Macroeconomic and financial impacts of compounding pandemics and climate risks

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Abstract

Climate risks often do not happen in isolation but can compound with other sources of stress such as pandemics and pre-existing financial vulnerabilities, particularly in emerging countries. Compounding events increase the complexity of risk, leading to cascading impacts in the economy and finance. Thus, tailoring macroeconomic models to include compound risk considerations, can inform effective recovery policies, avoiding to underestimate risk. We build on the EIRIN macrofinancial model (Monasterolo & Raberto, 2018, 2019) to quantitatively assess the direct and indirect impacts of compound COVID-19 and climate physical risks in the economy and finance, accounting for the fiscal and monetary policy response to shocks. EIRIN captures the richness of climate risk transmission to the economy and finance in a rigorous accounting framework. In addition, EIRIN explicitly embeds a financial sector and financial market, thereby allowing the analysis of the impact of financial feedbacks on endogenous investment and consumption decisions, and on policy effectiveness. Then, via a compound risk indicator, we quantify the non-linearity of compound risk on GDP through time. We calibrate the model on Mexico, a country that is highly exposed to hurricane hazard and COVID-19, and deeply integrated in the global value chain, representing a potential channel of cascading risks. We show that compounding climate physical and COVID-19 risk can give rise to non-linear dynamics that amplify losses, with implications on private and public debt sustainability. The initial shocks' magnitude and their specific risk transmission channels contribute to explain the evolution of compound risks, given the country's pre-shock characteristics. Credit market constraints can amplify the shock by limiting firms' recovery investments, thus mining the effectiveness of increasing fiscal spending. Fiscal policies that depart from a business as usual recovery, and align to climate objectives, could help to build resilience to compound risk, avoiding increases in countries' divergence and debt sustainability challenges.

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1. Introduction

In 2020, the COVID-19 crisis represented the largest global economic shock since 1929 (Gopinath, 2020), and implications on public debt sustainability (Georgieva et al., 2020; Stiglitz & Rashid, 2020), financial stability (Adrian & Natalucci, 2020; Brunnermeier et al., 2020) and inequality (Ahmed et al., 2020) are expected, especially in emerging and developing countries (IMF, 2021).

The year 2020 was also the record year of the Atlantic hurricane season (NOAA, 2020), showing that climate change (Coronese et al., 2019) already represents a main source of risk for several countries. Climate change is expected to have large yet differentiated economic (Burke et al., 2015; Hsiang et al., 2017), financial (Mandel et al., 2021) and distributive impacts (Diffenbaugh & Burke, 2019).

Climate risks often do not happen in isolation but can compound with other sources of stress (Phillips et al., 2020; Zscheischler et al., 2018), such as pandemics and financial vulnerability, thus increasing the complexity of risk and of policy response (Battiston, Billio, et al., 2020). For instance, by damaging the countries' productive capacity and socio-economic infrastructures, natural hazards provide a fertile ground for pandemics to spread, delaying recovery times and exacerbating the long-run effects. Most of these impacts are characterized by deep uncertainty and their evolution can be largely influenced by policy introduction and by agents' expectations about them.

Neglecting compounding risk can lead to misunderstand the risk transmission channels and to underestimate the magnitude of impacts in the economy and finance, thus impairing the implementation of effective response from public policy and investors. Analyzing compound risk introduces new challenges for macroeconomic analysis, as well as for fiscal and financial risk management, requiring adaptation of our analytical tools. The complexity, uncertainty and endogeneity of compound risk require to smooth underlying assumptions of traditional macroeconomic models such as market-clearing prices and agents' perfect foresight. Further, it requires to include finance and its complexity, in order to assess the feedback from financial agents' risk assessment to the economy and policy response (Monasterolo, 2020). Indeed, when banks introduce their expectations about the impact of climate risk on firms in their risk assessment, they eventually revise their lending conditions (e.g. the cost of capital), thus affecting firms' investment decisions (Battiston et al., 2020; Dunz et al., 2021).

Recent literature has addressed climate risks, financial risk and the economic consequences of pandemics individually, including in the recent COVID-19 crisis (see e.g. Eichenbaum et al., 2020;

Guerrieri et al., 2020). A framework to quantitatively assess the macroeconomic and financial impacts of compounding epidemics, climate and financial risks is not available yet. We contribute to fill this knowledge gap by further developing the EIRIN macrofinancial model (Monasterolo & Raberto, 2018) to quantitatively assess the direct and indirect impacts of compounding COVID-19 and climate risks on main macroeconomic variables, as well as on private and public debt. We design four scenarios of individual and compound COVID-19 and climate-related shocks (i.e. hurricanes) characterized by different timing and magnitude and calibrated on data for Mexico. Considering the role of fiscal and monetary policies introduced in the COVID-19 recovery phase, we assess the sensitivity of public spending effectiveness to credit market constraints, and the implications for GDP recovery.

EIRIN captures the richness of COVID-19 and climate risks transmission channels to agents and sectors of the economy and finance, considering how the nature of risk affects agents' heterogeneous beliefs, inter-temporal preferences, and the formation of expectations and decisions in response to shocks. Importantly, EIRIN includes a financial sector and market, thereby enabling the analysis of financial feedbacks on endogenous investment and consumption decisions, and on policy effectiveness.

