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Compounding COVID-19 and climate risks: The interplay of banks' lending and government's policy in the shock recovery

Nepomuk Dunz[a,c], Arthur Hrast Essenfelder[b,e], Andrea Mazzocchetti[b], Irene Monasterolo[c,d,*], Marco Raberto[f]

[a] *The World Bank, USA*
[b] *Ca' Foscari University of Venice, Italy*
[c] *Vienna University of Economics and Business, Institute for Ecological Economics, Welthandelsplatz 1, Wien 1020, Austria*
[d] *Global Development Policy Center, Boston University, USA*
[e] *Risk Assessment and Adaptation Strategies Division, Euro-Mediterranean Center on Climate Change, Italy*
[f] *University of Genoa, Italy*

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ABSTRACT

We assess the individual and compounding impacts of COVID-19 and climate physical risks in the economy and finance, using the EIRIN Stock-Flow Consistent model. We study the interplay between banks' lending decisions and government's policy effectiveness in the economic recovery process. We calibrate EIRIN on Mexico, being a country highly exposed to COVID-19 and hurricanes risks. By embedding financial actors and the credit market, and by endogenising investors' expectations, EIRIN analyses the finance-economy feedbacks, providing an accurate assessment of risks and policy co-benefits. We quantify the impacts of compounding COVID-19 and hurricanes on GDP through time using a compound risk indicator. We find that procyclical lending and credit market constraints amplify the initial shocks by limiting firms' recovery investments, thus mining the effectiveness of higher government spending. When COVID-19 and hurricanes compound, non-linear dynamics that amplify losses emerge, negatively affecting the economic recovery, banks' financial stability and public debt sustainability.

1. Introduction

The COVID-19 pandemic has generated a systemic economic shock that is unprecedented in scale. It affected several markets simultaneously and fast spread to public and private finance. According to the International Monetary Fund (IMF)'s World Economic Outlook (IMF, 2021), the COVID-19 recession is the deepest since the end of World War II, with 7% output loss relative to the IMF's 3.4% growth forecast of October 2019, and its consequences will likely be long-lasting. Governments and central banks have reacted in an unprecedented manner to mitigate the socio-economic impacts of COVID-19, including in low-income countries (The World Bank, 2020a).

Recent research discussed the implications of the COVID-19 crisis on public debt sustainability (Stiglitz and Rashid, 2020), on socio-economic inequality (Ahmed et al., 2020; Levy Yeyati and Filippini, 2021), and on financial stability (Andries et al., 2020; Adrian and Natalucci, 2020; Brunnermeier et al., 2020). On the banking side, Beck and Keil (2021) analysed the exposure of US banks to the COVID-19 crisis and their ability to support the economy with lending, showing that governments'support programs played an important role in lending decisions. Furthermore, a stream of research has focused on the design of public interventions during the COVID-19 pandemic and their the macroeconomic impacts (Boissay and Rungcharoenkitkul), finding that the effectiveness of government's response measures depends on the conditions of implementation (Bayer et al., 2020; Guerrieri et al., 2020),

* Corresponding author at: Vienna University of Economics and Business, Boston University, EDHEC Business School, EDHEC-Risk Institute, Austria.
E-mail address: irene.monasterolo@wu.ac.at (I. Monasterolo).

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and on who is bearing their economic costs (Kaplan et al., 2020). Cox et al. (2020) highlighted that results about the effectiveness of government's policy strongly depend on the model assumptions and design. Eichenbaum et al. (2020) and Jones et al. (2020) incorporated a SIR (acronym for susceptible-infected- recovered or removed, developed by Kermack and McKendrick, 1927) feedback mechanism to provide a dynamic interaction between economic activity and the epidemic spread.

However, three main research gaps persist in the assessment of the macroeconomic and financial impacts of the pandemic. First, macroeconomic analyses of the COVID-19 crisis have mostly focused on its direct impacts, neglecting its indirect impacts, their drivers and transmission channels to agents and sectors of the economy and finance.

The second gap regards the understanding of how adjustments in banks lending in the aftermath of the shock affect firms' investment decisions and the implementation (and success) of government's recovery policies.

Third, in several countries, COVID-19 did not happen in isolation but it compounded with climate change physical risk (Phillips et al., 2020; Zscheischler et al., 2018; Mahul, Monasterolo, & Ranger, 2021). Being climate change on the rise (IPCC, 2021), the compounding of shocks could become more frequent in the future. When shocks compound, they increase the complexity of risk and of the policy response (Battiston et al., 2020). For instance, by damaging countries' productive capacity and socio-economic infrastructures, natural hazards provide a fertile ground for pandemics to spread, potentially delaying the economic recovery, and exacerbating the long-run effects on financial stability (Mahul and Signer, 2020). Com Compound shocks' impacts are characterised by complex macro-financial feedbacks, and their evolution can be largely influenced by policy introduction and by investors' inv expectations about their outcome.

Addressing these three research gaps is crucial to inform the design of fiscal and financial policies able to strengthen resilience to compounding pandemics and climatephysical risks. Nevertheless, it introduces new challenges for fiscal and financial risk management, as well as for macroeconomic analysis, calling for an adaptation of our analytical tools (Mahul et al., 2021).

Accounting for the complexity and endogeneity of compound risk requires, on the one hand, to smooth underlying assumptions of equilibrium, market-clearing prices and agents' perfect foresight of traditional macroeconomic models. On the other hand, it requires to embed financial actors and their risk assessment in macroeconomic analyses in order to assess the feedbacks from financial risk assessment to economic and policy responses (Monasterolo, 2020). Indeed, banks' expectations about climate change and policy impacts, and their anticipation (i.e. their climate sentiments Dunz et al., 2021), can lead to a revision of lending conditions to firms, depending on firms' firms' risk exposure. The adjustment in investors' risk assessment, in turn, affects investment decisions in the economy, influencing the policy outcomes and the realisation of climate mitigation scenarios (Battiston et al., 2021).

In this paper, we further develop the EIRIN macrofinancial model (Monasterolo and Raberto, 2018; 2019) to quantitatively assess the impacts of COVID-19, either occurring as an individual shock or compounding with climate physical risks, in the real economy and credit market, considering the role of fiscal and monetary policies introduced during the pandemic crisis. Then, we analyse the sensitivity of the effectiveness of government's spending to adjustments in banks' leverage and lending conditions , and the implications on GDP recovery, banks and sovereign financial stability. We calibrate the model on Mexico, a country with high relative numbers of COVID-19 contagions and deaths (Ibarra-Nava et al., 2020). In addition, Mexico is also highly exposed to climate risks, e.g. via hurricanes, and is deeply integrated in the global value chain, thus making it a potential lchannel of cascading risk (e.g. to the USA).

EIRIN is a Stock-Flow Consistent model populated by heterogeneous interacting agents of the economy and finance, endowed with adaptive expectations about the future. The model has three useful features for the assessment of compound risk. First, it allows to capture the richness of COVID-19 and climate physical risks' direct and indirect impacts, and their transmission channels to the economy and finance. Second, it considers how the nature of risk affects agents' heterogeneous beliefs, inter-temporal preferences, and the formation of expectations and decisions in response to shocks. Third, EIRIN includes a financial sector and market connected to economic agents, thereby enabling the analysis of financial feedbacks on endogenous investment and consumption decisions, and on policy effectiveness.

The remainder of the paper is organised as follows. Section 2 describes the methodology, focusing on the main characteristics of the EIRIN model. Section 3 presents the model initialisation and calibration on Mexico data. Section 4 introduces the COVID-19, climate physical risk (focusing on hurricanes) and compound risk scenarios, while Section 5 discusses the simulation results. Section 6 concludes with policy recommendations aimed to increase the resilience to compounding pandemic and climate physical risks, and provides insights for future research.

2. Methodology

2.1. Overview

We extend the EIRIN model (Monasterolo and Raberto, 2018; 2019) to analyse how the compounding of COVID-19 and physical risk (in our analysis, hurricanes) affect the Mexican economy, its credit sector and public finance. In particular, we analyse:

- To what extent and through which channels the COVID-19 crisis impacts on banks' lending decisions and financial stability;
- How procyclical revisions of banks' lending affect firms' investment decisions and the effectiveness of government fiscal policies in the recovery process;
- The conditions for amplification of economic losses to emerge when COVID-19 compounds with climate physical risk (hurricanes).

2.2. The EIRIN model

EIRIN is a Stock-Flow Consistent (SFC) model of an open economy (Caverzasi and Godin, 2015; Dafermos et al., 2017; Dunz et al., 2021; Naqvi and Stockhammer, 2018; Ponta et al., 2018; Dafermos and Nikolaidi, 2021; Caiani et al., 2016) composed by agents and sectors, which are heterogeneous in terms of characteristics (e.g. income, wealth) and preferences, and are characterised by adaptive expectations about the future.

In particular, we can distinguish: wage and capital-income earning households, respectively represented by a working class (H_w) and a capitalist household sector (H_k); a labour intensive consumption goods producer (service sector, CGPl, abbrev. by F_L), which also includes a touristic sector (Tu); a capital intensive consumption goods producer (CGPk, abbrev. by F_K); a capital goods producer (K); a fossil-fuel mining company ($MINEOIL$) and an utility company (EN) that can produce electricity out of either fossil fuel or renewable energy; a bank (BA), a central bank (CB), a government (G) and a foreign sector (ROW), capturing imports and exports of commodities and consumption goods, as well as migrants' remittances. EIRIN's agents depart from perfect foresight in presence of deep uncertainty about climate physical risk impacts, of market imperfections (e.g. potential mispricing) and of market power (e.g. in the energy sector).

EIRIN's sectors are represented as a network of interconnected balance sheets items and calibrated on real data (when available), 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 study (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 (PD), Non-Performing Loans (NPL)), and (iii) the reinforcing feedbacks from the financial sector that are capable of amplifying shocks, thus leading to cascading economic losses.

Importantly, EIRIN models the finance-economy feedback (Gourdel et al., 2021; IIF, 2021), which allows us to translate financial actors' expectations towards pandemic and climate scenarios into adjustments in risk assessment and into the cost of capital for firms. This, in turn, affects firms' investments in the transition, and the feasibility of climate mitigation scenarios (Battiston et al., 2021). For this analysis, we tailor the EIRIN model to the characteristics of Mexico.

Our approach has several advantages for the assessment of pandemics and climate risks, either considered individually or compounding. In particular, we can:

- Identify and quantitatively assess the richness of risk transmission channels and impacts in the economy and finance;
- Embed the heuristics and behavioural patterns of agents and representative sectors that contribute to the generation of emerging phenomena and out-of-equilibrium states of the economy;
- Account for the role of heterogeneous beliefs and expectations, and for the interplay between finance and public policy, in the COVID-19 recovery trajectories;
- Consider how the uncertainty of climate risks and of pandemics (Battiston, Billio, Monasterolo, 2020) feeds into financial risk assessment and banks' reactions (e.g. banks revision of lending policy).

Fig. 2.1 shows the framework of the EIRIN economy and its capital and current account flows across sectors.[1]

2.3. Markets

EIRIN's agents and sectors interact with each other and with the foreign sector through a set of markets:

- Consumption and capital goods markets
- Labour market
- Energy market
- Raw materials market
- Bonds market
- Credit market.

The formation of demand, supply and prices in each market (except for the credit market) is independent from each other at any given simulation step. In the credit market, demand depends on the demand for capital goods. The demand rationing affects the effective demand of capital goods by the CGPl and CGPk, and by the energy company. In each market, the prices are made by the supply side as a mark-up on unit costs. In addition, in the financial market, the sovereign bond price is determined based on the existing stock of public debt, and on the performance of the real economy.

[1] For a more detailed description of all sectors, market interactions and behavioural equations, please refer to Monasterolo and Raberto (2018, 2019).

2.4. Sequence of events

The sequence of events occurring in each simulation step is the following:

1. Policy makers take their policy decisions. The *CB* sets the policy rate according to a Taylor-like rule, which targets both the inflation and the potential output, but differs from the original one in the definition of the output gap.
2. The credit market opens. The bank sets its maximum credit supply according to its equity base. If supply is lower than demand, proportional rationing is applied and prospective borrowers (i.e. the consumption goods producer F_K and F_L and the energy company *EN*) revise down their investment and production plans accordingly.
3. Real markets open in parallel. Prices of the exchanged goods or services are determined, then the nominal or real demand and supply are provided by the relevant agent in each market. Finally, transactions occur generally at disequilibrium, i.e. at the minimum between demand and supply.
4. The sovereign bond market opens. The capitalist household and the bank determine their desired portfolio allocation of financial wealth on sovereign bonds. The government offers newly issued bonds to finance a budget deficit, which includes the COVID-19 related expenditures. Then, new asset prices are determined.
5. All transactions and monetary flows are recorded, and the balance sheets of the agents and sectors of the EIRIN economy are updated accordingly (see Appendix A for the Balance Sheet matrix, the Cash flow matrix and the Net worth matrix of the EIRIN economy).

2.5. Agents and sectors' behaviour

EIRIN's agents and sectors are characterised by the following properties[2]:

Heterogeneous households (H_w and H_k). By building on Goodwin (1967) and the Lotka–Volterra's predator-prey model, households are divided into two classes; i.e., a working class (H_w) and a capitalist (H_k) income class, respectively. H_w lives on wages (Eq. (1)), while H_k earns her income out of financial markets through government bonds' coupons and firms' dividends (Eq. (2)). Furthermore, both household classes receive remittances flows from abroad. Income class heterogeneity is functional to assess the distributive effects of the policies introduced for COVID-19 and/or disaster response on the channels of inequality. All households pay their energy bills and income tax. This leaves them with Y_m^{net} as net disposable income (Eq. (3)), whereas remittances R_m sent from relatives across the world add to households' net disposable income. Households' consumption plans (Eq. (4)) are based on the Buffer-Stock Theory of savings (Deaton, 1991; Carroll, 2001), which balances the *impatience* of households of consuming all their income and wealth right away with their *prudence* about the future, thus preventing them to draw down their assets too far. This results in a quasi target wealth level that households pursue. Then, households allocate their consumption budget C_m between b etwo types of consumption goods, i.e., $\beta\, C_m$ to labour intensive and $(1-\beta)\, C_m$ to capital intensive consumption goods.

$$Y_{H_w} = (N_{high} + N_{low})\, w \tag{1}$$

$$Y_{Hk} = n_{bond}\, c_{bond} + \sum d_i \tag{2}$$

[2] For better readability we abstain from labeling variables within the same time period with a time index. Previous period's variables are labeled with the time index $t-1$.

