated direct damage rates to the physical capital stock can be interpreted as an immediate direct shock (equivalently, a depreciation shock) to the capital stock in an aggregated macroeconomic model. However, it is important to contextualize the macro-financial impact of climate risk driven estimated damages in terms of a country's specific physical risk characteristics. In this regard, the overall size, geographical location of the country, and exposure of various locations of the country to a variety of physical hazards, play a fundamental role in driving the aggregate damage estimates as reported above. Additionally, the limitations of the methodologies and models as discussed above also apply.

The damage estimates from the extreme season scenarios discussed above constitute the key input in generating scenario dependent macro-financial paths. One of the key objectives of the standard stress testing analysis (such as the ones used in FSAPs) is to use extreme but plausible risk scenarios. This is because the analysis largely attempts to quantify channels and mechanisms of risk propagation and their implications due to potential materialization of tail risk events. Given the objective of quantifying impacts from tail risks and considering the materiality of the estimated damage rates, the natural choice is to explore macroeconomic impact of the extreme season scenarios (ES1). Thus, the results discussed below will correspond to these set of scenarios and corresponding damages. The horizon of the analysis is three years.[12] The macroeconomic impacts conditioned on the estimated damages are modeled using the same underlying Global Macrofinancial Model (GFM) model as in the 2022 Mexico FSAP stress test, to enable comparability of the results relative to baseline without a climate risk overlay (i.e., isolating the impacts of the potential changes to tropical cyclone and flood hazard due to climate change from other potential future macroeconomic changes). This is a global multi-country DSGE model of the world economy, covering forty countries, featuring macro-financial linkages and a rich set of transmission channels. The model is regularly to generate scenarios in IMF's FSAP risk analysis such as solvency stress tests. The model allows for generating general equilibrium paths of macro-financial variables given various shocks, such as those arising from labor market frictions, productivity etc. Some of these shocks, the primary one being the immediate destruction of physical capital stock (analogous to shocks to capital depreciation), were applied in this analysis as discussed above. Thus, it forms the starting point of the more comprehensive stress testing exercise.[13]

It is well known that the direct effects of physical hazards are also generally accompanied by indirect effects via other channels that could potentially amplify the initial direct effects resulting

[12] The short term three years horizon is consistent with the analysis in the stress testing exercises by central banks and regulators around the world, with the historical and future climate change conditions modeled as added risks to this underlying framework (which was calibrated using recent data). Although the damage estimates from future climate change scenarios explore mid-century and end-of-century physical risk (from tropical cyclones and floods), it is possible that the damages from these risks could materialize within the short horizon, albeit with a substantially lower probability.

[13] Since the GFM is a commonly used model across various FSAPs at the IMF, it is beyond the scope of this paper to discuss the intricate details of this model. We refer the readers to Vitek (2018) that documents the empirical and theoretical features of the model, available at: https://www.imf.org/en/Publications/WP/Issues/2018/04/09/The-Global-Macrofinancial-Model-45790.

from physical hazards. In this regard, the team considered three additional channels and amplifiers to account for impact that is not captured by immediate direct damages. Note that there could be multiple other channels in addition to these. However, given the data and model limitations, these shocks lend themselves to easy integration into the existing macro modeling framework (GFM), while also capturing relevant economic dynamics one would likely observe in the immediate aftermath of extreme events.

- **Direct destruction of physical capital:** The direct damages to the existing physical capital were estimated at the regional state level and aggregated to arrive at the damages to the national capital level. This constitutes the direct channel of risk transmission from climate events, leading to an immediate impact or shocks to the physical capital in the macro model.
- **Impact on TFP:** The analysis considered shocks to the TFP arising from the direct damages to the capital stock. Disasters reduce the productivity since it may not be possible to rebuild the capital quickly in order for the output to recover. One of the drivers of TFP reduction after a disaster could come from the complementarity of infrastructure and non-infrastructure capital, meaning that if infrastructure capital is damaged by a disaster, then non-infrastructure capital also becomes unproductive, which can magnify the impact of the disaster (Hallegatte and others, 2022b). The shock was calibrated to be twice as much as the damage rate and assumed to be highly persistent. This is consistent with a general finding in the literature that overall productivity tends to be significantly lower after the disaster events (e.g., Dieppe and others (2020)).
- **Impact on unemployment:** Since capital stock and labor also complement each other during production, it is economically intuitive to consider a concurrent shock to unemployment in the event of large/immediate destruction to capital stock. For example, as factories and other productive infrastructures are damaged, the workers that complement the use of this capital stock are likely to be displaced as well. The shock is informed by the elasticity of unemployment to changes in capital stock in Mexico.
- **Effects from financial markets:** Given the sequence of climate events considered in the extreme season scenario, it is highly plausible that equity markets might also experience negative shocks. Since markets are forward looking, such disaster events could imply potential negative impact on the cash flow generating capacity of the firms, thereby lowering the market value of the equity of the firms. The shock is informed based on the elasticity of changes in overall equity market returns to changes in capital stock in Mexico.[14]