2. Methodology

2.1. Model description

We further develop the EIRIN macrofinancial model (Monasterolo & Raberto, 2018, 2019)[5] to analyze how compound COVID-19 and climate physical risks (e.g. hurricanes) affect the economy, the credit sector and public finance. EIRIN allows to consider the richness of compound risk transmission channels and impacts in the economy and finance; the role of agents' heterogeneous beliefs and expectations; the interplay between finance and public policy in the COVID-19 recovery.

EIRIN is a Stock-Flow Consistent (SFC) model of an open economy composed by agents and sectors which are heterogeneous in terms of characteristics (e.g. income, wealth) and preferences, and are characterized by forward-looking expectations about the future of the economy. Agents and sectors include wage and capital-income earning households; an energy company and an utility company, which can produce electricity out of either fossil fuel or renewable energy; a capital good producer; a service sector, which includes tourism; an industry

[5] The analysis is based on the methodology developed in the World Bank Policy Research Working Paper "Macroeconomic and financial impacts of compounding pandemics, climate and financial risk: a methodological framework" by Monasterolo et al. (2021).

sector; a banking sector; a central government; a central bank; a foreign sector providing import and export of commodities and consumption goods. EIRIN's sectors are represented as a network of interconnected balance sheets items (Monasterolo & Raberto, 2018) calibrated on real data (when possible), making it possible to trace a direct correspondence between stocks and flows. The rigorous accounting framework allows to display the dynamic relations of agents and sectors' balance sheets and to analyze (i) the direct impact of the shock on individual agents and sectors of the economy (at the level of balance sheet entry), (ii) the indirect impact of the shock on macroeconomic variables (e.g. GDP, unemployment, interest rate) and financial risk variables (e.g. banks' Probability of Default, Non-Performing Loans), and (iii) the reinforcing feedbacks that generate in the financial sector and that could amplify the original shocks, leading to cascading economic losses.

This approach has several advantages for the assessment of compound risks of different nature, such as climate physical risks, pandemics and financial risk. First, we can quantitatively assess the richness of risk transmission channels and of impacts on heterogeneous agents and sectors of the economy and finance. Second, we can analyze the interplay between private finance, public policies, and economic growth, considering the sensitivity of public spending effectiveness to different levels of credit and labor market constraints, and identifying sensitive intervention points. Third, we can consider the deep uncertainty of climate-related risks and of pandemics (Battiston, Billio, et al., 2020), that feeds into financial agents' risk assessment and reactions (e.g. banks' revision of lending policy). Finally, we allow agents to depart from perfect foresight presence of market imperfections (e.g. potential mispricing), market power (e.g. in the energy sector), and uncertainty of impacts.

We tailor the EIRIN model to the characteristics of Mexico by including a tourism sector, migrants' remittances and government COVID-19 spending (e.g. healthcare, unemployment measures). Mexico is highly exposed to hurricanes and COVID-19 risk, and deeply integrated in the global value chain, thus making it a potential channel of cascading risk.

Agents and sectors in EIRIN are heterogeneous in terms of characteristics (e.g. income, wealth) and behavioral rules. Agents are characterized by adaptive expectations about the future of the economy: firms form adaptive expectations about future demand based on their sales in previous time periods. Those demand expectations $\widehat{\mathrm{q}_{\mathrm{j}}^{\mathrm{C}}}$, composed of private, public and external demand, then determine firms' production and investment plan. The investment decision of firms is endogenous and based on firms' Net Present Value (NPV) (Eq. 1), considering (i) investment costs $p_K\, I_j$, (ii) expected future discounted revenue streams $\widehat{q_j^C}\, p_j$ (e.g. external and endogenously generated demand), (iii) expected future discounted additional variable costs due to investment

($w_j \, \Delta N_j$ $(labor)$, $\Delta q_j^R \, p_R$ $(resource\ inputs)$, $\Delta \, q_j^E \, p_{EN}$ $(energy)$), (iv) the sector dependent interest rate set by the commercial bank r_D^j :

$$NPV_j = -p_K \, I_j + \sum_{t=1}^{\infty} \frac{\Delta \, \widehat{q_j^C} \, p_j - w_j \, \Delta N_j - \Delta q_j^R \, p_R - \Delta \, q_j^E \, p_{EN}}{1+r_D^j} \qquad \text{(Eq.1)}$$

Compound risks can lead risk-averse agents to revise their expectations about the economy and finance, and thus their investment decisions.

Banking and finance include several financial actors and assets, as well as a financial market for sovereign bond trading. The banking sector is connected via loans and deposits to the agents and sectors of the economy, as well as to a sovereign bond market, and to a central bank. The commercial bank sets sector specific interest rates for loans. The commercial bank endogenously creates money (Jakab & Kumhof, 2015; McLeay et al., 2014), thus expanding its balance sheet with every new granted loan. The commercial bank receives deposits from all economic actors. Further, it provides loans to finance firms' investment plans. Depending on the outstanding firm's leverage ratio the bank sets sector specific interest rates that affect firms' capital costs and NPV decision. The maximum credit supply of the bank is set by its equity level divided by the Capital Adequacy Ratio (CAR) parameter, in order to comply to banking regulator provisions, meaning that credit may be rationed due to insufficient equity capital on the bank's side. The central bank sets the policy rate based on the Taylor rule and can engage in unconventional monetary policies (e.g. Quantitative Easing). The explicit consideration of money and finance and endogenous money creation in the model allows us to capture the dynamics of amplification of financial distress and deriving distributive effects (inequality)[6].