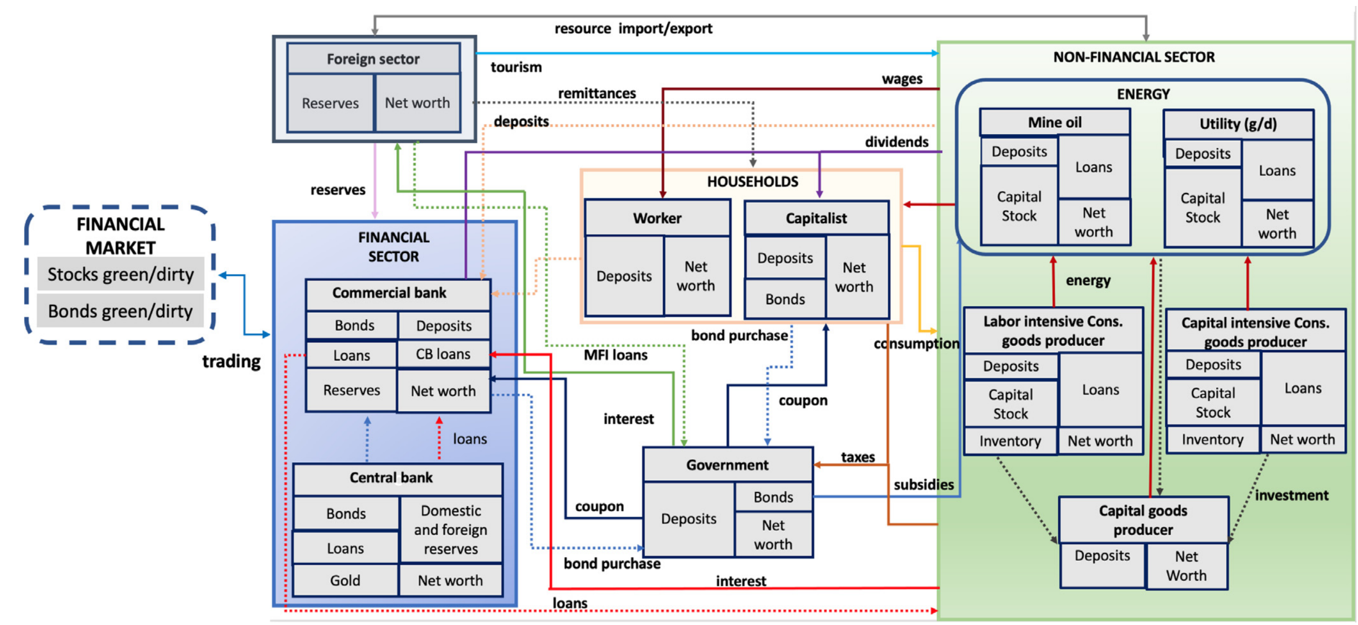


Fig. 2.1. The EIRIN model framework: capital and current account flows of the EIRIN economy. For each sector and agent, a representation in terms of assets and liabilities is provided. The dotted lines represent the capital account flows, while the solid lines represent the current account flows. The model is composed of five sectors i.e. the non-financial sector, the financial sector, households, the government and the foreign sector. The non-financial sector is composed of (i) an energy firm that supplies energy to households and to firms as an input factor for production (red solid line); (ii) capital intensive (e.g. industry) and a labour intensive (e.g. service, tourism, agriculture) consumption goods producers that provide households heterogeneous consumption goods (yellow solid line). The energy firm and the consumption goods producers require capital as an input factor for production. To build-up their capital stock, they invest in capital goods (grey dotted line), which are produced by the capital goods producer. To finance investment expenditures, firms can borrow from the commercial bank (red dotted line), which applies an interest rate to their loans (red solid line). Households, firms and the government have deposits in the commercial bank (pink dotted line). The commercial bank also holds reserves at the central bank (blue dotted line) that could provide refinancing lines (red dotted line). The government sector pays public employees. In case of COVID-19 and of climate shocks, the government provides emergency relief to households, purchases consumption goods and grants investment subsidies to firms (blue solid line). The government collects tax revenues from households and firms (brown solid line) and finances its current spending by issuing sovereign bonds (dark blue dotted line). Sovereign bonds are bought by capitalist household, by the commercial bank and by the central bank. Furthermore, the government may receive loans from Monetary Financial Institutions (MFI, green dotted line). The government pays coupons (dark blue solid line) and interest (green solid line) respectively to the sovereign bonds and MFI loans (if applicable). Households are divided into workers and capitalists, based on their functional source of income. Workers receive wage income (wine-coloured solid line). Capitalists own domestic firms for which they receive dividend income (purple solid line) and coupon payments for their sovereign bond holdings (dark blue solid line). The foreign sector provides remittances (grey dotted line) and consumption goods to households (dark grey solid line), and resources to firms as inputs for the production factors (black solid line). The foreign sector also generates tourism flows and spending in the country (grey solid line), exports of service sector and industry goods (dark green solid line) and provides financial support to the government via MFI (green dotted line). Finally, it provides reserves to the domestic central bank (light purple solid line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$Y_m^{net} = (1-\tau)\, Y_m - p_{EN}\, q_m^{EN} + R_m \tag{3}$$

$$C_m = Y_m^{net} + \rho\left(M_m - \phi\, Y_m^{net}\right) \tag{4}$$

$$C_m^{F_L} = \beta\, C_m \tag{5}$$

$$C_m^{F_K} = (1-\beta)\, C_m \tag{6}$$

with $m = H_w, H_k$. $\sum d_i$ are the dividends received by the capitalist household H_k and R_m are the remittances received by households.

Skills are heterogeneous (low/high) and uniformly distributed among workers. Capital intensive consumption goods producer and capital goods producer always employ workers with the highest skills, in exchange of higher salaries. Workers in the labour intensive consumption goods' sector require lower skills, thus receiving lower wages (Blanchard, 2017). Firms form adaptive expectations about future demand based on their sales in previous time periods. Demand expectations determine firms' production plan $\widehat{q_j^C}$. Labour demand $\hat{N}_j$ by both consumption goods producers (with $j = F_L, F_K$) is determined by their production plan $\widehat{q_j^C}$, their capital endowment K_j and by the Leontief technology.

$$\widehat{N}_j = \min\left(\widehat{q_j^C}, \gamma_j^K K_j\right) / \gamma_j^N \tag{7}$$

where γ_j^K and γ_j^N are, respectively, the sector-dependent capital and labour productivity. This setup prevents firms to hire more labour than necessary. Capital goods producer only relies on labour as input factors, and hires workers based on labour productivity to satisfy the firms' investment demand for capital goods,

$$\widehat{N_K} = \min\left(\sum_n \widehat{I_n}/\gamma_K^N,\ (1+\chi)\, N_{K,t-1}\right) \tag{8}$$

where $\hat{I}_n$ represents firms' planned investment demand γ_K^N represents labour productivity in the capital producer's sector, and χ is an exogenous parameter which limits the maximum amount of workers that can be hired by the capital producer's sector in one time period. We assume labour supply to be fully elastic and employment to be endogenously determined by labour demand. Wage setting for high and low-skilled workers is endogenous and determined according to the average workers' skills in each sector (Eqs. (10) and (9)), following a Phillips curve-like rule (Keen, 2013). The average money wage growth (Eq. (11)) depends on the employment level e (Eq. (32)), declining with rate $-\theta_1$ in case the labour force is entirely unemployed (i.e. $e = 0$), and growing with a maximum of $-\theta_1 + \theta_2$ (with $\theta_2 > \theta_1$ and $\theta_{1,2} > 0$) in case of full employment (i.e. $e = 1$). The steady state money wage, keeping the money wage constant, is given by $e = \frac{\theta_1}{\theta_2}$. The total wage bill of the economy in EIRIN $Y_w = N_{high}\, w_{high} + N_{low}\, w_{low}$ is consistent with the setting of the average wage (Eq. (11)). Thus, it is independent of labour force allocation in high and low wage sectors. Instead, it only depends on the employment level. Hence, we can prove the identity Eq. (12).

$$w_{high} = ((1-z)\, w_{\max} + z\, w_{\min} + w_{\max})/2 \tag{9}$$

$$w_{low} = ((1-z)\, w_{\max} + z\, w_{\min} + w_{\min})/2 \tag{10}$$

$$\Delta w = (-\theta_1 + \theta_2\, e) \tag{11}$$

$$N_{high}\, w_{high} + N_{low}\, w_{low} = (N_{high} + N_{low})\, w \tag{12}$$

Two consumption goods producers (F_L and F_K) produce an amount q_j^C of heterogeneous consumption goods by relying on a Leontief technology, since the model is applied to the short-term (e.g. up to 5 years). This implies no substitution of input factors (Eq. (13)), meaning that if an input factor is constrained (e.g. limited access to credit to finance investments), the overall production is proportionately reduced. In contrast, several macroeconomic models allow for substitution of input factors (elasticity of substitution equals 1) by using a Cobb–Douglas production technology. In our case, this would imply a substitution of constrained input factors such as capital stock with labour or energy, while still generating the same level of output.

$$q_j^C = \min\,(\gamma_j^N\, N_j,\ \gamma_j^K\, K_j,\ \gamma_j^{EN}\, q_j^{EN},\ \gamma_j^R\, q_j^R) \tag{13}$$

with $j = F_L, F_K$. F_L is labour intensive, meaning that $\gamma_{F_L}^N < \gamma_{F_K}^N$ but employs low-skilled workers only, receiving low wages w_{low}. F_K is more capital intensive, meaning that $\gamma_{F_K}^K < \gamma_{F_L}^K$ and employs high-skilled workers only, receiving high wages w_{high}. The two consumption goods producers set their consumption goods price as a mark-up μ_j on their unit labour costs $w_j\, N_j$, unit capital costs $r_D^j\, L_j$, unit energy $p_{EN}\, q_j^{EN}$ and unit resource costs $p_R\, q_j^R$ (Eq. (14)). Higher prices as a consequence of higher credit, imports, energy, or labour costs constrain households' consumption budgets, which in turn lower aggregate demand. This represents a counterbalancing mechanism on aggregate demand.

$$p_j^C = \frac{w_j\, N_j + r_D^j\, L_j + p_{EN}\, q_j^{EN} + p_R\, q_j^R}{q_j} \tag{14}$$

The minimum between real demand of the two consumption goods and the real supply (Eqs. (16) and (15)) determines the transaction amount $\widetilde{q}_j$ that is traded in the goods market. The supply of capital intensive consumption goods also takes firm's inventories (IN_{F_K}) into account. In case demand exceeds supply, both capitalist and worker households are rationed proportionally to their demand, whereas tourism demand is prioritised. The share of newly produced but unsold products add up to the inventory stock of F_K's inventories (IN_{F_K}). Finally, both consumption goods producers make a production plan $\widehat{q_j^C}$ for the next simulation step based on recent sales and inventory levels.

$$\widetilde{q_{F_K}} = \min\left(IN_{F_K} + q_{F_K},\ \frac{C_{H_w}^{F_K} + C_{H_k}^{F_K}}{p_{F_K}^C}\right) \tag{15}$$

$$\widetilde{q_{F_L}} = \min\left(q_{F_L},\ \frac{C_{H_w}^{F_L} + C_{H_k}^{F_L} + Tu_{F_L}}{p_{F_L}^C}\right) \tag{16}$$

An energy sector (EN) produces energy and receives demand by households and firms as an input factor for consumption and for production, respectively (Eq. (17)). The energy sector in developing and emerging countries requires large investments, access to credit and often support from government's subsidised feed-in tariffs. Therefore, it is an important sector for the analysis of shocks' transmission. Households' (H_w and H_k) energy demand is inelastic (i.e. the daily uses for heat and transportation). Firms' energy requirements depend on the sector's market share in the economy and on the overall economic business cycle. The energy company requires capital stock and oil as input factors for production. The energy price is endogenously set by the energy firm and based on a mark-up μ^{EN}, on its unit capital $r_D^{EN}\, L_{EN}$ and on the unit oil price $p_O\, q_O$ costs (Eq. (18)). The oil price p_O is assumed to be determined in international markets and thus is modelled as an exogenous variable characterised by a constant growth rate μ_o. H_w and H_k subtract the energy bill from their wage bill as shown by their disposable income (Eq. (4)). Industry transfers the energy costs via mark-ups on its unit costs to their customers (Eqs. (14) and (23)). To be able to deliver the energy demanded, the energy producer requires capital stock. EN conducts investment to maintain depreciated capital stock and to expand its capital stock to be able to satisfy new energy demand.

$$q_{EN} = q_{H_w}^{EN} + q_{H_k}^{EN} + q_{F_L}^{EN} + q_{F_K}^{EN} + q_K^{EN} \tag{17}$$

$$p_{EN} = (1 + \mu_{EN})\left(\frac{r_D^{EN}\, L_{EN} + p_O\, q_O}{q_{EN}}\right) \tag{18}$$

Endogenous investment decision. Both consumption goods producers (F_L and F_K) make investments based on the expected production plans $\widehat{q_j^C}$ that determine a target capital stock level $\bar{K}_j$. As a difference from supply-led models (e.g. Solow, 1956), in EIRIN the investment decision is fully endogenous and is based on firms' Net Present Value (NPV). This, in turn, is influenced by six factors, i.e (i) investment costs, (ii) expected future discounted revenue streams (e.g. endogenously generated demand), (iii) expected future discounted variable costs, (iv) the sector-dependent interest rate set by the commercial bank, (v) government's fiscal policy and (vi) government's subsidies. The NPV calculations allow us to compare the present cost of investments with the present value of future expected (positive or negative) cash flows (Eq. (21)). In particular, we can distinguish four cash flows: (i) a positive cash flow is given by the additional sales due to investment, and three negative cash flows, including (ii) an additional labour cost required to match the need for increased production capacity; (iii) an additional raw materials cost incurred to produce the additional output, and (iv) an extra energy requirement for producing additional output. The energy firm relies on capital and on oil as production inputs, and considers the costs of using additional oil units for an additional unit of output. This formulation helps to understand agents' intertemporal behaviour by comparing the short-term costs of investments with their long- term benefits. The sign of the NPV determines whether the agent makes the decision. The planned investment amount is set by the target capital level $\bar{K}$ considering the present capital endowment K_n subject to depreciation $\delta\, K_n$ and potential capital destruction as a consequence of climate physical shocks ξK_n (Eq. (19)). The implementation of the target investment plan is then potentially constrained by the firms' available liquidity, i.e. M_n, plus the possibility to take new debt $\Delta\, L_n$ with the bank given a constraint on the maximum allowed leverage α_n (Eq. (20)).

$$\hat{I_n} = \max\left(\bar{K_n} - (1 -\ \delta\, K_n) - (1 -\ \xi\, K_n),\, 0\right) \tag{19}$$

$$I_n \leq M_n + \Delta L_n \tag{20}$$

$$NPV_j = -p_K\, I_j + \sum_{t=1}^{+\infty} \left(\frac{\Delta\, \widehat{q_j^C}\, p_j - w_j\, \Delta\, N_{j,t} - \Delta q_j^R\, p_R - \Delta\, q_j^{EN}\, p_{EN}}{\left(1 + r_D^j\right)^t} \right) \tag{21}$$

where I_j represents real investments in new capital goods; p_K is the present price of capital goods; $\Delta\, \widehat{q_j^C}$ is the additional expected production (and sale) due to investments; p_j^C is the expected consumption goods sale price at the next tth simulation step; r_D^j is the present sector dependent loan interest rate on debt set by the commercial bank; w_j is the salary paid to workers in the consumption goods production sectors; ΔN_j is the additional amount of workers required at the next tth simulation step to match the additional production capacity due to investments; p_R is the expected raw materials price at the next tth simulation step; Δq_j^R is the additional amount of raw materials required at the next tth simulation step to match the additional production capacity due to investments; p_{EN} is the expected energy price at the next tth simulation step; Δq_j^{EN} is the additional amount of energy required at the next tth simulation step to match the additional production capacity due to investments.

A capital goods producer (*K*) produces capital goods to fulfill the production capacity of consumption goods producers and of the energy firm (Eq. (22)). The capital goods producer relies on energy and high-skilled labour as input factors that represent its unit costs. Capital goods price p_k is set as a fixed mark-up μ_k on unit costs (Eq. (23)). Newly produced capital goods will be delivered to the consumption goods producers and the energy firm at the next simulation step.

$$q_K = I_{F_L} + I_{F_K} + I_{EN} \tag{22}$$

$$p_K = (1 + \mu_K) \left(\frac{w_{high}\, N_K + q_K^{EN}\, p_{EN}}{q_K} \right) \tag{23}$$

A financial sector composed of a commercial bank sets sector-specific interest rates for granted loans. The commercial bank endogenously creates money (Jakab and Kumhof, 2015), meaning that it increases its balance sheet at every lending (i.e. the bank creates new deposits as it grants a new credit). This is consistent with most recent literature on endogenous money creation by banks (McLeay et al., 2014). A central bank sets the policy rate based on the Taylor-like rule. A sovereign bonds market determines the price and spreads for sovereign bonds by balancing demand and supply.