Financial sector impact model

The approach follows a standard stress testing methodology where the CAR of the entire financial system was projected, although this is not a standard stress testing exercise. Standard stress testing practice is generally designed to assess the resilience of banks and the financial system against pass-fail criteria, based on the impact on CARs relative to the regulatory minimum requirements.

[14]While other macroeconomic and financial variables (including interest rates, probabilities of default of loans/debt) could also be impacted after materialization of climate events, their impact (other than the endogenous impact already captured by the scenario model) is not considered in this stage of macro- financial path generation for simplicity given data limitations.

Importantly, the standard stress tests generally rely on historical relationships between macro-financial tail risks and the consequent impacts on banks and the financial sector. The corresponding adverse risk scenarios are extreme but plausible based on historical episodes. In the case of climate risks, the scenarios are similarly defined to be extreme but plausible, considering potential future changes in the likely severity of extreme events due to climate change.

The team applied the fully-fledged scenarios based macro-financial solvency stress testing framework to quantify the impact of climate related risks in the Mexican financial sector. This internally developed model is the one also used in the 2022 Mexico FSAP solvency stress testing analysis. The full details of the methodology are available in the published technical note[15] and here we summarize the key features to highlight various kinds of effects the framework captures.

The analysis considered a full top-down risk analysis that includes various risk components in the banking books: credit risk, interest rate risk, impact on risk-weighted assets, market risk etc. Analysis used granular bank level regulatory/supervisory data as of end 2021, covering ten largest commercial banks by asset size (including six domestically-systemically important banks), representing over 80% of the banking sector assets. Such granularity allows for quantifying the impact on the aggregate capital ratio (CAR) in the banking system in an exhaustive way.[16] The aggregate CAR impacts in the banking sector under different climate scenarios were obtained from aggregating up the granular bank-portfolio level impact on credit impairments, net interest income, net trading income, risk weighted assets, non-interest expense and so on.

The translation from the macro-financial scenarios to the bank level and ultimately aggregate capital impact is non-linear but a comprehensive, granular exercise that captures effects from various segments of banks' portfolios -- credit impairments, net interest income, market effects, risk-weighted assets etc. In this regard, the scenarios represent starting point inputs to the stress testing framework that generates heterogeneous and non-linear impact across banks and risk segments/portfolios given the intermediate estimated satellite models that link the scenario outputs to bank CAR level impact, ultimately generating impact on systemwide CAR.

The impact on CAR is represented as deviation from baseline CAR projections for the baseline plus current/historical condition scenario and baseline plus climate change conditions scenario. The baseline of the exercise is the same one used in the risk analysis of the 2022 Mexico FSAP and based on available 2022 World Economic Outlook projections. Given that the two climate related scenarios are

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[15] Mexico FSAP TN on Systemic Risk Analysis and Stress Testing (December 2022) available at: https://www.imf.org/en/Publications/CR/Issues/2022/12/08/Mexico-Financial-Sector-Assessment-Program-Technical-Note-on-Systemic-Risk-Analysis-and-526751.

[16] Further, since the macro-financial scenarios, consisting of pathways of various macro-financial variables were used as input to the stress testing framework, the spillover from the aggregate macro-financial channels to bank specific impact is already implicitly captured in the framework. However, second-round effects from financial sector to the economy and the feedback loops may not be fully captured. Modelling of such effects is a highly complicated exercise and thus, an active area of research in stress testing.

considered as additional risks on top of the baseline, the impact on CARs can also be interpreted analogous to that in the baseline versus adverse scenario(s) setting of the standard stress test exercise.[17]