2.2. Model calibration and validation

To ensure that the shocks' dimensions are quantitatively meaningful, we initialize and validate the EIRIN model to mimic the main structural characteristics of Mexico, using World Bank data. We follow a twofold calibration strategy in line with Zezza & Zezza (2019) and Fagiolo et al. (2019). First, we replicate the main structural macroeconomic and financial characteristics of Mexico, by adapting the EIRIN model structure (Monasterolo & Raberto, 2018, 2019). To do so, we collected and analyzed the main macroeconomic data and features of the economies using statistical information provided by the World Bank database of world development indicators (WDI) between 2015 and 2019[7] (The World Bank, 2020). Data shows the importance that export, tourism, and remittances' flows from abroad play in Mexico as sources of aggregate demand and household income. Second, we initialize the model to a quasi-steady-state in which the core

[6] A synthetic description of the model's characteristics is provided in Table A1 in the Appendix. For a full description of the EIRIN model, the reader can refer to the technical note developed in the first phase of the project.
[7] Except for tourism, which relies on Statista (2020) for the years 2014-2018 due to limited WDI data availability.

variable ratios and growth rates are stable. Finally, we dimension the simulated economy to quantitatively mimic the main macroeconomic and sectoral growth rates and ratios of Mexico via core model parameter settings. The model's accounting structure is represented by a balance sheet, a transaction flow and a net worth matrix (see Supplementary Methods C) that further ensures the internal model consistency and validation. A detailed description of the initialization and dimensioning of the model is contained in Supplementary Methods B; the description of the model itself is available in Supplementary Methods A.

2.3. Climate physical risk and COVID-19 scenarios design

Climate physical risk: Hurricanes are a major cause of economic losses in Mexico, representing more than 40% of the economic losses due to climate related hazards in that country (Guha-Sapir et al., 2009; UNISDR, 2021). Annually, expected losses to infrastructures due to hurricanes in Mexico are in the order of USD 39 million, while losses associated with a return period of 1 in 1,500 years are in the order of USD 1.18 billion (Jaimes & Niño, 2018). Historically, Hurricane Wilma in 2005 is the most significant event in terms of damages and losses ever recorded in Mexico, with direct damages estimates in the order of USD 500 million and total economic losses around USD 1.3 billion, most of which affecting the tourism sector of Quintana Roo state (CENAPRED, 2006). The magnitude of the economic losses due to hurricanes mainly occur due to wind destruction, flooding, and storm surge, all of which are strongly dependent on the maximum sustained wind speeds experienced at ground levels (Ishizawa et al., 2019). To estimate the potential destruction of capital stock in Mexico, we use a hurricane damage function proposed by Emanuel (2011) that allows for three main features: i) damages are accounted for only when sustained winds speeds are larger than a specified minimum threshold; ii) damages vary as the cube of the sustained wind speed over a threshold value, and; iii) the damage potential approaches unity at very high wind speeds, and it cannot exceed unity in any event. The formulation employed is shown Eq. 2 (Emanuel, 2011):

$$F_{index} = \frac{v^3}{1+v^3}$$
$$v = \frac{\max(W_{spd} - W_{thresh},\ 0)}{W_{half} - W_{thresh}} \qquad \text{(Eq. 2)}$$

Here, the damage function allows to translate wind speed into damages to capital stock via the cubic power of wind speed on the physical grounds, defining a lower bound threshold W_{thresh} of no damage occurrence and a threshold W_{half}, where half of the damages occur. In order to apply such a function for Mexico, we use open-access data from EM-DAT disaster risk data base (2020), covering the past 30 years (1990-2020), to calibrate the above-mentioned damage function for the assessment of hurricane risk in Mexico. We estimate W_{thresh} to be 65km/h and W_{half} to occur at a wind speed value of 253km/h.

Probabilistic wind speed data is obtained from UNEP-GRDP database on tropical cyclones and hurricanes (Cardona et al., 2015; UNISDR, 2015). The UNEP-GRDP database on tropical cyclones provides a series of probabilistic wind hazard maps at 0.25° resolution and for the return periods of 1 in 50, 1 in 100, 1 in 250, 1 in 500, and 1 in 1000 years. Wind speed data is provided as 3-seconds gusts over the surface, hence being converted to sustained wind speed following the methodology proposed by (Harper et al., 2010). In order to account for the return period of 1 in 10 years, wind speed data is interpolated from the available expected frequencies using a logarithmic regression function fitted independently for each spatial cell. We then calculate the damage index factor, Findex, to obtain the relative losses with respect to different levels of sustained wind speed, in Eq. 2 ranging between 0 and 1. Results are shown in Figure 4.