The commercial bank (*BA*) provides loans to the two consumption goods producers and the energy firm. The EIRIN economy money supply is displayed by the level of demand deposits. These include the deposits of worker and capitalist households, of the consumption and production sectors, of the energy firm as well as of government. Further, *BA* gives out loans to finance firms' investment plans. Depending on the firm's leverage ratio of outstanding debt to equity $\frac{L_n}{E_n}$, *BA* sets sector specific interest rates (Eq. (25)) that affect firms' capital costs and NPV decision. The maximum credit supply of the bank is set by its equity level E_{BA} divided by the Capital Adequacy Ratio (*CAR*) parameter, in order to comply to banking regulator provisions. The additional credit that the bank can provide at each time step is given by its maximum supply, minus the amount of loans already outstanding (Eq. (26)). Thus, credit demanded by firms may be rationed due to insufficient equity capital on the bank's side. In case of rationing, credit is allocated proportionally to the demand schedules of the two consumption goods firms and of the energy firm, and the effective credit received $\Delta\, L_n$ may be lower than the amount demanded. Therefore, the consumption goods firms and the energy firm can be rationed in the credit market. In case of credit rationing, firms have to scale down their investment plans, while the bank stops paying dividends in order to increase its equity capital.

$$r_D^{n,T} = r_{D,t-1}^n \left(1 + \left(\frac{\frac{L_n}{E_n} - \psi}{\psi} \right) \right) \tag{24}$$

$$r_{D,t}^n = r_{D,t-1}^n + \lambda_r\, (r_D^{n,T} - r_{D,t-1}^n) \tag{25}$$

$$\Delta\, L_n \leq \max \left(\frac{E_{BA}}{C\bar{A}R} - L_{n,t-1}, 0 \right) \tag{26}$$

where $r_{D,t-1}^n$ is the previous period sector-specific interest rate; $\frac{L_n}{E_n}$ is the n-firm's debt to equity ratio; ψ is a target debt to equity ratio *BA* considers to be acceptable without additional risk premium, $r_D^{n,T}$ is a target interest rate, while λ_r is an adjustment speed parameter, considering the fact that *BA* cannot achieve itsits target rate immediately.

A foreign sector (*RoW*) composed of: migrants' remittances sent to both households; tourism (Tu_{F_l}); raw materials ($p_{EN}\, q_{EN}^x$), consumption goods exports ($p_{F_L}\, q_{F_L}^x$, $p_{F_K}\, q_{F_K}^x$) and intermediate goods exports ($p_K q_K^x$); development finance (grants or loans) (L_{ROW}); consumption goods imports ($q_{Hm}\, p_{Rc}$); oil ($p_O\, q_O$) and raw materials supply ($p_R\, q_R$) to the domestic economy. These latter are provided in infinite supply and at a given price to meet the internal production needs. Touristic inflows consist in the consumption of labour-intensive consumption goods. Remittances are implemented as monetary flows from the foreign sector to the worker and capitalist households. Development finance (MFI) is implemented as a monetary flow to the government. Raw material, consumption goods and intermediate goods exports are a calibrated share of the country's GDP and are sold at world prices. Tourism sector demand, remittances and development finance's amount and growth rate are defined via exogenous parameters. This allows to assess the indirect impact of COVID-19 health crisis on a country's economy. Impacts are negative in case of tourism and remittances, and affect the exports of raw materials, consumption goods and intermediate goods via price or demand shocks. In this way we channel shocks from the global markets to the EIRIN economy. In contrast, impacts are positive or neutral in case of financial inflows to face the COVID-19 crisis.

A government (*G*) is in charge of implementing the fiscal policy via tax collection and public spending, including welfare expenditures, subsidies (e.g. for households' consumption of basic commodities), public sectors' workers and public consumption. To cover running expenses, the government raises taxes and issues sovereign bonds, which are bought by the capitalists , the commercial bank and the central bank. The government pays coupons on its outstanding bonds ($n_G\, c_B$) and interest on loans granted by multilateral development finance institutions ($r_{ROW}\, Loans_{ROW}$). Taxes are applied to labour income (wage), to capital income (dividends and coupons), and profits of firms. To meet its budget balance target level, the government adjusts its tax rate. In case of a budget deficit, the tax rate is increased by a fixed amount $\Delta\, \tau$. In case of a budget surplus exceeding a given threshold, the tax rate is decreased by the same fixed amount $\Delta\, \tau$. Otherwise, the tax rate τ is kept constant. Furthermore, if government's deposits are lower than a given positive threshold $\bar{M}$, i.e., $M_G < \bar{M}$, the government issues a new amount $\Delta\, n_B$ of bonds to cover the gap:

$$\Delta\, n_B = \frac{\bar{M} - M_G}{p_B} \tag{27}$$

where p_{bond} is the endogenously determined sovereign bond price. Government's spending during crises contributes to avoid a credit crunch and compensates households and firms' liquidity constraints (Brunnermeier et al., 2020). Government's spending is given by a fixed percentage of revenues deriving from tax collection:

$$G_c = \kappa \, R_G \tag{28}$$

where R_G represents the government's revenues and κ is an exogenous parameter.

A Central Bank (CB) sets interest rates, the inflation and the employment targets according to a Taylor-like rule[3] (see Monasterolo and Raberto, 2018 for details). In EIRIN, the interest rate indirectly affects households' consumption via price increase stemming from firms that adjust their prices, in case of higher credit costs. Households have a target level of wealth stemming from the Buffer-Stock Theory of saving but do not inter-temporally maximise their consumption. This prevents monetary policies to have a crowding-out effect on households' consumption. The policy interest rate depends on the inflation $(\pi - \bar{\pi})$ and on the output gaps (measured as employment gap $(u - \bar{u})$, i.e. the distance to a target level of employment $\bar{u}$), and influences agents' expectations and investments through the NPV. In particular, π is the inflation of the weighted average of consumption goods prices (Eq. (30)) between two consecutive simulation steps. The inflation gap is computed as the distance of the actual inflation π to the target inflation rate $\bar{\pi}$. The unemployment rate u is computed in Eq. (31) as the fraction of people employed in the capital goods and the two consumption goods producers of the overall labour force N_{tot}. Eq. (32) constitutes the employment rate. Furthermore, the central bank can also provide liquidity to the commercial bank in case of shortage of liquid assets.

$$r_{CB} = \omega_\pi (\pi - \bar{\pi}) + \omega_u (u - \bar{u}) \tag{29}$$

$$\pi = \frac{q^C_{F_L}}{q^C_{F_K} + q^C_{F_L}} \frac{\Delta p_{F_L}}{p_{F_L}} + \frac{q^C_{F_K}}{q^C_{F_K} + q^C_{F_L}} \frac{\Delta p_{F_K}}{p_{F_K}} \tag{30}$$

$$u = 1 - \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{31}$$

$$e = \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{32}$$

3. Model dimensioning and calibration

Mexico is a middle-income country in North America. The country is the 11th largest economy in the World, and is characterised by large regional disparity and unequal income distribution, with 46% of the population living below the poverty line (The World Factbook, 2020). The economy is highly integrated into the global value chain, where a large industry and manufacturing sector (31% of 2018 GDP, see The World Bank, 2020b) produces goods for global export markets ranging from agricultural products to intermediate and final consumption goods in the automotive, computer and electronic industries (Atlas of Economic Complexity, 2020). As such, Mexico strongly depends on international trade and on foreign direct investment (FDI), with Mexico's exports constituting 39%, imports 41% and net FDI inflows being 3.1% of its 2018 GDP (The World Bank, 2020b). The USA is Mexico's main economic partner, being its major customer country (76% of its exports, WITS (2020)). Moreover, several Mexican citizens work in the USA and send back remittances, which constitute 3% of GDP, or $37bn, being by far the highest recipient of absolute remittances flows in the region (The World Bank, 2020b). Tourism is an important sector of economic activity for Mexico (8% of 2018 GDP), and for some regions it is the main source of income. Thus, Mexico shows strong dependence on external demand as well as a slowing down economy, due to trade disputes during the Trump administration in the US, and high inflation (4% as 5 year average). The Mexican government has limited fiscal space, with debt to GDP ratios of 46% of GDP in 2018 (Trading Economics, 2020) and limited access to capital markets.

These structural characteristics of the Mexican economy contribute to increase its vulnerability to external demand shocks that arise from the spread of the COVID-19 pandemic. Thus, Mexico is an interesting case study for compound riskfr analysis.

3.1. Model calibration

We replicate the main structural macroeconomic and financial characteristics of Mexico by adapting and tailoring the EIRIN model (Monasterolo and Raberto, 2018; 2019). To do so, we collect and analyse macroeconomic data and statistical information provided by the World Bank database of world economic indicators (The World Bank, 2020b)[4]; COVID-19 data from John Hopkins COVID-19 tracker (John Hopkins University, 2021); and COVID-19 policy response information (on fiscal and monetary policy) provided by the IMF COVID-19 policy tracker (IMF, 2020). In particular, the collected data show the importance of export, tourism and remittances in Mexico's economy as sources of aggregate demand and households' income.

Second, we initialise the model to a quasi steady-state in which the core variable ratios and growth rates are stable. We dimension the simulated economy to quantitatively mimic the main macroeconomic growth rates and ratios of Mexico via core model parameter settings. This indirect inference strategy allows us to deal with limited availability of detailed macroeconomic data. The model's accounting structure, which is represented by a balance sheet, a transaction flow and a net worth matrix (see Appendix A), contributes to ensure the internal model consistency.

We present the results by comparing the model's indicators with the observed data, during a time span of 5 years. Then, we present the EIRIN model flows at the beginning of the simulation period in a Sankey diagram, showing the dimensioning of the macroeconomic flows of Mexico.

This two-step strategy helps us to justify our choice of parameters in an interactive and dynamic process, which goes through multiple rounds of testing. In addition In , it contributes to increase the validity of our results in order to draw evidence-based policy-relevant conclusions on the impact of compound COVID-19, climate cliphysical, and financial risks in Mexico.

Our study provides a methodological advancement for macro-financial risk assessment of compound risks, offering insights on weak-spots that are relevant for increasing resilience to compound COVID-19, physical and financial risks at the country level.

In particular, our calibration and dimensioning exercise focuses on:

- Macroeconomic indicators (e.g. real GDP growth rate);
- Sectors' value added;
- Relations between the domestic economy and the foreign sector (e.g. remittances and export).

We first calibrate the main macroeconomic indicators, represented by the GDP growth rate, the unemployment rate, the in-

[3] Differently from the traditional version of the Taylor rule, we do not define the potential output based on the non-accelerating inflation rate of unemployment (NAIRU). Indeed, NAIRU's theoretical underpinnings are rooted in general equilibrium theory, while EIRIN is not constrained to equilibrium solutions and focuses on the analysis of out of equilibrium dynamics. Thus, in EIRIN the output gap is proxied by the difference between actual and full employment.

[4] Due to data gaps, we for 2018 data on Mexico's debt to GDP ratio we relied on Trading Economics (2020) and Mexico's tourism to GDP ratio on Statista (2020).

Table 1
The table reports the yearly mean and standard deviation computed both on simulated and on real variables of Mexico for a time span of 5 years.

Variable name	Mean of simulated values	Standard deviation of simulated values	Mean of real values	Standard deviation of real values
Real GDP growth rate	2.13%	0.02%	2.06%	1.33%
Unemployment rate	3.8%	0.11%	3.66%	0.42%
Inflation rate	3.34%	0.01%	4.02%	1.43%
Government debt (% of GDP)	48.31%	0.71%	45.94%	1.51%
Government spending (% of GDP)	12.18%	0.02%	11.85%	0.32%

Table 2
The table reports the yearly mean and standard deviation computed both on simulated and on real variables of Mexico for a time span of 5 years.

Variable name	Mean of simulated values	Standard deviation of simulated values	Mean of real values	Standard deviation of real values
Value Added of industry sector, including manufacturing (% of GDP)	30.46%	0.08%	30.28%	0.59%
Value Added of service sector (% of GDP)	63.18%	0.13%	63.92%	0.32%

Table 3
The table reports the yearly mean and standard deviation computed both on simulated and on real variables of Mexico for a time span of 5 years.

Variable name	Mean of simulated values	Standard deviation of simulated values	Mean of real values	Standard deviation of real values
Remittances (% of GDP)	3.2%	0.02%	2.74%	0.32%
International tourism (% of GDP)	8.75%	0.06%	8.68%	0.11%
Import (% of GDP)	41.04%	0.29%	39.08%	1.63%
Export (% of GDP)	40.06%	0.26%	37.53%	1.9%

flation rate, the government debt (as % of GDP) and government's spending (as % of GDP), which are shown in Table 1.

After dimensioning the main macroeconomic indicators, we provide a detailed comparison of aggregates considering the sectors' value added, as shown in Table 2. EIRIN includes two different consumption goods producers, i.e. a labour intensive and a capital intensive producer. They are identified by by the service and the industry sectors, respectively.

The last set of variables considered in the dimensioning exercise includes indicators related to the relation of the domestic economy with the rest of the word, i.e. remittances, tourism, import and export (Table 3).

3.2. Sankey plot of the Mexican economy

We display the simulated cash flows at the beginning of the simulation run (i.e., before the shock scenarios) with a Sankey plot to ensure that the flows of the EIRIN model are consistent with its accounting framework (Fig. 3.1). The Sankey plot provides a visual representation of the distribution and proportionality of inflows and outflows among EIRIN's agents and sectors, consistently with the model initialisation and calibration.

4. Scenarios

4.1. COVID-19

The COVID-19 pandemic generated large negative socio-economic shocks in Mexico. The number of infected people (3,271,128)[5] and COVID-19 related fatalities (255,452)[6] are high (John Hopkins University, 2021)[7] despite government's COVID-19 containment measures (e.g. curfew and border restrictions) and vaccination campaign. As a result, domestic consumption and exports (which represents 39% of the Mexican economy) were estimated to decrease by 8.3% and 9.2% in 2020, respectively (OECD, 2020). International tourism, of particular itnerest to our case study, was expected to drop by 50% in 2020 in Mexico due to travel restrictions all over the world (UNWTO, 2020). Finally, remittances, which represent up 3% of Mexican GDP, were expected to drop by 19.3% in 2020 (The World Bank and KNOMAD, 2020) due to economic downturns in the host countries (especially in the USA).

The Mexican government responded with fiscal measures aimed to mitigate the negative socio-economic impacts of the COVID-19 outbreak. The measures include health and private household support, and business liquidity and guarantees, equalling to 1.2% of the country's 2019 GDP (IMF, 2020). Banco de Mexico, i.e. the central bank of Mexico, lowered its policy rate by 250 basis points and implemented monetary policy measures equivalent to 3% of 2019 GDP to ensure financial stability and sufficient market liquidity (IMF, 2020).

In our COVID-19 scenarios we include both international and domestic drivers of economic shocks, as well as government response measures (see Section 5.2 for an analysis of the results).

In addition, we analyse the effectiveness of government fiscal and monetary response measures in a given scenario when varying their magnitude (see Section 5.3 for an analysis of the results).

4.2. Climate disaster risk assessment

Hurricanes represent more than 40% of Mexico's economic losses due to climate related hazards (Guha-Sapir et al., 2009; UNISDR, 2021). 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

[5] This constitutes the 15th highest confirmed cases across the world (JHU, 2021).
[6] Mexico has with 7.7% the third highest observed case-fatality ratio across the world (JHU, 2021).
[7] As of August, 26, 2021.