V. Results

Direct damages for the most severe scenario, namely the extreme season scenario, are estimated to be approximately 0.9 percent of the total national capital stock for "historical conditions" (ES1-hist) and 1.9 percent for "climate change conditions" (ES1-cc end-of-century) (Table 1).[18] Direct damages for individual scenarios vary from 30 billion MXN (approximately <0.1 percent of capital stock) to 600 billion MXN (approximately 0.7 percent of capital stock) under "historical conditions". The return period of the direct damages at a national scale is broadly estimated as 50 years for TC1-hist, 50-100 years for TC2-hist, 500 years for TC3-hist, and 50-100 years for F1-hist, based on comparisons with wind event modelling from the Global Assessment Report 2015 analysis (UNISDR, 2015) and a statistical analysis of historical flood event data from EMDAT using the World Bank Financial Risk Assessment Tool (WB, 2021b). However, there is substantial uncertainty associated with these estimates due to the lack of access to a full catastrophe model, and limitations of the datasets used for comparison. A comparison with the "climate change conditions" scenarios indicates that damages may increase by 40-50 percent by mid-century under RCP8.5, and by more than 100 percent by end-of-century, yet these results are highly dependent on the modelling assumptions and are subject to substantial uncertainty.

Table 1. Direct Damage Estimates for Physical Risk Scenarios

Scenario	Climate conditions[1]	Direct damage rate (percent of capital stock)	Climate change impact (relative to "historical conditions" scenario)
	historical conditions	0.14 percent	
TC1	climate change conditions mid-century	0.21 percent	43 percent
	climate change conditions end-century	0.23 percent	59 percent
	historical conditions	0.03 percent	
TC2	climate change conditions mid-century	0.05 percent	54 percent
	climate change conditions end-century	0.08 percent	124 percent

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18 These estimates are for an extreme season scenario with a high return period (i.e., they are not expected to occur at this level of severity every year). The estimated damages are the total damages for the entire season.

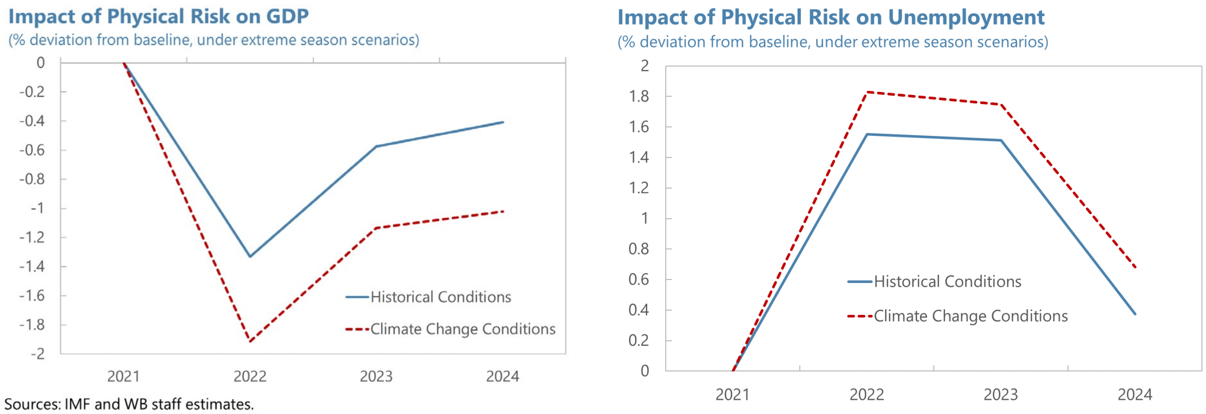
TC3	historical conditions	0.67 percent	
	climate change conditions mid-century	1.01 percent	51 percent
	climate change conditions end-century	1.45 percent	118 percent
F1	historical conditions	0.05 percent	
	climate change conditions mid-century	0.08 percent	54 percent
	climate change conditions end-century	0.13 percent	145 percent
ES1	historical conditions	0.90 percent	
	climate change conditions mid-century	1.35 percent	50 percent
	climate change conditions end-century	1.89 percent	110 percent

Note: 1/ "Climate change conditions" are based on RCP8.5.