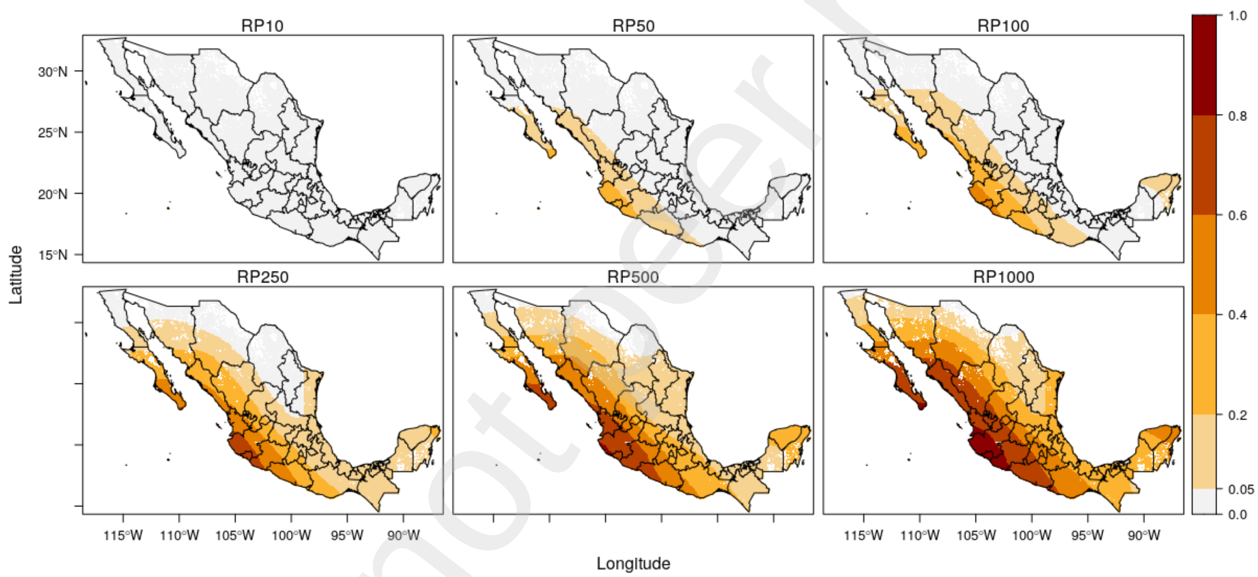

Figure 5: Damage index factor, Findex, computed for six different hurricanes return periods in Mexico based on UNEP-GRDP data (Cardona et al., 2015; UNISDR, 2015).

Mexico is a large country with a diversified economy and heterogeneous distribution of population and assets, thus being heterogeneously exposed to hurricane hazard. In order to identify the most relevant economic and touristic states in Mexico in terms of exposure to hurricanes (see Supplementary Material D) we obtain Mexican state-level GDP from the Mexican Statistical Institute (2020). The relative contribution of those states to total Mexican GDP is used to rank potential damages to those economic and touristic important states in Mexico. We identify the cities of Mexico City, Cancun (Quintana Roo), Acapulco (Guerrero), Huatulco (Oaxaca), Monterrey (Nuevo Leon), Saltillo (Coahuila), Guadalajara (Jalisco), and San Francisco de Campeche (Campeche) as particularly exposed to hurricane hazard Mexico. Country-wise, historical capital stock losses are quantified as destroying 0.98% of productive capital stock in Mexico for a strong-impact hurricane hazard event (i.e. 1 in 100-year event), while a mild impact hurricane hazard event (i.e. 1 in 50-year event) is quantified to destroy 0.43% of productive capital stock.

COVID-19 has a large negative socio-economic impact on Mexico. Numbers of infections (2,280,213) and COVID-19 related fatalities (209,338)[8] are high (John Hopkins University, 2021), despite government containment measures (e.g. curfew, border restrictions). In turn, domestic consumption was estimated to decrease by 8.3% in 2020 (OECD, 2020). Further, external shocks were expected to be significant for Mexico. Exports (in particular of cars, electronics and intermediate goods), constituting 39% of the Mexican economy, were expected to drop by 9.2% in 2020 (OECD, 2020). International tourism were expected to drop by 50% in 2020 in Mexico due to travel restrictions all over the world (UNWTO, 2020). Finally, remittances, making up 3% of Mexican GDP, were expected to drop by 19.3% in 2020 (The World Bank & KNOMAD, 2020) due to economic downturns in the host countries (especially in the USA). The Mexican government responded with fiscal measures to mitigate the negative socio-economic impacts of the COVID-19 outbreak. The measures specifically include health, private household support and business liquidity and guarantee measures, equal to 1.2% of 2019 GDP (IMF, 2020). The central bank of Mexico also took a supportive role by lowering its policy rate by 250 basis points and implementing monetary policy measures of an equivalent of 3% of 2019 GDP to ensure financial stability and sufficient market liquidity (IMF, 2020).

We design four scenarios that allow us to isolate the effects of COVID-19 and climate physical risks (i.e. a hurricane hazard) on the Mexican economy and public finance and to assess impact changes, when those risks compound. We consider two different dimensions of the COVID-19 and hurricane hazard shock. First, both shocks occur as individual events or in sequence. Second, the shock size of the hurricane hazard could vary, inducing mild or strong impacts on the productive capacity of firms in the EIRIN economy. Giving the current lack of data, we base the COVID-19 scenario impact assumptions for Mexico on estimates from a several official data sources. Impacts include exports (-9.19%)[9], remittances (-19.3%)[10], tourism (-50%)[11] and domestic consumption reductions (-8.26%)[12]. COVID-19 fiscal and monetary response measures are taken from the IMF Policy Tracker. We then compare scenario outcomes to a business as usual (BAU) scenario, where no shocks occur. In addition, we assess the relevance of government's fiscal measures for economic recovery, considering varying levels of government

[8] As of April 12, 2021
[9] OECD (2020)
[10] World Bank and KNOMAD (2020)
[11] UNWTO (2020)
[12] OECD (2020)

spending during the crisis ΔG. We contrast results with constraining factors such as bank's credit supply (CAR), showing the relevance of financing conditions and access to credit in the disaster aftermath.