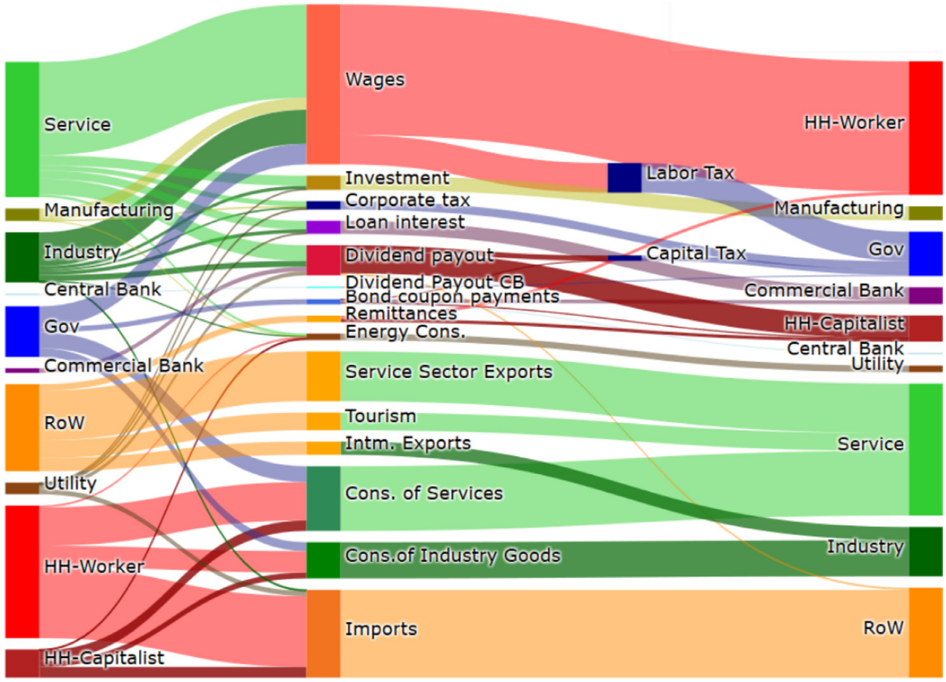


Fig. 3.1. Sankey plot of the EIRIN economy: The Sankey plot represents all current account outflows and inflows of EIRINs agents and sectors at the beginning of the policy simulation. Left and right side of the figure include the main agents and sectors of EIRIN tailored to the Mexican economy. The central part of the figure represents the use of the monetary flows. How to read the Sankey plot: moving from the left to the right side we capture, respectively, the outflows to the use and the inflows from the use to the agents and sectors. Unit of measurement: $ US Dollars.

of which affecting the tourism sector of the Quintana Roo state (CENAPRED, 2006).

The magnitude of direct damages due to hurricanes is strongly dependent on wind power and flooding, the later usually occurring as a consequence of storm surge events in coastal areas. Those hazards, in turn, 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 due to hurricane hazard, we rely on the use of a hurricane damage function proposed by Emanuel (2011) that accounts 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 (thus accounting for wind power), and; (iii) the damage potential approaches unity at very high wind speeds, and it cannot exceed unity in any event. The formulation used is shown in Eq. (33) (Emanuel, 2011):

$$F_{index} = \frac{\nu^3}{1+\nu^3} \qquad (33)$$

$$\nu = \frac{\max\left(\left(W_{spd} - W_{thresh}\right), 0\right)}{W_{half} - W_{thresh}}$$

The damage function in Eq. (33) allows to translate wind speed into direct damages to capital stock via the cubic power of wind speed on the physical grounds. It defines a lower bound threshold W_{thresh} of no damage occurrence and a value W_{half} where half of the damages occur. In order to apply Eq. (33) to Mexico, we use open-access data from the EM-DAT disaster risk database, covering the past 30 years (1990–2020) to calibrate the damage function in Eq. (33). We consider the range of possible values for W_{half} as discussed in Emanuel (2011) and Ishizawa et al. (2019), retaining those between 225 and 320 km/h, while also using as initial value of W_{thresh} the value of 92 km/h, as in Emanuel (2011). We estimate W_{thresh} to be 65 km/h and W_{half} to occur at a wind speed value of 253 km/h.

The damage potential from hurricane events are also strongly dependent on their landfall area and track. Indeed, 2004 ranks among the costliest Atlantic hurricane seasons, while Mexico was barely hit during that season; in contrast, 2007 was a slightly above-average Atlantic hurricane season (not being ranked among the top ten costliest Atlantic hurricane seasons) but causing major socio-economic impacts in Mexico (e.g. hurricane Dean in 2007 caused major damages in Mexico in the order of USD 180 million).

In order to quantify the potential direct damages to capital stock due to hurricanes in Mexico, we perform a probabilistic risk assessment of direct hurricane damages over the country. 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 provides a series of probabilistic wind hazard maps at 0.25° resolution and for the return periods of 1 in 50, 100, 250, 500, and 1,000 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). We account for the return period of 1 in 10 years by interpolating the wind speed data from the available expected frequencies using a logarithmic regression function fitted independently for each spatial cell. We then calculate the damage index factor, F_{index} as shown in Eq. (33), to obtain the relative impact potential with respect to different levels of sustained wind speed, ranging between 0 and 1. Results are shown in Fig. 4.1.

Country-wise, considering the above mentioned probabilistic approach, we estimate that a mild-impact hurricane (i.e. 1 in 50-year event) results in the destruction of 0.43% of the productive capital stock in Mexico, while a large-impact natural hazard shock (i.e. 1 in 100-year event) destroys 0.98% of the productive capital stock (see Section 4.2 for details).

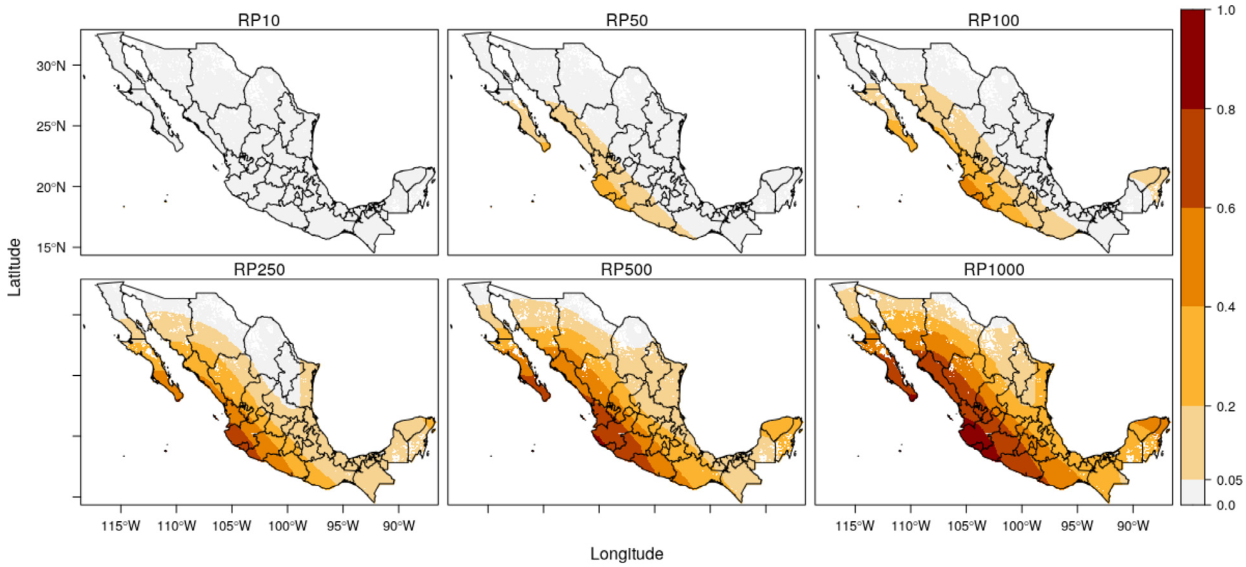


Fig. 4.1. Damage index factor, Findex, computed for six different hurricanes return periods in Mexico based on UNEP-GRDP data (Cardona et al., 2015; UNISDR, 2015).

Table 4
Selected state contribution and damages for a mild (R 1–50 year) and strong (R 1–100 year) hurricane in Mexico.

State	Role for country	Share of total Mexican GDP	RP 1–50 year	RP 1–100 year
Mexico City	Capital, Most important cultural, political and economic city in Mexico	17.67%	1.09%	3.2%
Quintana Roo	Tourism	1.62%	0.25%	0.44%
Guerrero	Tourism	1.36%	0.47%	0.68%
Oaxaca	Tourism	1.476%	0.12%	0.3%
Nuevo Leon	Industrial Production	7.65%	0.01%	0.11%
Coahuila	Industrial Production	3.44%	0.00%	0.04%
Jalisco	Electronic and Textile Industry	6.82%	1.47%	2.86%
Campeche	Mining	2.99%	0.03%	0.19%

Being Mexico a large country with a diversified economy and heterogeneous distribution of population and assets, the country is heterogeneously exposed to hurricane hazard. In order to select the most relevant economic and touristic states in Mexico in terms of exposure to hurricanes (see Table 4), we first obtain Mexican state-level GDP from the Mexican Statistical Institute (2020). Then, we identify the Mexican state-level that are more exposed to hurricane events by spatially analysing the probabilistic wind speed data obtained from UNEP-GRDP database (Cardona et al., 2015; UNISDR, 2015). Finally, we use the relative contribution of those states to total Mexican GDP to rank potential damages to those states that contribute the most to economic activities, including tourism, in Mexico. As a result, 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. Results are shown in Table 4.

The direct impacts from hurricanes are just one facet of the total damages from this kind of extreme weather events. Indirect damages often follow a hurricane event, in particular when landfall occurs over populated area. Indirect damages occur mainly due to business interruption, shutdown of touristic attractions, and the cancellation of touristic reservations, potentially leading to lower productivity and increased unemployment. For instance, in the case of hurricane Wilma, more than 60% of the total damages are attributed to indirect losses (CENAPRED, 2006). To capture the transmission channels of direct damages into indirect losses due to hurricanes in the identified Mexican cities, we shock the EIRIN model with the estimated relative productive capital stock destruction, as shown in Table 4. Shocks are assumed to occur in the fourth quarter of 2020, as the hurricane season in Mexico usually lasts from the end of June until the end of November[8].

We develop four shock scenarios (Fig. 4.2) to isolate the effects of COVID-19 and climate climaphysical risks (i.e. hurricanes) on the Mexican economy and finance, as well as to assess how impacts change when the the shocks compound. We consider two dimensions of the COVID-19 and hurricane shocks. First, both shocks occur as individual events or in sequence. Second, the climate physical risk shock is set to be either mild (i.e. 1 in 50-year event) or strong (i.e. 1 in 100-year event), thus resulting in different impacts on the productive capacity of firms in the EIRIN economy.

COVID-19 impact scenarios are formulated on estimates obtained from a several official data sources. Impacts include exports (−9.19%), remittances (−19.3%), tourism (−50%) and domestic consumption reductions (−8.26%). COVID-19 fiscal and monetary response measures are taken from the IMF Policy Tracker. We then compare the scenario outcomes to a business as usual (BAU) scenario, where no shocks occur. In addition, we assess the relevance of governments fiscal measures for economic recovery (see Section 5.3), considering varying levels of government spending during the crisis ΔG.

We contrast results with constraining factors such as banks credit supply (represented by the capital adequacy ratio (CAR)),

[8] NOAA (2020).

Scenario No	COVID-19 Lockdown and Policy-response measures	Natural Hazard Occurrence	Graphical Representation
1 Strong hazard	No	Timing: Q4 2020 Impact Size: ς_H = 0.98%	
2 COVID-19 emergency	**Impact from RoW:** • Remittances: **-19.3%** (World Bank & KNOMAD) • Tourism: **-50%** YTD (June 2020) UNWTO • Exports: **-9.19%** (OECD Economic Outlook Double Hit Scenario September 2020) **Impact from domestic economy:** • Private consumption: **-8.26%** (OECD Economic Outlook Double Hit Scenario September 2020) **Gov response measures** (IMF) : *Fiscal:* • Government support increase: **1.2%** of 2019 GDP *Monetary* • Policy rate reduction by **250bps** • Measures to support the financial system: **3.3%** of 2019 GDP	No	
3 Compound COVID-19 and mild hazard		Timing: Q4 2020 Impact Size: ς_L = 0.43%	
4 Compound COVID-19 and strong hazard		Timing: Q4 2020 Impact Size: ς_H = 0.98%	

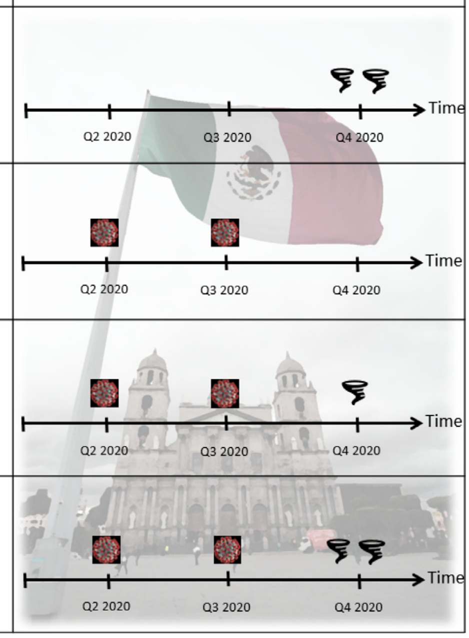


Fig. 4.2. Compound COVID-19 and climate risk scenarios: Affected sectors by COVID-19 and hurricanes occurrence and respective shock sizes.

showing the relevance of financing conditions and access to credit in the disaster aftermath.

5. Results

We exploit the EIRIN model's characteristics to analyse (i) the direct and indirect impacts, and their risk transmission channels, (ii) the interplay between private finance, public policies and economic growth, considering the sensitivity of public spending effectiveness to different levels of credit constraints, and (iii) the sensitivity of intervention points.

5.1. Risk transmission channels

We 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 (Fig. 5.1), 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 indirect impacts that give rise to spillover effects in the economy, public and private finance, conditioned to the type of shock and the country's economic and financial characteristics. Our analysis builds on a stream of recent literature (Battiston et al., 2017; Battiston and Monasterolo, 2020; Gallagher et al., 2021; Semieniuk et al., 2021; Volz et al., 2020; Mahul et al., 2021).

Hurricanes enter the economy by destroying productive capital, which affects firms' production (direct impact), because 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, and thus start to lay-off people, increasing unemployment. This, in turn, directly affects households' income and indirectly lowers workers' wage bargaining power. Lower households' consumption negatively affects real GDP. Note that different sectors are impacted differently by an hurricane shock, allowing the capital goods production sector to use unused capacity to serve the additional investment demand.

COVID-19 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. 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, households' 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 lead to increases in government's deficit, requiring new public debt (i.e. sovereign bonds issuance) to finance the COVID-19 spending. Lower GDP and higher sovereign debt move the public 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 crises.

Private finance: negative economic conditions increase firms' leverage ratios and their probability of default. As a consequence, banks tighten the credit conditions to firms, increasing their capital costs. A wide range of investment projects become unprofitable, with negative implications on firms' new investments.