The impact of physical hazards from floods and tropical cyclones on the overall macroeconomy could be significant as observed from the impact on GDP. Under the extreme season scenario, the impact on GDP in growth terms (in deviation from the baseline) under the "historical conditions" (ES1-hist) is about 1.4 percent in 2022. However, considering the impact of climate change (ES1-cc end-of-century), the effect on GDP rises to as much as 2 percent in 2022 (Figure 5). These results confirm that increased climate risks could have significant impacts going forward and the economic costs of climate driven risks are non-trivial. Additionally, the initial impact of the risk could persist well into the future from additional indirect channels as discussed above.[19]

[19] Since our climate risk methodology was first applied in context of 2022 Mexico FSAP, we used banking sector data as of end 2021 as the starting point of macro-financial impact projections up to three years. Further, these scenario conditional projections, as in general stress testing-based approach, concern extreme but plausible tail risks and thus, do not constitute forecasts. Thus, the projection horizon of three years from 2022 to 2024 in the results largely serve to illustrate the applicability of our approach while also emphasizing the potential materiality and importance of extreme seasons for financial stability in the short term. This means that whenever most recent regulatory and other macro-financial data required for the analysis are available in a given country, our approach can be well adapted and applied there as well.

Figure 5. Impact of Extreme Season Scenarios on Macroeconomic Variables



Sources: IMF and WB staff estimates.

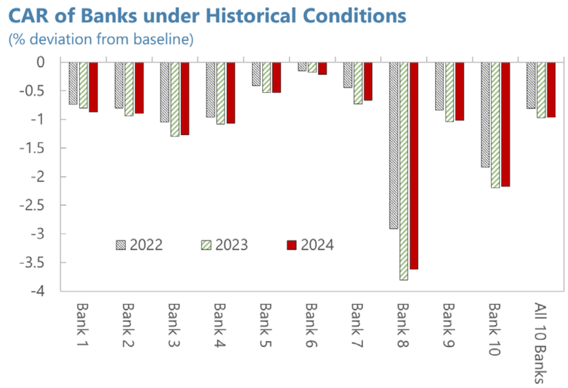
Sources: IMF and WB staff estimates.

Note: The extreme season scenarios shown are ES1-hist (historical conditions) and ES1-cc end-of-century (climate change conditions based on RCP8.5).

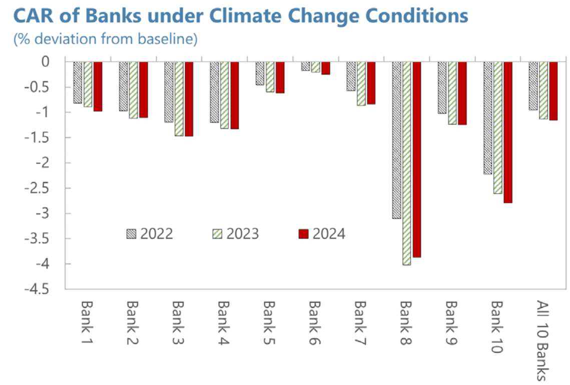
The current physical risk analysis suggests that impacts on the banking system might occur in the near term, but not at a scale to generate a systemic stress event. Figure 6 shows that under the extreme season scenario under historical conditions (ES1-hist), the aggregate CAR of the Mexican banking system would decline by about 1 percentage point versus the baseline. Considering risk under climate change conditions (ES1-cc end-of-century), the CAR depletion is approximately 1.2 percentage points. While these are relatively modest effects, they nevertheless suggest non-trivial capital impacts that increasingly severe climate events could generate in the future. Furthermore, there is also significant heterogeneity of capital depletion across banks. For example, at some banks the CAR could decline by almost 4 percent under historical conditions and over 4 percent under climate change conditions, relative to the baseline. These estimates show that significant vulnerabilities do exists among some individual banks, even if the system-wide aggregate impact is relatively modest.

While the system CAR would remain above regulatory requirement, the depletion of 1.2% capital relative to baseline is indeed non-trivial. This shows that climate risk could indeed pose challenges going forward, because while the starting CAR in the system was relatively higher at end 2021, in the future this might not be the case. Hence, the analysis highlights that the banking system could in fact face pressures in the future if the prevailing state of the economy and banking sector is weaker. In this context, and bearing in mind the implicit constraints due to modelling assumptions, the CAR depletion does highlight potential future vulnerabilities.