3. Results

3.1. Risk transmission channels

We first identify the most relevant climate physical risks (i.e. hurricanes, blue) and the COVID-19 (red) transmission channels to the real economy and banking sector of Mexico (Figure 1), which we then quantitatively assess with the EIRIN model. The analysis of risk transmission channels is crucial to identify the shocks' entry points, the direct and the indirect impacts in the economy, public and private finance, given the type of shock and country's characteristics. Our analysis of the climate risk transmission channels stands on a body of recent literature (Battiston et al., 2017; Battiston & Monasterolo, 2020; Gallagher et al., 2021; Semieniuk et al., 2021; Volz et al., 2020).

Hurricanes enter the economy by destroying productive capital, which impacts firms' production (direct impact), as it requires capital as an input factor. Hurricanes represent a supply shock that limits firms' ability to serve demand. In the short run, firms cannot easily substitute capital as an input factor, laying-off people. This increases unemployment, which directly affects household income and indirectly weakens workers' wage bargaining power, lowering household consumption and real GDP. Note that sectors are affected differently by the hurricane shock, allowing the capital goods production sector to use unused capacity to serve the additional investment demand.

COVID-19 (red) originates as a demand shock to the economy. External demand from tourism, remittances and exports is reduced due to global travel restrictions and lower economic growth globally. Internal demand, especially domestic private consumption, falls as a consequence of lockdown and curfew measures. The contraction in external and domestic demand negatively affects firms' production. Consequently, unemployment increases, household consumption decreases and real GDP falls. The COVID-19 shock indirectly impacts public and private finance. **Public finance**: lower tax revenues due to lower real GDP, leading to increases in government deficit, which requires the issuance of new public debt to finance the COVID-19 spending. Lower GDP and higher sovereign debt move government debt to GDP ratio upward and thus the cost of refinancing on international markets. This, in turn, reduces government's future fiscal space and its ability to react to the crisis. **Private finance**: negative economic conditions increase firms' leverage ratios and higher risk of default. As a consequence, banks tighten credit conditions to firms, increasing capital costs. A wide range of investment projects become unprofitable, with negative implications on firms' new investments.

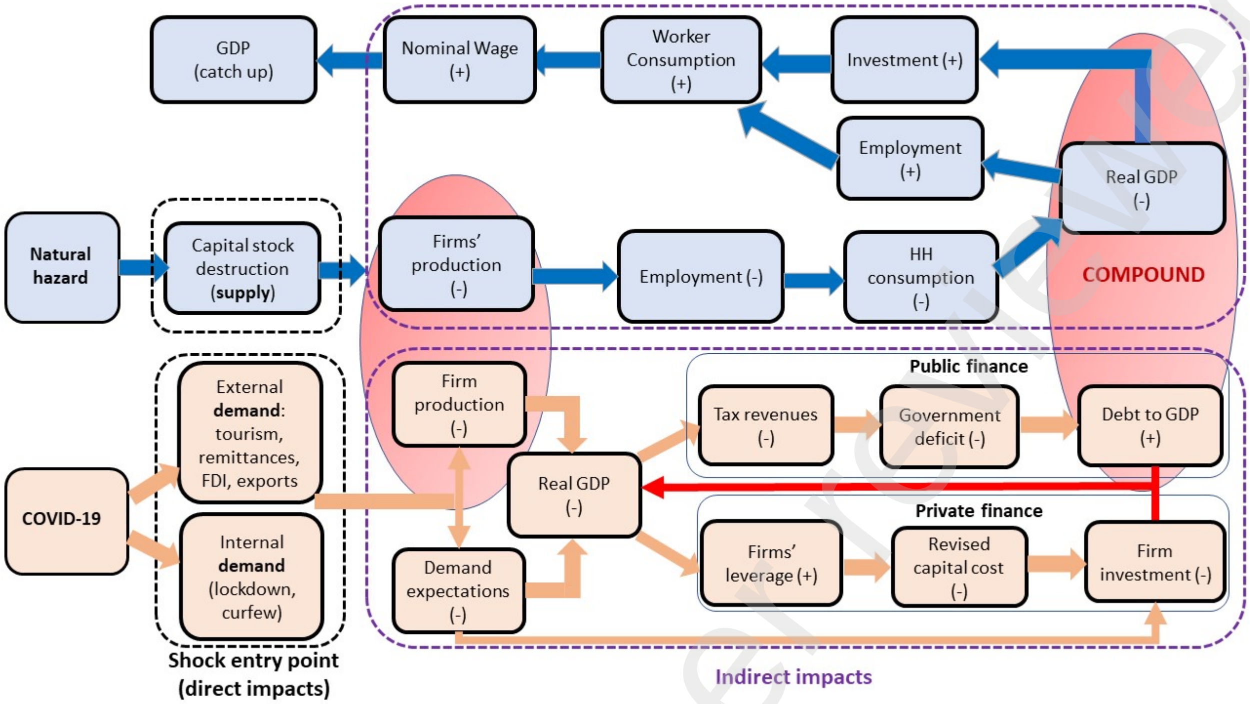

Figure 1: *Individual and compound risk transmission channels. The figure shows the COVID-19 and hurricane's entry points (black dotted boxes) and transmission channels to the main variables of the real economy, public and private finance. Direct impacts correspond to the input shocks considered and are identified by the black dotted boxes, while indirect impacts are identified by the purple dotted box. The red arrow shows the reinforcing feedback loop, while the shaded red areas identify the compound effect. The signs (+/-) indicates the direction of the impact (+: variables move in the same direction; -: variables move in opposite directions, i.e. an increase in A leads to a decrease in B). The COVID-19 shock affects domestic and international demand (export, tourism, remittances), while the hurricane affects the supply by hitting firms' production. The shocks then are transmitted in the economy via real and financial flows.*

We calibrate the EIRIN model on Mexico, a country that is highly exposed to both COVID-19 and hurricane risks and is highly integrated in the global value chain. This, on the one hand, exposes the country to external shocks (tourism, export, remittances, Foreign Direct Investments (FDI), while on the other hand, makes the country a potential shock propagator in the regional and global economy.