5.2. Simulation results: macroeconomic indicators

In this section, we present the results of the assessment of compound risk on main macroeconomic indicators for Mexico (see Fig. 4.2 for details).[9]

A single hurricane hazard (SC1) destroys productive capital stock, entering the EIRIN economy as a supply shock. The temporary shortage of production capacity negatively affects GDP (Fig. 5.2). Since domestic and foreign demand are high when the hurricane hits, firms face a shortage in production capacity to fulfill aggregate demand. The high demand supports firms' investment in reconstruction investments to rebuild the damaged plants, offices

[9] The model is initialised by the model calibration (see Section 3.1)

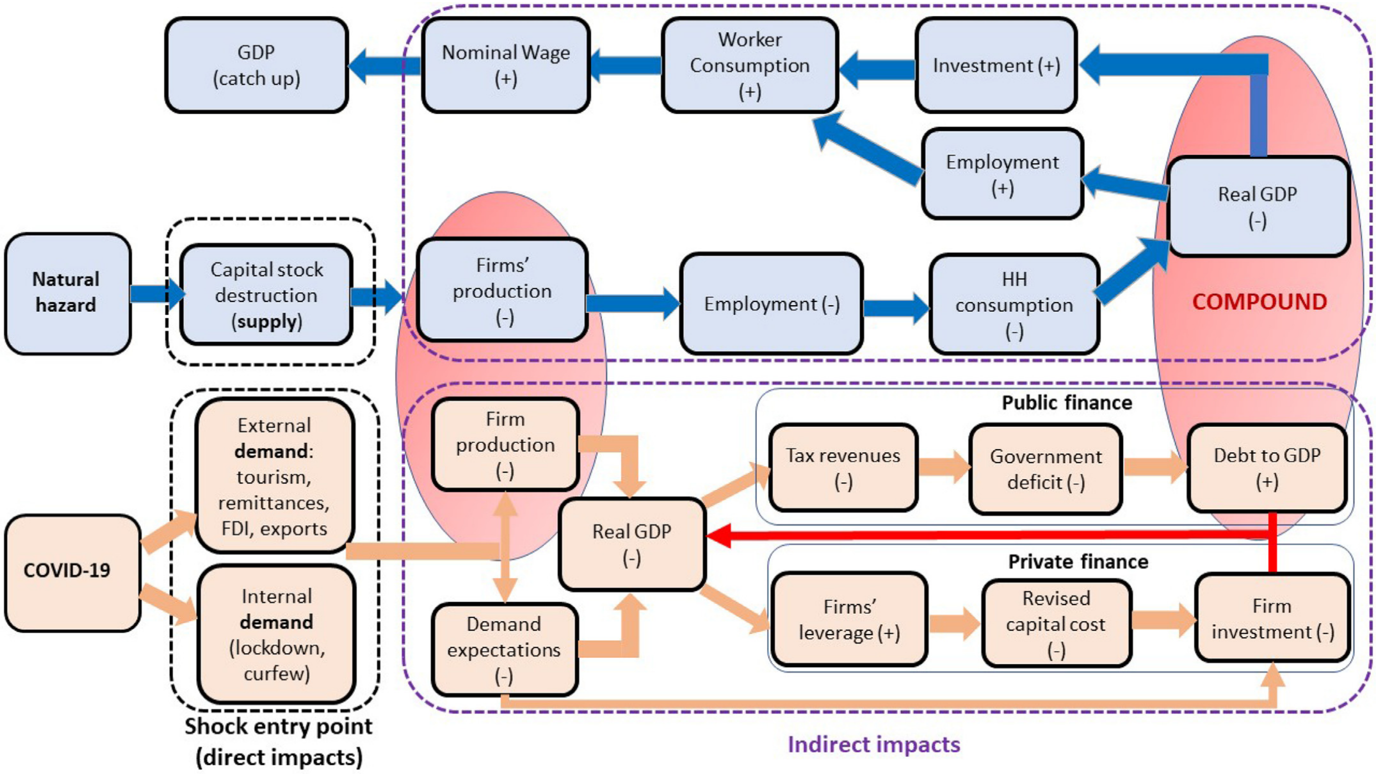


Fig. 5.1. Individual and compound risk transmission channels. The figure shows the COVID-19 and hurricanes entry points (black dotted boxes) and transmission channels to the main variables of the real economy, public and private finance. Direct impacts correspond to the input shocks considered and are identified by the black dotted boxes. In contrast, indirect impacts are identified by the purple dotted box. The red arrow shows the reinforcing economy-finance 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 supply by hitting firms' production. The shocks are transmitted in the economy via real and financial flows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

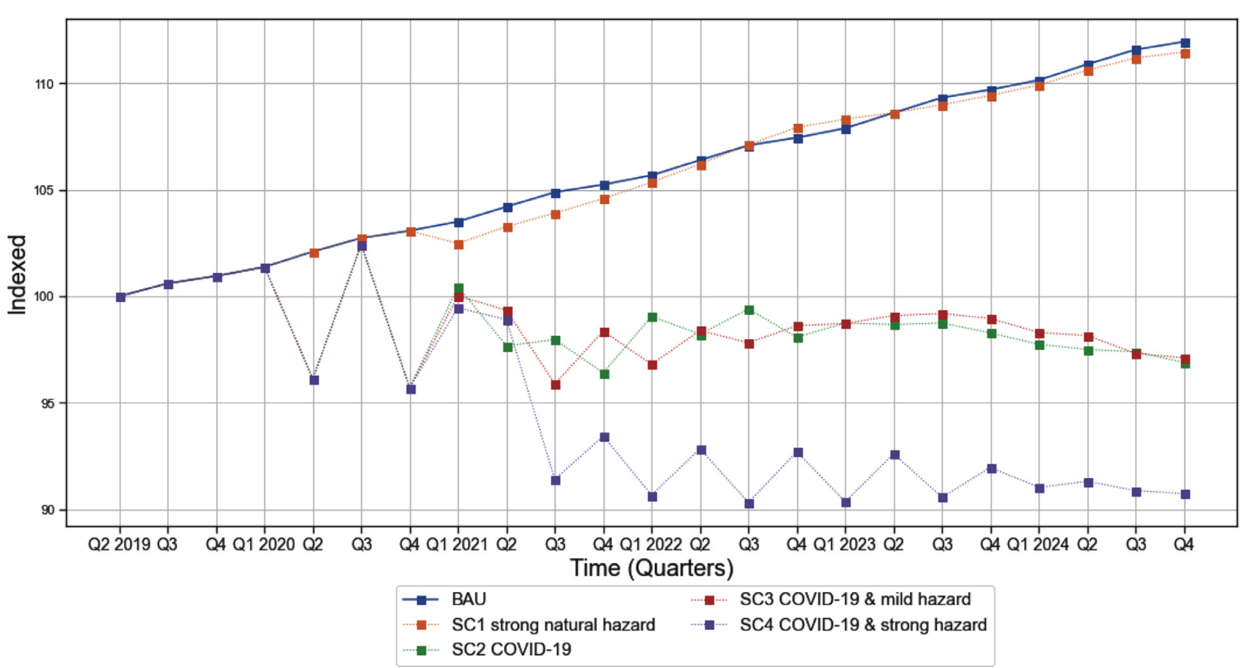
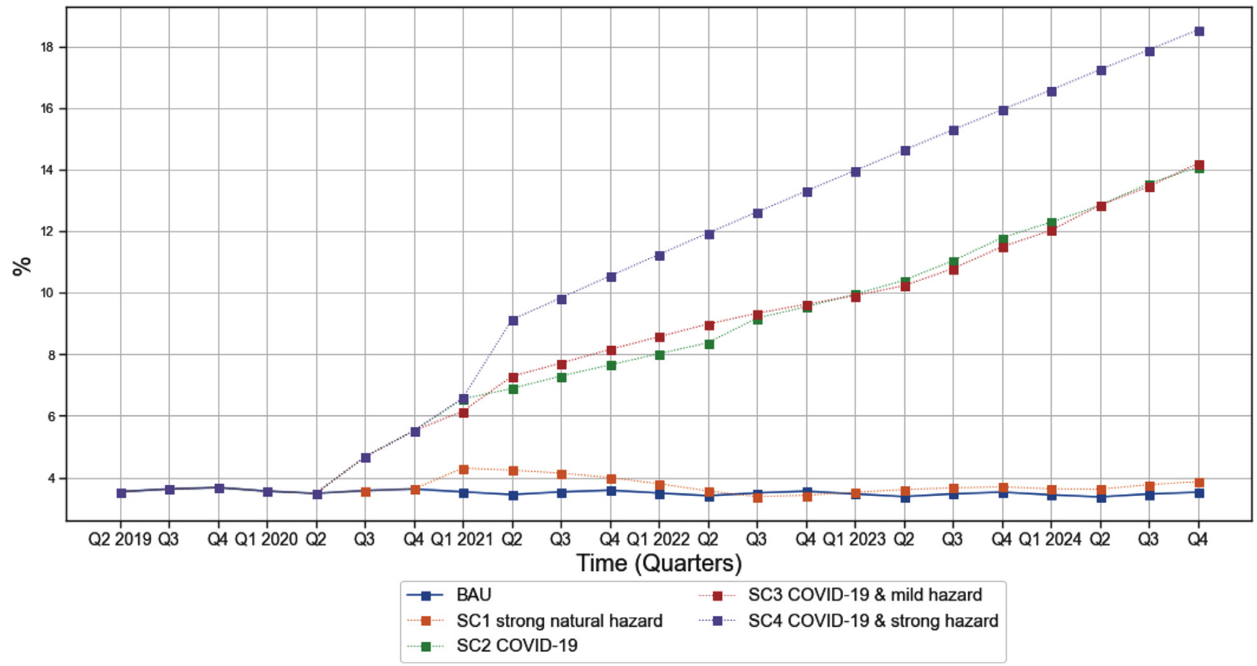
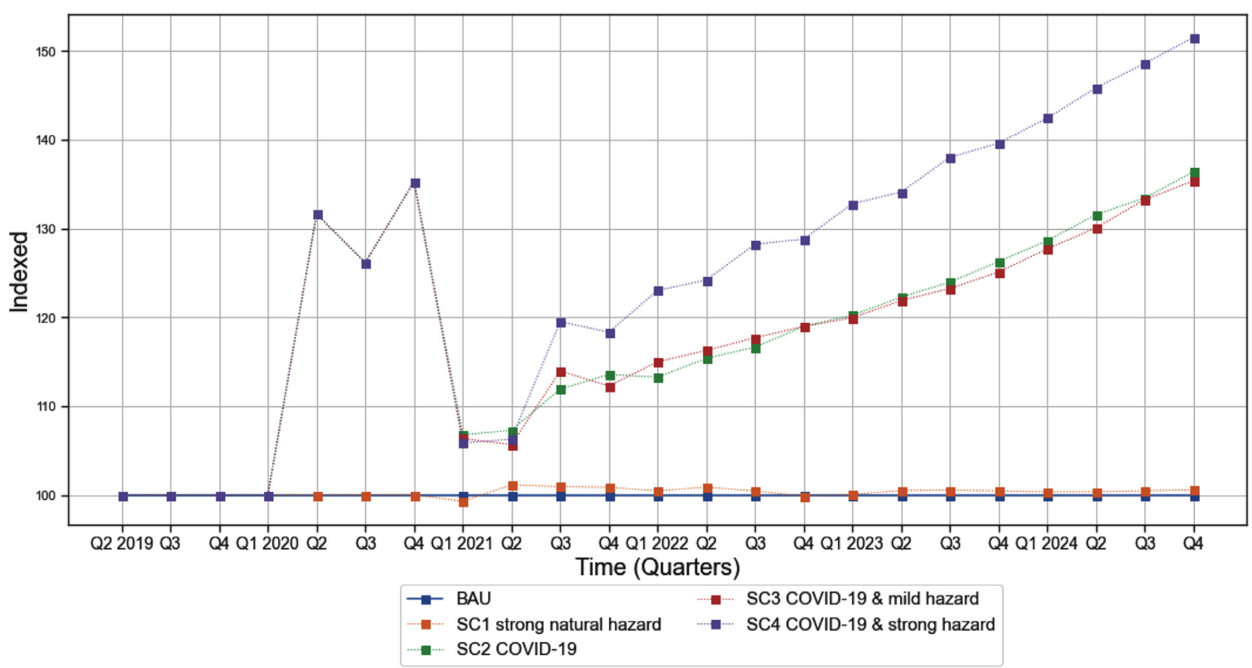


Fig. 5.2. Real GDP (5 years time span). The *x*-axis shows the timeline of the simulation lasting until the fourth quarter of 2024 on a quarterly basis. The *y*-axis shows real GDP for Mexico indexed against the 2019 pre-shock value (GDP 2019 = 100). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



(a) Unemployment Rate

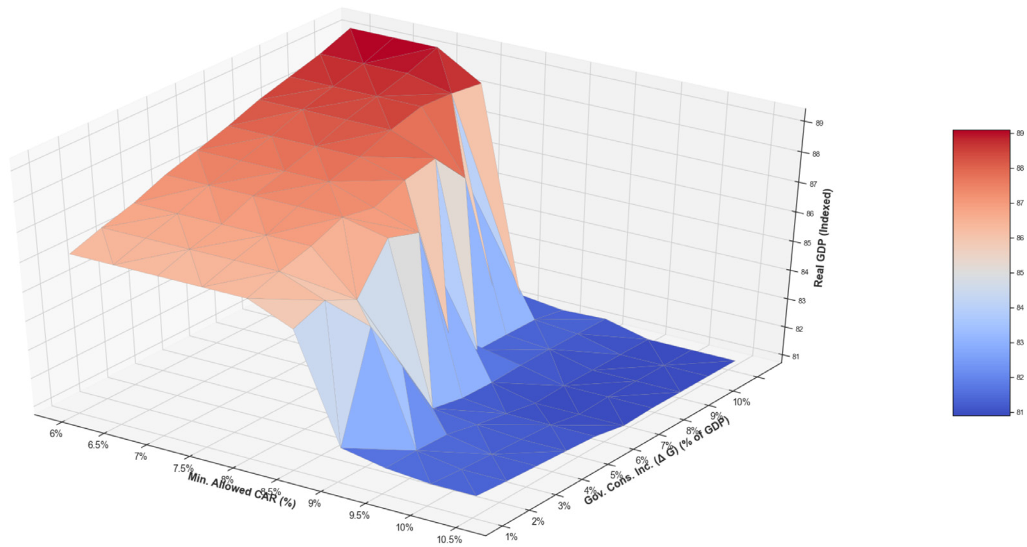


(b) Public Debt to GDP Ratio

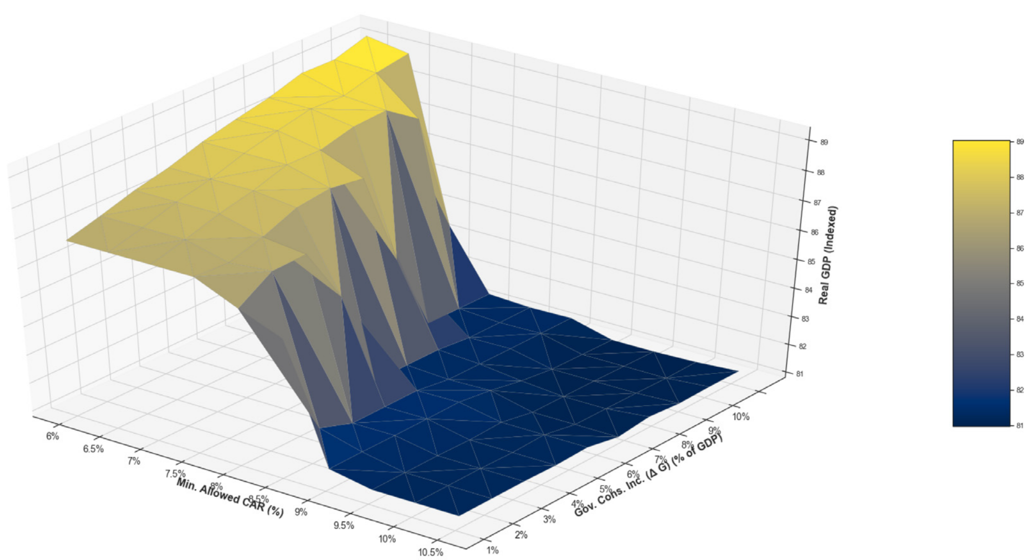
Fig. 5.3. Unemployment rate and public debt to GDP ratio (5 years time span). The *x*-axis shows the timeline of the simulation lasting until the fourth quarter in 2024 on a quarterly basis. The *y*-axis shows a) the unemployment rate (upper figure) for Mexico in percentage terms and b) public debt to GDP ratio (lower figure) for Mexico indexed against the BAU scenario considering no COVID-19 or natural hazard shock occurring (BAU = 100). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and warehouses. This allows the economy to quickly recover and GDP to catch up with the BAU GDP levels.