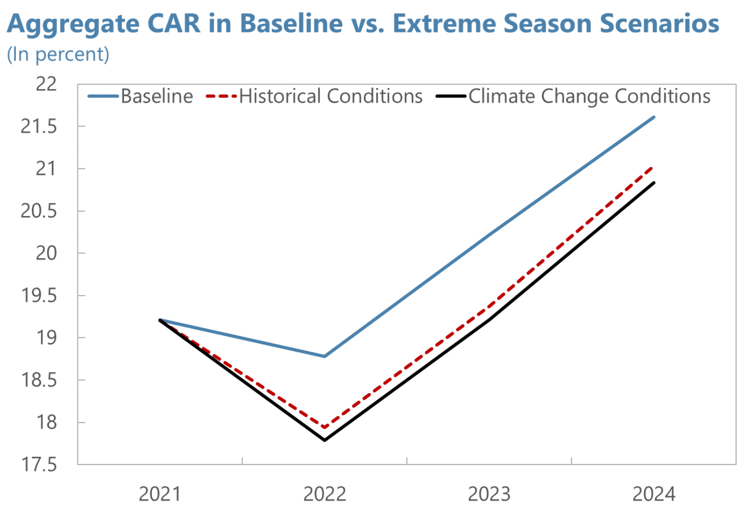
Figure 6. Impact of Extreme Season Scenarios on Capital Adequacy Ratio



Sources: IMF and WB estimates.



Sources: IMF and WB estimates.



Sources: IMF and WB estimates.

Note: The extreme season scenarios shown are ES1-hist (historical conditions) and ES1-cc end-of-century (climate change conditions based on RCP8.5).

VI. Discussion and Conclusion

Uncertainties, limitations, and interpretation

The results of the physical risk analysis (focused on acute risks associated with tropical cyclones and floods) highlight the potential for non-trivial impacts of these hazards on the financial system in Mexico. Material impacts due to flood and tropical cyclone disasters may be realized both under historical/current climate conditions and considering the impacts of climate change, albeit with greater severity. Although the results of our analysis are not directly comparable with those of other studies (due to differences in the methodology, analyzed risks and scenarios, country specificities, and reported metrics), the magnitude of the estimated impacts is within the range of estimated impacts found in other analyses of physical risk in the region.[20] For example, whereas our analysis estimated a CAR depletion of 1 percentage point under ES1-hist, a study of severe flood scenarios in Colombia estimated average declines in the CAR between 0.3 and 1.0 percentage point for domestic banks (Reinders et al. 2021). It is important to recognize that the analysis is only limited to tropical cyclones and floods, and that the materiality of the physical risks associated with climate change could be much larger if other risks (e.g., droughts, heatwaves, and chronic risks) are also considered. Furthermore, whilst our analysis focuses on financial sector impacts, it is important to acknowledge that the risks analyzed may also have more widespread impacts on livelihoods and communities, some of which may not be directly reflected in financial sector impacts, due in part to financial inclusion challenges, particularly for poor and vulnerable households (WB, 2019).

The analysis is subject to uncertainty at multiple levels, and the results should thus be regarded as a preliminary "first estimate" using the data and tools available. Uncertainties exist in all layers of the physical risk analysis, including the definition of climate and disaster scenarios, the model used to estimate direct damages, the transmission channels in the macro-financial model, and the financial sector impact model. However, although there is substantial uncertainty on the quantitative side (i.e., strength of climate change risks), the qualitative effects (i.e., the sign of risk materialization) are increasingly well understood.

The modelling approach is limited in its ability to capture indirect impacts and non-linear effects, but nonetheless highlights that the order of magnitude of potential impacts may be significant and of relevance from a financial stability policy perspective. Whilst the modelling of direct damages captured impacts to physical capital stock by taking into account the geographical distribution of hazard and exposure, this geospatially explicit modelling did not include modelling of potential indirect effects, including those associated with business interruption and large-scale disruptions in supply chains. While the macroeconomic model attempted to capture some of these indirect effects, important limitations exist. Given the aggregated national-scale macro model used to arrive at impact on GDP and other macro relevant variables, the regional variations, and interconnected dynamics across different parts of the country, could not be captured in a sufficiently granular way. Additionally, given the linearized dynamics of the model, the significant non-linearities that could potentially be associated with amplifications effects are not fully captured. Further, the analysis also does not account for potential future adaptation policies that could mitigate the impact of extreme climate events and thereby reduce the severity of the impact on the banking sector. Nevertheless, despite the obvious limitations due to the coverage of a smaller set of risk propagation mechanisms, the non-negligible impact on the CAR, coupled with potential for significant future risks, shows that our approach can capture and sharply quantify the materiality of physical risks to the financial system. Thus, our approach can be integrated into existing policy assessment frameworks to better inform future financial stability risks from climate