3.2. Simulation results

Insights from our simulation results are threefold. First, a singular hurricane hazard (SC1) destroys productive capital stock, entering the EIRIN economy as a supply shock. The temporary shortage of production capacity negatively affects GDP (Figure 2a). However, high domestic and foreign demand at the time of the shock fuel firms' investment in reconstruction, allowing the economy to quickly recover[13]. In contrast, the COVID-19 crisis (SC2) induces a demand shock, leading to lower domestic consumption, tourism and exports as a consequence of global lockdowns, that strongly hit the export-dependent Mexican economy. Those direct impacts induce cascading effects in the economy via unemployment (Figure 2b), reduction in households' income and increase in public debt, thus prolonging the impact of the original COVID-19 shock.

When COVID-19 compounds with the hurricane (SC3 and SC4), the interaction of demand and supply side shocks leads to non-linear amplification of direct impacts on GDP. This is captured by the compound risk indicator (Figure 3)[14]. Firms revise future demand expectations and consequently cut investments, reducing aggregate supply because no additional capacity is needed to serve demand. Unemployment increases, wages fall due to the Philipps curve dynamics, and the public debt to GDP ratio increases. The degree of non-linearity, however, depends on the size of the hurricane shock (Figure 3). A larger but less frequent hurricane shock leads to higher non-linearity. This indicates high future vulnerability as climate change is expected to shift the distribution of hurricane occurrence (IPCC, 2018) and increases risk of compound events (Zscheischler et al., 2018).

[13] See the Methods section for an extensive explanation of risk transmission channels and feedback mechanisms.

[14] The compound risk indicator was developed under the World Bank Technical Assistance project "COVID-19 Pandemic, Financial Shock and Natural Disasters: Assessing compound risks in four countries". For more details see Monasterolo et al. (2021). For the indicator, real GDP loss of the compounding COVID-19 and hurricane shock scenario is plotted over time against the sum of real GDP loss of the individual shock simulations of a singular hurricane and singular COVID-19 scenario. The sum of both represents the index 100, whereas values greater than 100 show non-linear amplification and values lower than 100 show positive spillovers.

a)

b)

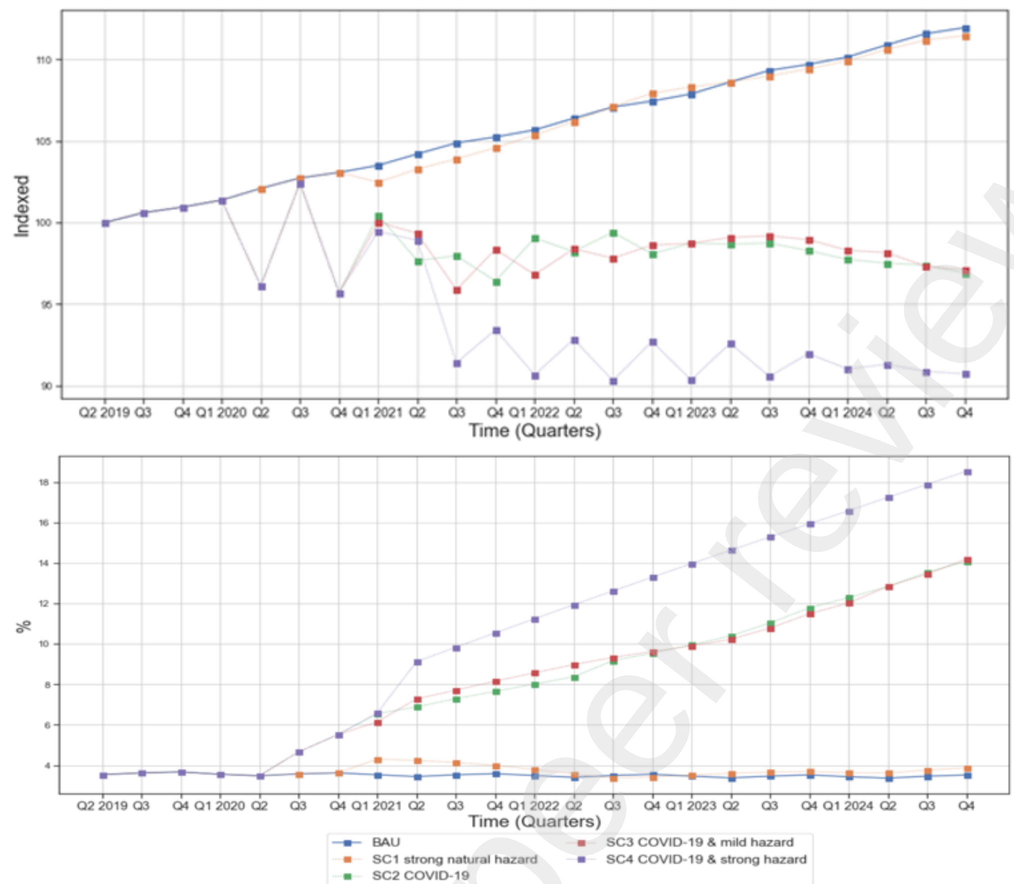

***Figure 2:** Upper graph (a) real GDP – Lower graph (b) unemployment rate (5 years time span). The x-axis shows the timeline of the simulation lasting until the fourth quarter of 2024 on a quarterly basis. The y-axis shows a) real GDP for Mexico indexed against the 2019 pre-shock value (GDP 2019 = 100) b) the unemployment rate for Mexico in percentage terms.*