In contrast, the COVID-19 crisis (SC2) induces a supply and a demand shock, leading to lower domestic consumption, tourism and exports as a consequence of global lockdown that strongly hit the export-dependent Mexican economy. These direct impacts induce cascading effects in the economy via unemployment (Fig. 5.3a). The cost of government response measures, including new debt (and thus the cost of debt service) in combination with lower real GDP, leads to a higher public debt to GDP ratio (Fig. 5.3b). The increase in government bond issuance to finance the COVID-19 response measures reduces the bond price. Lower bond prices and higher sovereign bond yields, in combination with shrinking tax revenues and sustained government spending, con-



(a) Sensitivity of real GDP - COVID-19 only scenario (SC2)



(b) Sensitivity of real GDP - compound COVID-19 and strong hazard scenario (SC4)

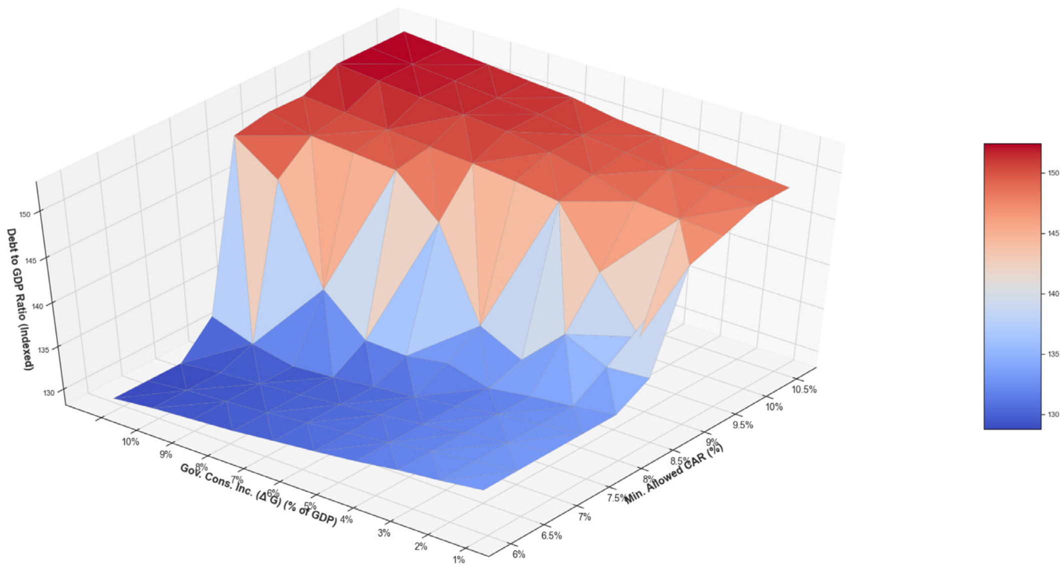
Fig. 5.4. Sensitivity of real GDP to an increase in government's spending and stronger credit constraints (represented by a minimum required CAR) 5 years after the shock. The red blue surface plot (a) refers to the COVID-19 only scenario (SC2). The blue yellow surface plot (b) refers to the compound 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 CAR. The *z*-axis shows the impact on real GDP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tribute to increase the government deficit. Thus, the direct impact of the original COVID-19 shock reverberates.

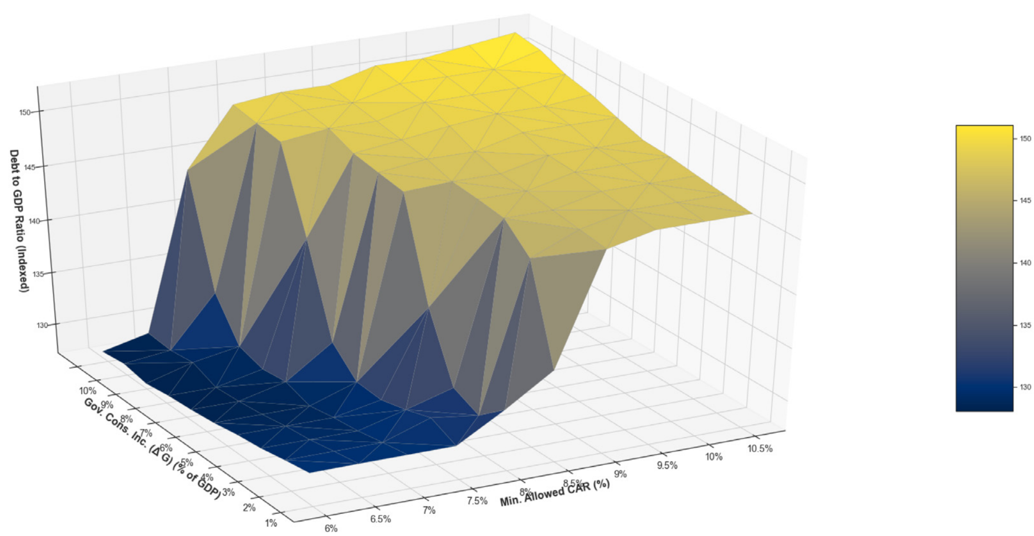
When COVID-19 compounds with hurricane (SC3 and SC4), the interaction of demand and supply side shocks leads to non-linear amplification of the direct impacts on real GDP. This is captured by the compound risk indicator (Fig. 5.8). Firms revise future demand expectations and consequently cut investments, reducing aggregate supply because no additional capacity is needed to serve the demand. Unemployment increases, wages decrease due to the Phillips curve dynamics, and the public debt to GDP ratio increases.

In summary, when COVID-19 compounds with hurricanes (SC3 and SC4), the following dynamics occur:

- The catching-up effect in the hurricane scenario (SC3) occurs in presence of mild hurricane damages (compared to the COVID-19 scenario). In contrast, a strong hurricane prevents the economy from catching-up (SC4);
- The amplification of the effect of strong hurricane damages that compound with COVID-19 (SC4), compared to the hurricane only scenario (Fig. 5.2), highlights the existence of non-linearity of impacts (Fig. 5.8).



(a) Sensitivity of the debt to GDP ratio - COVID-19 only scenario (SC2)



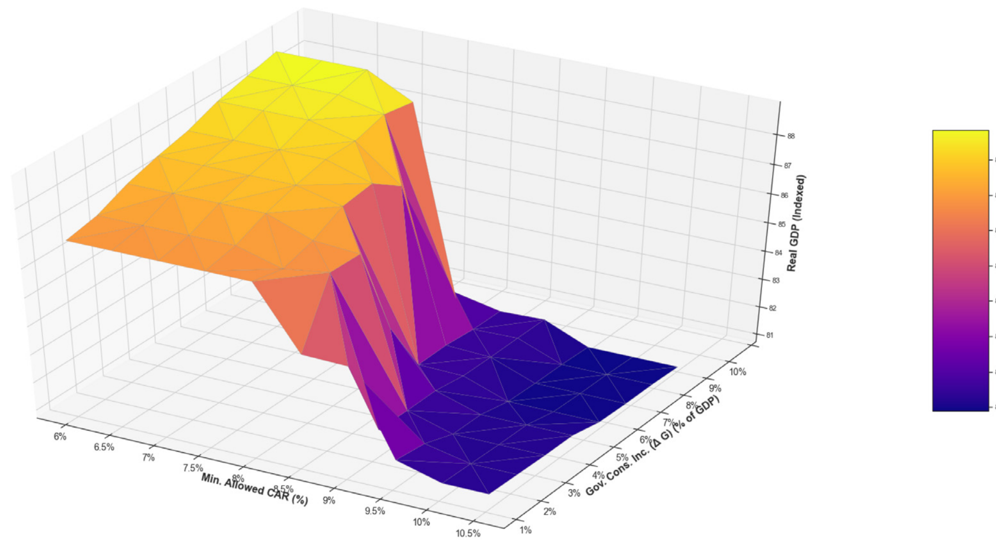
(b) Sensitivity of the debt to GDP ratio - compound COVID-19 and strong hazard scenario (SC4)

Fig. 5.5. Sensitivity the debt to GDP ratio to an increase in government's spending and stronger credit constraints (represented by a minimum required CAR) 5 years after the shock. The red blue surface plot (a) refers to the COVID-19 only scenario (SC2). The blue yellow surface plot (b) refers 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 CAR. The *z*-axis shows the impact on the debt to GDP ratio. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

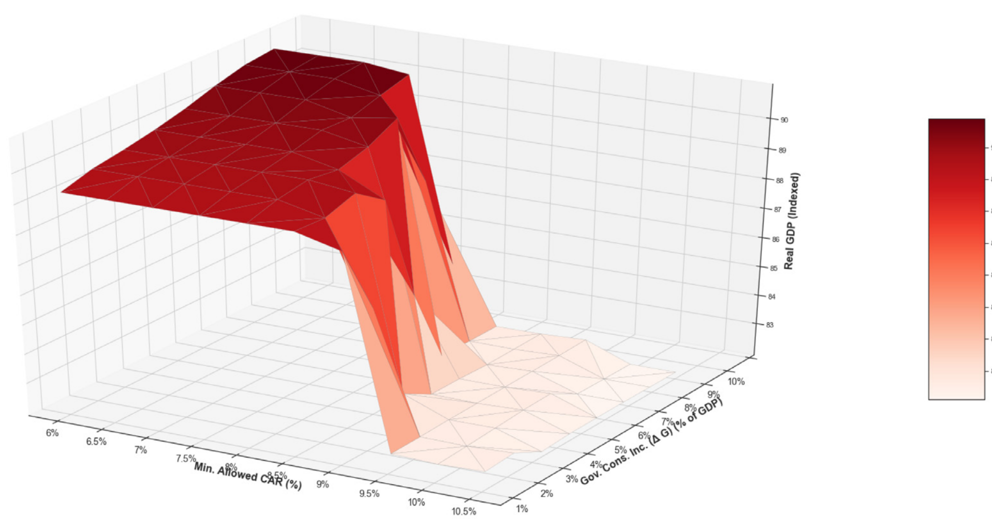
5.3. Simulation results: government's response and credit constraints

Governments and central banksand call over the world responded in an unprecedented way to the COVID-19 pandemic with fiscal and monetary policies, respectively (The World Bank, 2020a). In this section, we analyse the impact of varying government's fiscal efforts on the recovery process. Furthermore, we consider scenarios characterised by fiscal and monetary policy coordination. We assess the effectiveness of public response measures with respect to different conditions in the credit market, i.e. the willingness and ability of banks to grant loans for firms to finance the recovery. Our aim is to investigate the conditions for effective crisis management via fiscal and monetary policies' intervention.

We conduct a sensitivity analysis of government's spending during the crisis ΔG as a percentage of Nominal GDP, considering varying levels of constraining factors (such as a minimum Capital Adequacy Ratio $\bar{CAR}$ proxying bank's credit supply, see Eq. (26)). We combine 10 feasible levels of government's spending with 10 credit market conditions for each COVID-19, hurricane or compound shock scenario. For each scenario, we obtain 100 observa-



(a) Sensitivity of real GDP - compound COVID-19 and mild hazard scenario (SC3) - fiscal policy only



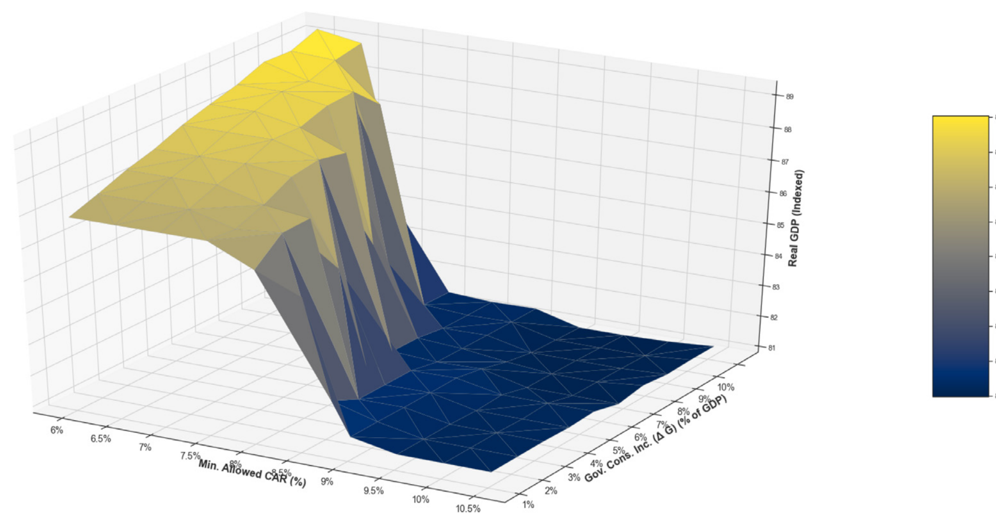
(b) Sensitivity of real GDP - compound COVID-19 and mild hazard scenario (SC3) - complementary fiscal and monetary policy

Fig. 5.6. Sensitivity of real GDP to an increase in government's spending, stronger credit constraints (represented by a minimum required CAR), with and without complementary monetary policy 5 years after the shock. The purple-yellow surface plot (a) refers to the COVID-19 and mild hazard scenario (SC3) with only fiscal policy response. The red surface plot (b) refers to the compound COVID-19 and mild hazard scenario (SC3) with monetary policy in place. The *y*-axis shows the percentage of additional government spending (ΔG) during the COVID-19 shock. The *x*-axis shows the minimum required CAR. The *z*-axis shows the impact on real GDP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

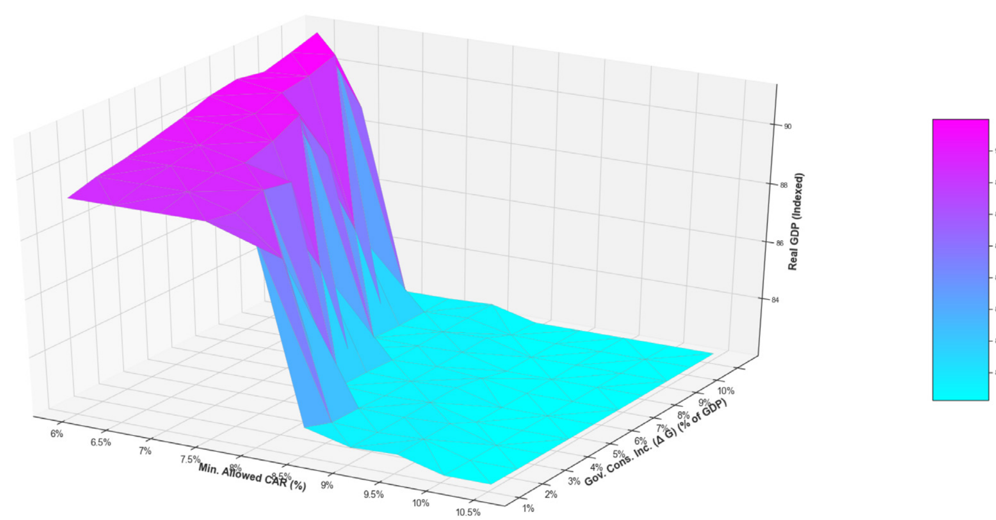
tions that show the effect on real GDP and on public debt to GDP ratio up to 4 years after the shock, as in the 3*D* plots (Figs. 5.4–5.7). Real GDP and public debt to GDP ratios are indexed against the BAU scenario. The sensitivity analysis is a powerful tool to understand the relevance of individual policy responses and their interaction with financial constraints. It also helps us to identify non-linearities, and the presence and drivers of tipping points.

Our results yield three important insights with respect to the role of banks' lending, the effectiveness of government's spending, and the role of fiscal and monetary policies' complementarity.

First, supply-side constraints in the economy, i.e. banks' pro-cyclical lending, add up to the non-linearity of economic impacts (Fig. 5.4a and b). In particular, banks' lending plays a key role in the recovery by providing liquidity and preventing firms from going out of business. In Mexico, when when banks adjust 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 long-lasting negative effects (hysteresis) as unemployment and public debt further increase, in a self-



(a) Sensitivity of real GDP - compound COVID-19 and strong hazard scenario (SC4) - fiscal policy only



(b) Sensitivity of real GDP - compound COVID-19 and strong hazard scenario (SC4) - complementary fiscal and monetary policy

Fig. 5.7. Sensitivity of real GDP to an increase in government's spending, stronger credit constraints (represented by a minimum required CAR), with and without complementary monetary policy 5 years after the shock. The dark yellow surface plot (a) refers to the COVID-19 and strong hazard scenario (SC4) with only fiscal policy response. The turquoise-pink surface plot (b) refers to the compound COVID-19 and strong hazard scenario (SC4) with complementary monetary policy in place. The *y*-axis shows the percentage of additional government spending (ΔG) during the COVID-19 shock. The *x*-axis shows the minimum required CAR. The *z*-axis shows the impact on real GDP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

reinforcing way. Overall, GDP does not catch up with pre-shocks levels, and the financial stability conditions of the country deteriorate.