[20] There is a growing number of physical risk analyses in Latin America, including at a regional level (Calice and Miguel, 2021), for floods in Colombia (Reinders et al., 2021), for drought in Brazil (Banco Central do Brasil, 2022), and for heavy rainfall and droughts in Peru (Romero et al., 2022). In Mexico specifically, Aguilar-Gomez et al. (2022) analyzed the impacts of extreme heat events on non-performing loans. However, the results of the analyses are not directly comparable due to differences in the methodology, analyzed risks and scenarios, country specificities, and reported metrics.

change. Further research will be needed before drawing strong prudential policy implications. Improved data collection and further modelling could support a more granular analysis and enable a more comprehensive understanding of the macro-financial risks shown in this study.

Moving from individual events to sequences of events

Future research on climate physical risk could help to further develop the methodologies to understand the potential for sequences or clusters of extreme events. Although our analysis has already uncovered potential for significant future financial stability risks from an extreme season scenario consisting of a simple sum of individual events, additional work is required to develop approaches to capture potential non-linear compounding or amplifying impacts of clusters of events which could further increase the materiality of modeled impacts. Whilst our analysis was only limited to events occurring within Mexico, future work could also consider the potential for sequences or clusters of extreme events occurring internationally (e.g., international breadbasket failures driven by regional drought events occurring simultaneously with national-scale disasters), considering potential teleconnections and other drivers of correlations in the occurrences of disasters.

Appendix I. Climate-related disasters in Mexico

Mexico is highly exposed to disasters associated with acute physical climate change risks, such as tropical cyclones, floods, droughts, and heatwaves. During the last two decades, floods and tropical cyclones have constituted a substantial hazard burden among hydrometeorological disasters, both in terms of frequency of occurrence and the number of people impacted, with more than 15 million people affected by these hazards over the last two decades. These perils are the focus of this analysis. However, other acute risks, including drought and heatwaves, as well as chronic risks, may nonetheless be substantial.[21] It is important to note that Mexico is also subject to substantial risk from other natural disasters that are not climate-related, including earthquakes.

Mexico is exposed to tropical cyclones from both the Atlantic and Pacific basins. Similar numbers of major hurricane landfalls originate from these two basins (AIR, 2018). These tropical cyclones impact the coastline with strong winds, heavy precipitation, and storm surges. Mexico's mountain ranges along the coast both impact the rate at which landfalling storms dissipate, and result in orographic lifting which increases rainfall, meaning that tropical cyclones in Mexico are often accompanied by heavy rainfall and substantial flooding. Precipitation often extends inland, where it can cause extensive flooding. Eight of the ten topmost impactful tropical cyclone events in Mexico since 2020 impacted states overlooking the Gulf of Mexico, according to data from CENAPRED. There are cases where some federal states were hit twice in a very short period (e.g., Hurricane Karl and Tropical Storm Matthew in Veracruz in 2010, which caused 25 billion MXN of economic losses and affected more than 500,000 people) or the storm had two landfalls (e.g., Hurricane Alex in 2010, which caused 25 billion MXN of economic losses and affected 650,000 people), significantly exacerbating financial losses and the impact on populations. Due to its inland location, the potential occurrence of tropical cyclones impacting Mexico City with high windspeeds is relatively low, compared with the tropical cyclone hazard experienced by coastal regions.

Mexico is subject to several different types of flooding, including river floods, pluvial floods, and coastal floods.[22] River floods and pluvial floods typically occur following extreme rainfall. Major drivers of rainfall in Mexico include tropical cyclones and easterly waves during summer, and cold fronts during winter (Magaña and others, 2003), with the rainy season running from June to November. Coastal floods are also common, due to the occurrence of tropical cyclones that generate storm surges.

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[21] For example, for heatwaves there is evidence of a relationship between extreme heat and credit performance in Mexico (Aguilar-Gomez and others, 2022). For droughts, although direct impacts of droughts on the banking sector may be limited, for example due to low credit exposures to agriculture, they can nonetheless have substantial impacts on communities and the economy. For example, 80 percent of farmers in Mexico are smallholder farmers, with limited access to credit and insurance, and a reliance on rainfed production – hence high vulnerability to drought risk. Recent drought and heatwave conditions in Mexico have highlighted the importance of these risks. For chronic risks such as sea level rise, modeling suggests the potential for substantial economic losses, for example due to loss of coastal ecosystem services (Fernández-Díaz and others, 2022). It is also important to acknowledge that other nature-related risks, including biodiversity-related risks, may interact with climate physical risks. Whilst an analysis of nature-related risks more broadly is beyond the scope of this paper, an initial analysis of exposures to biodiversity loss has been completed by Banco de Mexico (Martínez-Jaramillo and Montanez-Enriquez, 2021).