Second, supply-side constraints in the economy, i.e. banks' countercyclical lending to agents, add up to the non-linearity of economic impacts (Figures 4a and 4b). When banks revise their lending conditions (i.e. the cost of capital) to firms in response to large, compounding shocks, firms' ability to invest in the recovery is impaired, and unemployment increases due to layoffs (SC4). As a consequence, the economy faces a long-lasting negative effect (hysteresis) and unemployment and public debt further increase.

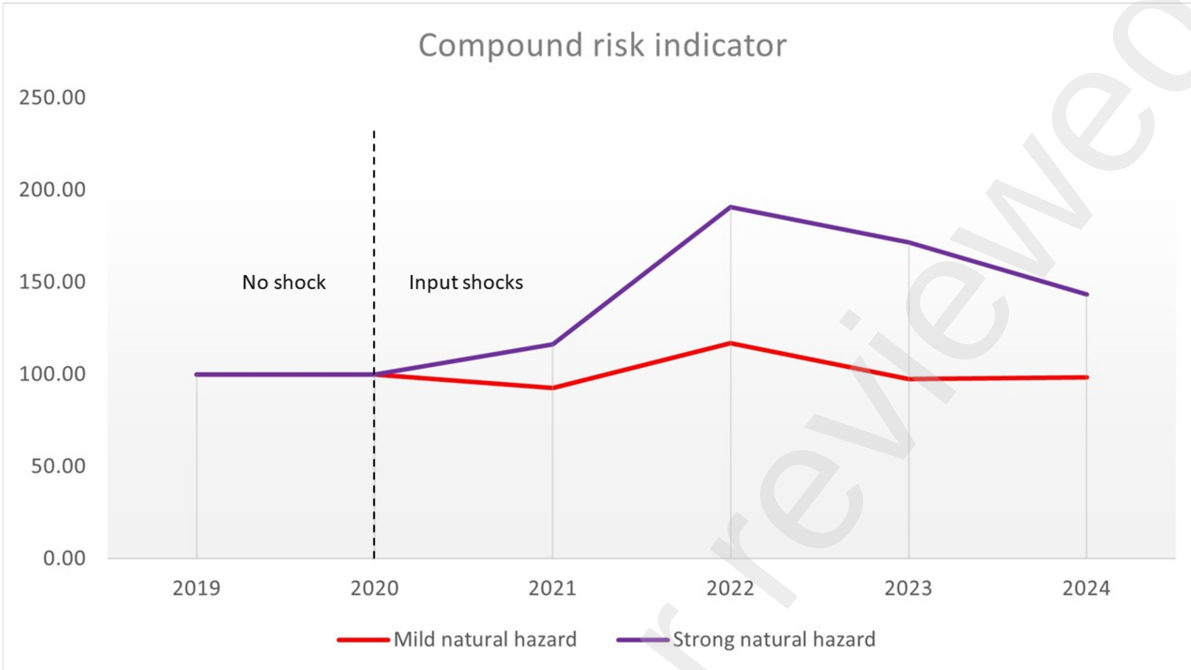

Figure 3: *Compound risk indicator that shows the non-linear amplification effects resulting from the compounding of COVID-19 and climate shocks happening in 2020. The x-axis shows the timeline of the simulation until 2024 on an annual basis. The y-axis shows the value of the compound risk indicator indexed against the sum of the singular event scenarios of hurricane only and COVID-19 only, at 100. The vertical dotted line represents the starting point of the input shocks, which occur during 2020. Two compound scenarios are considered: (i) COVID-19 and mild hurricane scenario (red line) and (ii) COVID-19 and strong hurricane scenario (purple line).*

Third, the increase in government spending in the aftermath of the shocks provides an important stimulus to domestic demand and thus to GDP (Figure 4a), creating the conditions for the recovery. Additional fiscal spending does not induce a trade-off for public debt sustainability if banks keep lending (Figure 4c). However, there is a threshold over which the increase in government spending (i.e. > 10% GDP) starts to be counter-effective for GDP and public debt ratios. At that point, firms are not able to satisfy the additional demand being constrained by lack of workers and access to credit. In addition, the worsening of firms' financial conditions in sectors affected by the hurricane (firms with productive capital located in areas exposed to the shock) and by COVID-19 (firms in tourism, export of raw materials and intermediate goods, and services) limits their ability to repay loans, thus weakening banks' balance sheets and financial stability. Banks, in turn, to comply with regulatory requirements (Basel III) tighten firms' access to credit and thus limit their new investments. In this context, the additional government spending is less effective because the economy does not offer the production capacities to satisfy public demand. Finally, the compound risk scenario shifts the window for government spending to be effective (Figure 4b and 4d).