Second, the increase in government spending in the aftermath of shocks provides an important stimulus to domestic demand and thus to GDP (Fig. 5.4), creating the conditions for the recovery. Additional fiscal spending does not induce a trade-off for public debt sustainability if banks keep lending (Fig. 5.5). However, there is a threshold over which the increase in government spending (i.e., over 10% of 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 in their access to credit. In addition, the worsening of firms' financial conditions in sectors affected by the hurricane (i.e. firms with productive capital located in areas exposed to the shock), and by COVID-19 (i.e. firms active in tourism, export of raw materials and intermediate goods, and services) limits their ability to repay loans. This, in turn, weakens banks' balance sheets and financial stability. Therefore, in order to comply with regulatory requirements (i.e., Basel III), banks tighten firms' access to credit and thus limit their new investments.

Finally, the coordination of fiscal and monetary policy strengthens the positive impact of government's spending on economic re-

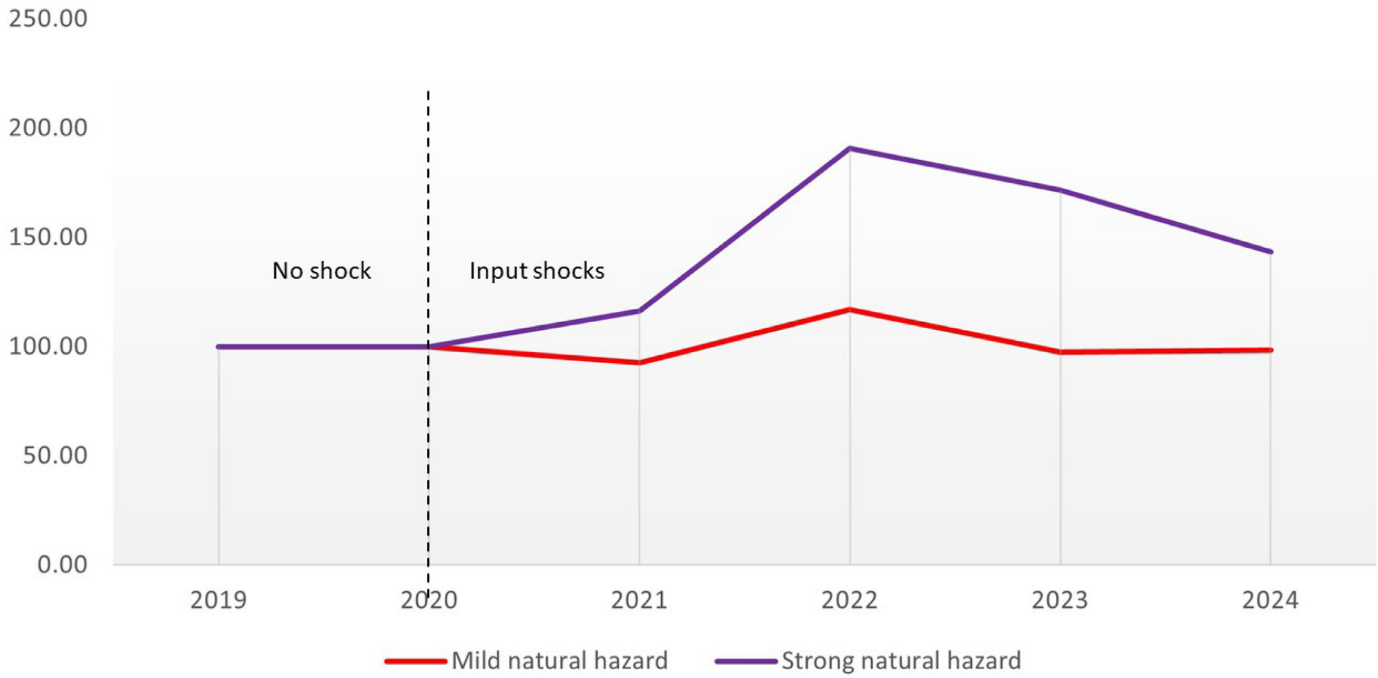


Fig. 5.8. Compound risk indicator showing the non-linear amplification effects resulting from the compounding of COVID-19 and climate shocks happening in 2020. The *x*-axis shows the timeline of the simulation until 2024 on an annual basis. The *y*-axis shows the value of the CRI indexed against the sum of the individual 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.e.: (i) COVID-19 and mild hurricane scenario (red line) and (ii) COVID-19 and strong hurricane scenario (purple line). Being an index, we do not present results in percentage terms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

covery. Our results suggest that central bank's monetary policy of lowering its policy rate has a positive effect on real GDP via price signaling (Fig. 5.6). The resulting GDP growth contributes to keep the public debt to GDP ratio under control and to improve access to liquidity. Nevertheless, the conditions for fiscal and monetary policy coordination to be effective depend on the size of the hurricane shock. If the shock is mild (SC3) (Fig. 5.6), the coordination of fiscal and monetary policy stimulates investments and consumption, and contributes to improve banks' balance sheet (i.e. to decrease decrease NPL) and their ability to lend to firms.

If the natural hazard shock is large (SC4) (Fig. 5.7), the effect of policy complementarity on the recovery is weaker. Therefore, structural adjustments in the labour and credit markets are needed to create the conditions for effective government's spending when risks compound.

Our results show that the magnitude and persistence of the COVID-19 shock in the economy depend on (i) the initial size of the shock, (ii) the credit market conditions (Figs. 5.4 and 5.5), and (iii) the coordination of fiscal and monetary policies (Figs. 5.6 and 5.7).

5.4. Compound risk indicator

With a compound risk indicator (*CRI*) we quantify the indirect impacts of compounding of COVID-19 and natural hazard (in our application, hurricanes) on GDP. We consider the potential non-linear dynamics that emerge as the result of endogenous interactions between sectors and agents of the EIRIN economy and finance. When non-linearities emerge, the shock caused by compound risks is more (or less) than the sum of the shocks generated by individual risks considered separately.

The *CRI* allows us to quantitatively assess the effects of the compound risks with respect to the individual pandemic and climate risks, as follows:

$$CRI_t = \frac{impact_{compound,t}}{impact_{natural\ hazard,t} + impact_{COVID-19,t}} \times 100 \qquad (34)$$

where the impact is measured in this application in terms of GDP loss, while the scenarios refer to COVID-19 only shock, natural hazard only shock and compound COVID-19 and natural hazard shock.

The CRI can present the following modes:

- $CRI < 100$: non-linearities emerge but the shock triggered by compound risk is lower than the sum of the individual shocks caused by the natural hazard and COVID-19 risks.
- $CRI = 100$: there is a linear relation between the shock caused by compound risk and the individual shocks resulting from natural hazard and COVID-19 risks.
- $CRI > 100$: non-linearities emerge causing the shock triggered by compound risk to be higher than the sum of the individual shocks caused by natural hazard and COVID-19 risks.

Fig. 5.8 shows the CRI in relation to the simulated scenarios. When COVID-19 compounds with the hurricane shock (SC3 and SC4), the interaction of demand and supply side shocks leads to non-linear amplification of the direct impacts on GDP. Firms revise future demand expectations and consequently revise investments downwards, reducing aggregate supply because no additional capacity is needed to serve demand. Unemployment increases, wages fall due to the Phillips curve dynamics, and the public debt to GDP ratio increases. However, the degree of non-linearity depends on the size of the hurricane shock (Fig. 5.8). A small compound hurricane shock (SC3) improves the COVID-19 situation in the short term (CRI $<$ 100), as a result of the additional investment stimulus. In the years after the shock (2022), impacts non-linearly increase (CRI $>$ 100) as the deteriorated economic conditions from COVID-19 lead to lower production capacity needs than firms anticipated before. Over-investments lead to additional private debt interest payments for slack capital stock. Both the stimulus and the over-investment are small in scale. Nevertheless, they contribute to smooth the non-linearity of compound shock impacts after 2023 (CRI = 100). A larger but less frequent hurricane shock (SC4) leads to higher non-linearity due to higher constraints, both from the labour and from the credit sides. Firms are impeded for investment by lacking access to credit, leading to non-linear shock amplification (CRI > 100) in the years to come. Therefore, risk may increase in the future as climate change is expected to shift the distribution of hurricane occurrence (IPCC, 2018) and to increase the magnitude of losses due to compound events (Zscheischler et al., 2018).

6. Conclusion

In this paper, we quantitatively assessed the direct and indirect impacts of indi the COVID-19 pandemicon the macroeconomic and credit market performance in Mexico, by further developing and calibrating the EIRIN Stock-Flow Consistent behavioral model. We analysed the impact of adjustments in banks' lending conditions on firms' investment decisions, on the effectiveness of government's fiscal policies, and on sovereign debt sustainability in the COVID-19 recovery process. Then, we assessed the macrofinancial impacts of compounding COVID-19 and climate physical risks (hurricanes), conditioned to scenarios characterised by varying magnitude and timing of climate shocks. Moreover, we studied the role of fiscal and monetary policy coordination in the shock recovery. Finally, we quantified the non-linearity of compound risk scenarios on real GDP with a compound risk indicator.

Our results yield the following policy-relevant insights:

- The risk transmission channels are shock specific and so are the drivers of reinforcing feedbacks on agents and sectors of the on economy and finance;
- Credit market constraints, i.e. banks' lending decisions, limit firms' ability to invest. Restricted access to credit imposes supply side constraints to the economy, in a similar way to the raw material shortages that are currently observed in global supply chains (e.g. computer chips);[10]
- 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 time (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 mid-term;
- Timely increase in government's fiscal spending is crucial to support the economic recovery. By replacing falling private demand, it affects banks' lending and firms' investment decisions;
- The coordination of fiscal and monetary policy strengthens the positive impact of government's spending on the economic recovery;
- However, procyclical banks' lending counteracts the effectiveness of fiscal stimulus.

Our analysis contributes to inform the design of COVID-19 recovery policies aimed to strengthen fiscal and financial resilience to future pandemics and climatic shocks. In this regard, In the introducing compound risk considerations in governments' fiscal and financial risk management to create the conditions for building resilience to compounding shocks that could be more likely in the near future. It is important that the economic analysis of compounding risks is supported by models that are able to embed financial actors and markets connected to economic agents, and both the direct and indirect impacts of shocks. This, in turn, requires to depart from strong assumptions on the structure of the economy and agents' behaviours.

The current version of the EIRIN model only indirectly includes global supply chain shocks. Their integration in the model would strenghten the assessment of cascading effects of individual or compounding shocks. Nevertheless, it would increase the model complexity, requiring the integration of Input-Output based information. In addition, the model's representation of financial markets could be extended to other type of agents and securities, and to to consider the role of financial complexity on risk amplification.

Avenues for further research in compound risk assessment may include the integration of spillover impacts of extreme weather events, which can trigger indirect economic impacts, such as the destruction of infrastructure across fine-grained supply chains. This would strengthen the assessment of cascading risks. Moreover, moving in the direction of a stress test exercise, the EIRIN model can be extended to integrate (i) a fully-fledged financial market, and (ii) a financial network model to analyse the contribution of financial interconnectedness to the amplification of losses and to the building up of systemic risk. Finally, our model can be tailored to consider other sources of risk, such as the role of biodiversity losses and ecosystems depletion in the dynamics of compound risk, thus supporting the analysis of biodiversity risk assessment.

Acknowledgements

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Appendix A. EIRIN balance sheet, transaction flow matrix and net worth matrix

Tables A.5 and A.7.

[10] In complementary analyses to the results presented in this paper, we observed that temporary labour shortages in recovery relevant sectors (e.g. the capital goods' sector) could also reduce the effectiveness of high levels of fiscal stimulus.

Table A.5
Balance sheet matrix of the EIRIN economy. Each column represents the balance sheet of an agent or sector. Assets are reported with no sign while liabilities with a negative sign. Each column always sums to zero to highlight the definition of equity (or net worth). Except for real assets, the table's rows also sum to zero to highlight the financial interlinkages among sectors, i.e. that what is a financial asset for a sector is a liability for another sector. In the matrix each subscript represents the index of the agent to which the stock refers.

	H_w	H_k	F_K	F_L	K	EN	BA	CB	G	ROW	$\sum$
Tangible capital			$p_K K_{F_K}$	$p_K K_{F_L}$		$p_K K_{EN}$					$p_K K$
Inventories			$p_{C_k} I_{F_K}$								$p_{F_K} I_{F_K}$
Gold in the vault								M_{CB}			M_{CB}
gov bonds		$p_B n_{H_k}$					$p_B n_{BA}$	$p_B n_{CB}$	$-p_B n_G$		0
Bank's loans			$-L_{F_K}$	$-L_{F_L}$		$-L_{EN}$	L_{BA}				0
CB's loan							$-L_{CB}$	L_{CB}			0
Bank's deposits	M_{H_w}	M_{H_k}	M_{F_K}	M_{F_L}	M_K	M_{EN}	$-D_{BA}$		M_G		0
CB's reserves							M_{BA}	$-M_{fiat}$		M_{ROW}	0
Equity (net worth)	$-E_{H_w}$	$-E_{H_k}$	$-E_{F_K}$	$-E_{F_L}$	$-E_K$	$-E_{EN}$	$-E_{BA}$	$-E_{CB}$	$-E_G$	$-E_{ROW}$	$-E_{EIRIN}$
$\sum$	0	0	0	0	0	0	0	0	0	0	0

Table A.6
Cash flow matrix of agents and sectors in the EIRIN economy. The matrix is divided into two sections. The first section refers to cash receipts or outlays of operating activities with an impact on net worth. The second section refers to cash flows generated by variations in real, financial and monetary assets or liabilities.

Cash flows from:	H_w	H_k	F_K	F_L	K	EN	BA	CB	G	ROW	Σ
Consumption of:											0
- goods	$-C_{H_w}$	$-C_{H_k}$	$p_{F_K} q_{F_K}$	$p_{F_L} q_{F_L}$					$-C_G$		0
- energy	$-p_{EN} q^{EN}_{H_w}$	$-p_{EN} q^{EN}_{H_k}$	$-p_{EN} q^{EN}_{F_K}$	$-p_{EN} q^{EN}_{F_L}$	$-p_{EN} q^{EN}_K$	$p_{EN} q_{EN}$					0
Imports	$-q_{H_w} p_{R_c}$	$-q_{H_k} p_{R_c}$	$-p_R q_R$							$p_R q_R + q_H p_{R_c}$	0
Exports			$p_{F_K} q^x_{F_K}$	$p_{F_L} q^x_{F_L}$		$p_{EN} q^x_{EN}$				$-p_{F_K} q^x_{F_K} - p_{F_L} q^x_{F_L} - p_{EN} q^x_{EN}$	0
Tourism				Tu_{F_L}						$-Tu_{ROW}$	0
Remittances	R_{H_w}	R_{H_k}								$-R_{ROW}$	0
Wages	Y_{H_w}		$-N_{F_K} w_{high}$	$-N_{F_L} w_{low}$	$-N_K w_{high}$				$-N_G w_{high}$		0
Interests:											
- bonds' coupons		Y^b_{Hk}					$c_B n_{BA}$	$c_B n_{CB}$	$-c_B n_G$		0
- bank's loans			$-r^{F_k}_D L_{F_K}$	$-r^{F_L}_D L_{F_L}$		$-r^{EN}_D L_{EN}$	Y_{BA}				0
- CB's loan							$-r_{CB} L_{CB}$	$r_{CB} L_{CB}$			0
Income tax	$-T_{H_w}$	$-T_{H_k}$	$-T_{F_K}$	$-T_{F_L}$	$-T_K$	$-T_{EN}$			T_G		0
Dividend payout		$Y^d_{H_k}$	$-d_{Ck}$	$-d_{Cl}$	$-d_K$	$-d_{EN}$	$-d_{BA}$				0
Seignorage								$-S_{CB}$	S_G		0
	$=$	$=$	$=$	$=$	$=$	$=$	$=$	$=$	$=$	$=$	
(Net Cash flow)	NCF_{H_w}	NCF_{H_k}	NCF_{F_K}	NCF_{F_L}	NCF_K	NCF_{EN}	NCF_{BA}	NCF_{CB}	NCF_G	NCF_{ROW}	0
	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	$+$	
Capital investment			$-p_K q^{F_K}_K$	$-p_K q^{F_L}_K$	$p_K q_K$						0
Δ Loans			ΔL_{F_K}	ΔL_{F_L}		ΔL_{EN}	$-\Delta L_{BA} + \Delta L_{CB}$	$-\Delta L_{CB}$			0
brown bond issues		$-p_B \Delta n_{H_k}$					$-p_B \Delta n_{BA}$	$-p_B \Delta n_{CB}$	$p_B \Delta n_G$		0
Δ bank's deposits	$-\Delta M_{H_w}$	$-\Delta M_{H_k}$	$-\Delta M_{F_K}$	$-\Delta M_{F_L}$	$-\Delta M_K$	$-\Delta M_{EN}$	ΔD_{BA}		$-\Delta M_G$		0
Δ CB's reserves							$-\Delta M_{BA}$	ΔM_{fiat}		$-\Delta M_{ROW}$	0
$\sum$	0	0	0	0	0	0	0	0	0	0	

Table A.7
Net worth change matrix. The matrix shows how sectors' net worth changes due to both net cash flows and the price changes of financial assets.