[22] River floods occur when water in a river, lake or other waterbody overflows onto adjacent land. Pluvial floods occur when extreme rainfall results in inundation independent of an overflowing waterbody.

The most impactful flood events in Mexico over the past two decades occurred in Tabasco, and its surrounding states (Chiapas, Veracruz, Oaxaca and Puebla), generating significant economic losses and impacting millions of people, based on data from the Centro Nacional de Prevención de Desastres (CENAPRED). For example, the October 2007 floods in Tabasco and surrounding states resulted in economic losses of more than 35 billion MXN and affected more than 2 million people. Whilst floods do occur in Mexico City, they are typically pluvial flood events that are restricted to a few neighborhoods.

The frequency and severity of floods and tropical cyclones in Mexico is likely to be impacted by climate change, though there are substantial uncertainties in projected changes. Projections of future changes in tropical cyclone frequency and severity are subject to considerable uncertainty, particularly when considering changes at a basin or sub-basin scale. Considering basin-scale projections, climate change is projected to impact tropical cyclone risk in Mexico, with tropical cyclone frequency estimated to decrease in the North Atlantic and increase in the Northeast Pacific under Representative Concentration Pathway (RCP) 4.5 (Knutson and others, 2015). Both basins, however, are expected to experience an increase in the frequency of tropical cyclones of at least Saffir-Simpson Category 4 intensity (Knutson and others, 2015). Results at a sub-basin scale vary between studies. Focusing on landfalling tropical cyclones in the Yucatan Peninsula, Appendini and others (2019) estimated that intense hurricanes will be more frequent under RCP 8.5. In comparison, Bloemendaal and others (2022) found only minor changes in 1-in-100-year and 1-in-1000-year maximum tropical cyclone wind speeds for a future climate (SSP 5-8.5[23]; 2015-2050) compared with a past climate (1980-2017). Sea level rise may exacerbate storm surge risk associated with tropical cyclones. The precipitation associated with tropical cyclones is projected to increase, with projected increases ranging from ~5 percent to 40 percent (Knutson and others, 2020), driven by increased tropical water vapor. Bruyère et al. (2017) found likely future increased precipitation for tropical cyclones in the Gulf of Mexico. However, there is substantial uncertainty associated with these projections.

Climate change is expected to affect the frequency and severity of extreme precipitation in Mexico. The historical (1985-2014) 1-in-100-year maximum 5-day cumulative precipitation for Mexico is expected to occur with a return period of less than 50 years by the end of the century under SSP5-8.5 (WB, 2021a). Similarly, the historical 1-in-100-year maximum 1-day cumulative precipitation is expected to occur with a return period of less than 40 years by the end of the century under SSP5-8.5. Such increases in the frequency of extreme rainfall events could in turn lead to increased flood risk. Although increased extreme precipitation may increase flood risk, it is important to note that other factors may influence flood risk too, including changes in antecedent conditions, due to increase temperature resulting in reduced soil moisture. Whilst some studies suggest increased flood risk in Mexico due to climate change, several studies have found that the risk may decrease in some regions, including in Tabasco and other southeastern states (Haer and others, 2018, Hirabayashi and others, 2013, Hirabayashi and others, 2021). There is substantial uncertainty in flood risk projections for Mexico (Alfieri and others, 2017).

[23] SSP5-8.5 represents an extreme climate change scenario, corresponding to Shared Socioeconomic Pathway (SSP) 5 with a total radiative forcing level by 2100 (cumulative measure of greenhouse gas emissions from all sources) of 8.5W/m^2.

Appendix II. Description of individual event scenarios

Scenario TC1 is defined as a North Atlantic tropical cyclone event with two landfalls in Mexico. The first landfall is on the Yucatan Peninsula as a Category 4 hurricane. The second landfall is in Tamaulipas in northeast Mexico, with lower wind speeds (Tropical Storm / Category 1 hurricane) but heavy rainfall impacting Nuevo León, including Monterrey. The initial landfall may be compared with other hurricanes impacting the Yucatan Peninsula, including Janet 1955, Gilbert 1988, Wilma 2005, and Dean 2007 (see Appendix II for map showing these events). The second landfall may be compared with other tropical cyclones that made landfall in northeast Mexico that were associated with flooding in Monterrey, including the 1909 Monterrey Hurricane, Hurricane Beulah 1967, Hurricane Gilbert 1988, and Hurricane Alex 2010.