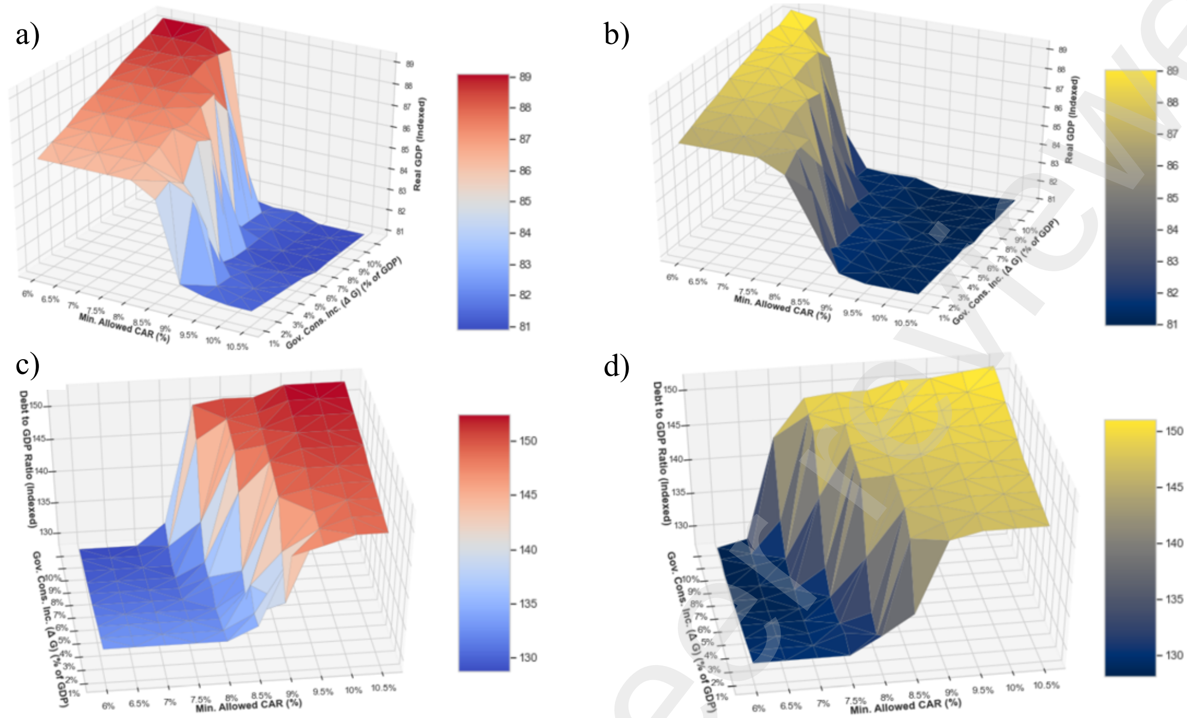

Figure 4: *Sensitivity of real GDP (upper graphs (a and b)) and debt to GDP ratio (lower graphs (c and d)) to an increase in government spending and stronger credit constraints (represented by a minimum required capital adequacy ratio (CAR)) 5 years after the shock. The red blue surface plots refer to the COVID-19 only scenario (SC2). The blue yellow surface plots refer to the compound COVID-19 and strong hazard scenario (SC4). The y-axis shows the percentage of additional government spending (ΔG) during the COVID-19 shock. The x-axis shows the minimum required Capital Adequacy Ratio (CAR). The z-axis shows the impact on real GDP (a and b) or on the debt to GDP ratio (c and d).*

4. Conclusion

Our assessment of the macroeconomic and financial impacts of compounding COVID-19 and climate physical risks shows that the risk transmission channels are shock specific, and so are the drivers of reinforcing feedbacks in the economy and finance. The quantitative assessment of compound risk yields the following insights:

- When COVID-19 and climate physical risks compound, they trigger non-linear dynamics that amplify the magnitude of the economic shocks and their persistence over several years (hysteresis effect). In particular, when strong hurricanes compound with the COVID-

19 shock, they prevent GDP from returning to its pre-COVID GDP path in the short- to midterm.

- The pre-shock characteristics of the economy, such as the strong import and export dependency, and the presence of supply-side constraints, contribute to explain the magnitude and persistence of the shocks and the recovery pathway.
- Timely increase in government's fiscal spending, coupled with central bank's monetary policy, is crucial to support the economic recovery by replacing falling private demand, affecting banks and firms' expectations about the recovery, and thus their lending and investment decisions. However, countercyclical bank's lending and credit market constraints counteract the effectiveness of fiscal stimulus.
- Post-crisis fiscal policies that support a "business as usual" recovery create the conditions for future socio-economic and financial vulnerabilities (e.g. debt sustainability).

Therefore, introducing compound risk considerations in governments' fiscal and financial risk management is important to create the conditions for building socio-economic and financial resilience to compound risk, which could be more frequent in the future. Importantly, it would help align the current design of COVID-19 recovery policies with the countries' climate mitigation and adaptation objectives, avoiding trade-off in spending. Thus, our results support recent analyses showing that COVID-19 recovery policies do not sufficiently target climate mitigation and adaptation investments (Vivid Economics & Finance for Biodiversity Initiative, 2021), preparing the ground for future climate and financial vulnerabilities, fostering countries' divergence (Georgieva, 2021).

Reporting Summary. Additional information on research design is available in the supplementary material of this article.
Available Code and Data. Code, data analysis and figures of this study are conducted in MATLAB, R, QGIS and Python and are available from the corresponding author on request.

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