	H_w	H_k	F_K	F_L	K	EN	BA	CB	G	ROW
(Net cash flows Table A.6)	NCF_{H_w}	NCF_{H_k}	NCF_{F_K}	NCF_{F_L}	NCF_K	NCF_{EN}	NCF_{BA}	NCF_{CB}	NCF_G	NCF_{ROW}
Capital depreciation			$-\delta_k K_{F_K}$	$-\delta_k K_{F_L}$		$-\delta_K K_{EN}$				
Capital destruction (potentially)			$-\xi_k K_{F_K}$	$-\xi_k K_{F_L}$		$-\xi_K K_{EN}$				
Change of inventories			$p_C \Delta I_C$							
Price change of:										
- tangible capital			$\Delta p_K K_{F_K}$	$\Delta p_K K_{F_L}$		$\Delta p_K K_{EN}$				
- inventories			$\Delta p_C I_C$							
- bonds		$\Delta p_B n_{H_k}$					$\Delta p_B n_{BA}$	$\Delta p_B n_{CB}$	$-\Delta p_B n_G$	
	$-\Delta E_{H_w}$	$-\Delta E_{H_k}$	$-\Delta E_C$		$-\Delta E_K$	$-\Delta E_{EN}$	$-\Delta E_{BA}$	$-\Delta E_{CB}$	$-\Delta E_G$	$-\Delta E_{ROW}$
$\sum$	0	0	0	0	0	0	0	0	0	0

Appendix B. Accounting equations

B1. Heterogeneous households

Worker (H_w) (receiving wage income)
Changes in assets:

$$\Delta M_{H_w} = Y^{net}_{H_w} - p_{F_L} C^{F_L}_{H_w} - p_{F_K} C^{F_K}_{H_w} - IM_{H_w} \tag{B.1}$$

where IM_{H_w} is worker household consumption goods imports. Y^{net}_{Hw} is the net disposable labour income, net of energy expenses $p_{EN}\, q^{EN}_{Hw}$ and income tax payments, i.e., $Y^{net}_{Hw} = (1-\tau)\big(N_{high}\, w_{high} + N_{low}\, w_{low}\big) - p_E N\, q^{EN}_{H_w} + R_{H_w}$, where R_{H_w} are remittances, τ is the tax rate and N_{high} is the share of the labour force employed in the capital intensive consumption goods sector, in public sector and in capital goods producer sector, while N_{low} represent the share of labour force employed in labour intensive sector, i.e. $N_{high} = N_{Gov} + N_{F_k} + N_K$ and $N_{low} = N_{F_l}$.
Changes in liabilities:

$$\Delta E_{H_w} = \Delta M_{H_w} \tag{B.2}$$

where changes in workers equity ΔE_{H_w} are all reflected in workers' changes in deposits being the only way workers accumulate wealth.

Capitalist (H_k) (receiving dividend and bonds income)

Changes in assets:

$$\Delta M_{H_k} = Y^{net}_{H_k} - p_{F_L} C^{F_L}_{H_k} - p_{F_K} C^{F_K}_{H_k} - \Delta n_{H_k} p_B - IM_{H_k} \tag{B.3}$$

where IM_{H_k} is capitalist household consumption goods imports. $Y^{net}_{H_k}$ is the net disposable income, net of energy expenses $p_{EN} q^{EN}_{H_k}$ and capital income tax payments, i.e. $Y^{net}_{H_k} = (1-\tau)\left(d_{F_L} + d_{F_K} + d_K + d_{EN} + + d_{BA} + n^B_{H_k} c_B\right) - p_{EN} q^{EN}_{H_k} + R_{H_k}$ where R_{H_k} are remittances, τ is the tax rate applied to the dividends payout and bonds coupons.

Changes in liabilities:

$$\Delta E_{H_k} = \Delta M_{H_k} + \Delta n_{H_k} p_B + n_{H_k} \Delta p_B \tag{B.4}$$

where $\Delta n_{H_k} p_B$, i.e. the change in value of the bond portfolio held by the capitalist household. The change depends both on the purchase of new bonds Δn_{H_k} issued by the government and the change in bond price Δp_B.

B2. Consumption goods producers (F_L + F_K)

Changes in assets:

$$\Delta M_j = \Pi_j - d_j - p_K I_j + \Delta L_j \tag{B.5}$$

where I_j represent the investment, Π_j is the net operating profit, i.e. $\Pi_j = p_j\,(C^j_{H_w} + C^j_{H_k}) + Tu_{F_L} + G_j + p_{C_m} q^X_{C_m} - w_x N_j - p_R q_R - p_{EN} q^{EN}_j - r^j_D L_j - T_j$, with $j = F_L, F_K$ and $x = high, low$. T_j is the corporate tax, G_j is the government spending expenditures, $p_{C_m} q^X_{C_m}$ are consumption goods and intermediate exports, L_j are new loans and d_j is the total dividends payout which is set equal to the net operating profits realised at the previous time step, if positive:

$$\Delta K_j = -\delta_j K_j - \xi_j K_j + I_j \tag{B.6}$$

$$\Delta I_{F_K} = q_{F_K} - C^{F_K}_{H_w} - C^{F_K}_{H_k} \tag{B.7}$$

Changes in equity:

$$\Delta E_j = \Delta M_j + \Delta\left(p^j_C IN_j\right) + \Delta(p_k K_j) - \Delta L_j \tag{B.8}$$

Changes in consumption goods firm's equity consist of deposit changes ΔM_j, changes in its inventory valuation where $\Delta\left(p^j_C IN_j\right) = \Delta p^j_C IN_j + p^j_C \Delta IN_j$ and changes in employed capital $\Delta(p_k K_j) = \Delta p_k K_j + p_k \Delta K_j$ as well as changes in liabilities ΔL_j.

B3. Capital goods firm (K)

Changes in assets:

$$\Delta M_K = \Pi_K - d_K \tag{B.9}$$

where Π_K is the net operating profit, i.e. $\Pi_K = p_K I_K - w_{high} N_K - p_{EN} q^{EN}_K - T_K$, and we have $I_K = I_j + I_E$. d_K is the total dividend payout set equal to the net operating profit, if positive, realised at the previous time-step.

Changes in liabilities:

$$\Delta E_K = \Delta M_K \tag{B.10}$$

(A.10)

B4. Energy firm (EN)

Changes in assets:

$$\Delta M_{EN} = \Pi_{EN} - d_{EN} - p_K I_{EN} + \Delta L_{EN} \tag{B.11}$$

where Π_{EN} is the net operating profit, i.e $\Pi_{EN} = p_{EN} \sum q^{EN}_n - p_O q_O - r^j_D L_{EN} - T_{EN}$, and d_{EN} is the total dividend payout set equal to the net operating profit, if positive, realised at the previous time step.

$$\Delta K_{EN} = -\delta_{EN} K_{EN} - \xi_{EN} K_{EN} + I_{EN} \tag{B.12}$$

Changes in equities:

$$\Delta E_{EN} = \Delta M_{EN} + \Delta p_K K_{EN} + p_K \Delta K_{EN} - \Delta L_{EN} \tag{B.13}$$

B5. Commercial bank (BA)

Changes in assets:

$$\Delta M_{BA} = \Pi_{BA} + \sum_n \Delta D_n + \Delta n_{BA} p_B - \sum_n \Delta L_n \tag{B.14}$$

where Π_{BA} is the operating profit, i.e. $\Pi_{BA} = r^n_D \left(\sum_n L_n\right) - r_{CB} L_{CB} + n_{BA} c_B$, D_n are deposits and d_{BA} is the total dividend payout set equal to the operating profit, if positive, realised at the previous time step, and if the bank fulfils a capital requirement rule, i.e. its equity capital is higher than a given percentage of total outstanding loans.

Changes in liabilities:

$$\Delta D_{BA} = \Delta M_{H_w} + \Delta M_{H_k} + \Delta M_{F_K} + \Delta M_{F_L} + \Delta M_{EN} + \Delta M_K + \Delta M_{Gov} \tag{B.15}$$

$$\Delta E_{BA} = \Delta M_{BA} + \sum_n \Delta L_n + \Delta n_{BA} p_B + n_{BA} \Delta p_B - \sum_n \Delta D_n - \Delta L_{CB} \tag{B.16}$$

B6. Government (G)

Changes in assets:

$$\Delta M_G = T_{H_w} + T_{H_k} + T_{F_K} + T_{F_L} + T_K + T_{EN} + S_G - n\,c_B - G_j + \Delta n_G p_B + n_G \Delta p_B + \Delta L_{ROW} \tag{B.17}$$

where S_G represent seignorage, L_{ROW} are loans provided by international institutions to support government spending. The different tax proceedings are computed as a $\tau\%$ of the labour income, capital income and operating profits realised at the previous time step. For the sake of simplicity, we assume that the operating profits of the bank are not subject to taxation.

Changes in liabilities:

$$\Delta E_G = \Delta M_G - \Delta n_G p_B + n_G \Delta p_B \tag{B.18}$$

B7. Central bank (CB)

Changes in assets:

$$\Delta M_{CB} = r_{CB} L_{CB} - S_G - \Delta L_{CB} \tag{B.19}$$

where Seignorage S_G is set equal to the value of $r_{CB} L_{CB}$ at the previous time step.

Changes in liabilities:

$$\Delta D_{CB} = \Delta M_{BA} \tag{B.20}$$

$$\Delta FB_{CB} = \Delta M_{ROW} \tag{B.21}$$

$$\Delta E_{CB} = \Delta M_{CB} + \Delta L_{CB} - \Delta D_{CB} - \Delta FL_{CB} \tag{B.22}$$

where FB_{CB} represent foreign liabilities.

B8. Foreign sector (ROW)

Changes in assets:

$$\Delta M_{ROW} = p_R\, q_R + IM_{H_w} + IM_{H_k} - R_{H_w} - R_{H_k} - EX_{F_L} - EX_{F_K} - TU_{F_L} - \Delta\, L_{ROW} \tag{B.23}$$

Changes in liabilities:

$$\Delta\, E_{ROW} = \Delta\, M_{ROW} \tag{B.24}$$

Appendix C. Behavioural equations

C1. Heterogeneous households (H_w and H_k)

$$Y_{H_w} = \sum (N_{high} w_{high} + N_{low} w_{low}) \tag{C.1}$$

$$Y_{Hk} = n_{H_k}\, c_B + \sum d_i \tag{C.2}$$

$$Y_m^{net} = (1-\tau)\, Y_m - p_{EN}\, q_m^{EN} + R_m \tag{C.3}$$

$$C_m = Y_m^{net} + \rho\left(M_m - \phi\, Y_m^{net}\right) \tag{C.4}$$

$$C_m^{F_L} = \beta\, C_m \tag{C.5}$$

$$C_m^{F_K} = (1-\beta)\, C_m \tag{C.6}$$

with $m = H_w, H_k$.

C2. Labour market

$$w_{high} = ((1-z)\, w_{max} + z\, w_{min} + w_{max})/2 \tag{C.7}$$

$$w_{low} = ((1-z)\, w_{max} + z\, w_{min} + w_{min})/2 \tag{C.8}$$

$$\Delta w = (-\theta_1 + \theta_2\, e) w \tag{C.9}$$

$$N_{high}\, w_{high} + N_{low}\, w_{low} = (N_{high} + N_{low})\, w \tag{C.10}$$

$$\widehat{N}_j = \min\left(\widehat{q}_j^C, \gamma_j^K K_j\right)/\gamma_j^N \tag{C.11}$$

$$\widehat{N_K} = \min\left(\sum_n \widehat{I}_n/\gamma_K^N,\ (1+\chi)\, N_{K,t-1}\right) \tag{C.12}$$

C3. Consumption goods producers (F_L and F_K)

$$q_j^C = min\,(\gamma_j^N\, N_j,\ \gamma_j^K\, K_j,\ \gamma_j^E\, q_j^{EN},\ \gamma_j^R\, q_j^R) \tag{C.13}$$

with $j = F_L, F_K$.

$$p_j^C = \frac{w_j\, N_j + r_D^j\, L_j + p_{EN}\, q_j^{EN} + p_R\, q_j^R}{q_j} \tag{C.14}$$

$$\widetilde{q_{F_K}} = \min\left(IN_{F_K} + q_{F_K},\ \frac{C_{H_w}^{F_K} + C_{H_k}^{F_K}}{p_{F_K}^C}\right) \tag{C.15}$$

$$\widetilde{q_{F_L}} = \min\left(q_{F_L},\ \frac{C_{H_w}^{F_L} + C_{H_k}^{F_L} + Tu_{F_L}}{p_{F_L}^C}\right) \tag{C.16}$$

C4. Energy firm (EN)

$$q_{EN} = q_{H_w}^{EN} + q_{H_k}^{EN} + q_{F_L}^{EN} + q_{F_K}^{EN} + q_K^{EN} \tag{C.17}$$

$$p_{EN} = (1+\mu_{EN})\left(\frac{r_D^{EN}\, L_{EN} + p_O\, q_O}{q_{EN}}\right) \tag{C.18}$$

Investment decision

$$\hat{I_n} = \max\left(\bar{K_n} - (1-\ \delta\, K_n) - (1-\ \xi\, K_n), 0\right) \tag{C.19}$$

$$I_n \le M_n + \Delta L_n \tag{C.20}$$

$$NPV_j = -p_K\, I_j + \sum_{t=1}^{+\infty}\left(\frac{\Delta\, \widehat{q_j^C}\, p_j - w_j\, \Delta\, N_j - \Delta q_j^R\, p_R - \Delta\, q_j^E\, p_{EN}}{1 + r_D^j}\right) \tag{C.21}$$

C5. Capital goods firm (K)

$$q_K = I_{F_L} + I_{F_K} + I_{EN} \tag{C.22}$$

$$p_K = (1+\mu_K)\left(\frac{w_{high}\, N_K + q_K^{EN}\, p_{EN}}{q_K}\right) \tag{C.23}$$

C6. Commercial bank (BA)

$$r_D^{n,T} = r_{D,t-1}^n\left(1 + \left(\frac{\frac{L_n}{E_n} - \psi}{\psi}\right)\right) \tag{C.24}$$

$$r_{D,t}^n = r_{D,t-1}^n + \lambda_r\, (r_D^{n,T} - r_{D,t-1}^n) \tag{C.25}$$

$$\Delta\, L_n \le max\left(\frac{E_{BA}}{CAR} - L_{n,t-1}, 0\right) \tag{C.26}$$

C7. Government (G)

$$\Delta\, n_G = \frac{\bar{M} - M_G}{p_B} \tag{C.27}$$

C8. Central bank (CB)

$$r_{CB} = \omega_\pi\, (\pi - \bar{\pi}) + \omega_u (u - \bar{u}) \tag{C.28}$$

$$\pi = \frac{q_{F_L}^C}{q_{F_K}^C + q_{F_L}^C}\, \frac{\Delta\, p_{F_L}}{p_{F_L}} + \frac{q_{F_K}^C}{q_{F_K}^C + q_{F_L}^C}\, \frac{\Delta\, p_{F_K}}{p_{F_K}} \tag{C.29}$$

$$u = 1 - \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{C.30}$$

$$e = \frac{N_K + N_{F_L} + N_{F_K}}{N_{tot}} \tag{C.31}$$

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