Scenario TC2 is defined as two tropical cyclones impacting the state of Veracruz 10 days apart with heavy precipitation. This scenario is based on a similar sequence of tropical cyclones that impacted Veracruz in 2010 (Hurricane Karl and Tropical Storm Matthew), which resulted in substantial damages, mainly due to flooding caused by heavy precipitation.

Scenario TC3 is defined as an Eastern Pacific tropical cyclone making landfall at Manzanillo, Colima as a Category 4 hurricane and impacting Guadalajara, Jalisco as a Category 1-2 hurricane.[24] The event may be compared with other Category 4+ hurricanes impacting the Jalisco/Colima region of Mexico, including Hurricane Patricia 2015. However, the estimated losses from this event are higher than those of Hurricane Patricia, since Hurricane Patricia did not make a direct hit on the exposure concentrations of Manzanillo and Guadalajara (AIR, 2015).

Scenario F1 is defined as a river flood event in Tabasco and surrounding states. This scenario is based on several historical floods that have impacted the region, including the 2007 Tabasco floods. Key factors that contributed to this flood event include heavy rains associated with the combination of a cold front and tropical storm Noel and the release of water from the Peñitas dam. This event was estimated to have a 1-in-100-year return period in the region (Ramos and others, 2009). Tabasco is an area of concern for flooding, having experienced frequent flood events over the past decades (Haer and others, 2017), including floods in 1993, 1999, 2007, 2008, 2009, 2010, 2011 and 2020.

Scenario ES1 is defined as an extreme season comprised of a sequence of several extreme tropical cyclone and flood events, namely TC1, TC2, TC3 and F1, all occurring within a few months of each other during one season. The extreme season scenario was included to analyze the potential for substantial economic and financial impacts if Mexico is impacted by a series of extreme events affecting different parts of the country in close succession. Such seasons with a series of extreme events have occurred historically, as illustrated by an analysis of event frequency (Table 2). Whilst multiple years have had high numbers of events (e.g., 2001, 2005, 2009, 2010, 2011, 2014, 2021), these events vary in severity. A recent example of a year with multiple severe events is 2010, when Hurricane Alex (one of

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[24] This event was selected from the STORM global synthetic tropical cyclone hazard dataset (Bloemendaal and others, 2020), which consists of 10,000 years of synthetic tropical cyclone tracks, generated using historical data from IBTrACS.

the similar events for the second landfall of Scenario TC1), Hurricane Karl and Tropical Storm Matthew (similar events for Scenario TC2), and flooding in Tabasco (albeit much less severe than in 2007, a similar event for Scenario F1) occurred. Whilst none of these events individually were the most expensive disaster to impact Mexico historically (e.g., the 2017 earthquake resulted in economic losses almost double the costliest 2010 event), in aggregate the economic losses from the sequence of disasters in 2010 were higher than any other year in the period 2000-2020, based on CENAPRED data. This highlights the importance of such sequences of events for the risk profile of Mexico, though the total economic losses from the 2010 sequence of events were still only estimated at less than 1 percent of GDP, due in part to the size of Mexico’s economy.

Table 2. Historical Frequency of Tropical Cyclone and Flood Events in Mexico[1]

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Mean
Flash flood	1	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	3	0	1	0	0	2	0.55
Riverine flood	0	0	1	1	1	2	1	1	0	5	2	3	0	1	0	1	0	1	0	0	0	0	0.91
Tropical cyclone	1	5	3	2	0	4	3	4	1	2	4	5	2	4	6	1	2	4	2	3	5	5	3.09
Total	2	6	5	4	2	6	4	5	2	7	6	8	2	5	6	2	5	5	3	3	5	7	4.55

Note: 1/ Number of events meeting EMDAT event criteria 2000-2021. At least one of the following criteria must be met for an event to be included in the EMDAT database: (i) 10 or more deaths; (ii) 100 or more people affected; or (iii) declaration of state of emergency or appeal for international assistance.

Source: author analysis of EMDAT data (CRED, 2022).

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