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Schumpeterian disaggregation and integrated assessment: An endogenous, stock-flow consistent economy in disequilibrium for FRIDA v2.1

Martin B. Grimeland[1], Benjamin Blanz[2], William Schoenberg[3, 4], Beniamino Callegari[1]
[1]School of Economics, Innovation, and Technology, Kristiania University of Applied Sciences, Oslo, 0107, Norway
[2]Research Unit Sustainability and Climate Risk, University of Hamburg, Hamburg, 20144, Germany
[3]System Dynamics Group, University of Bergen, P.O. Box 7802, 5020, Bergen, 5020, Norway
[4]isee systems inc., 24 Hanover St. Suite 8A, Lebanon, New Hampshire, 03766, USA
Correspondence to: Martin B. Grimeland (Martin.Grimeland@kristiania.no)

Abstract. Integrated assessments of climate change require models capable of capturing the coupled dynamics of natural and socioeconomic systems. This paper presents the economy module of FRIDA v2.1, a Schumpeterian, disequilibrium framework of endogenous growth designed to address several limitations of contemporary integrated assessment models (IAMs). The module incorporates monetary and financial dynamics, innovation-driven productivity, and endogenous business cycles, allowing explicit representation of how climate impacts propagate through various institutional sectors and economic processes. Its process-based structure replaces aggregated damage functions with disaggregated, empirically grounded mechanisms, improving the traceability of assumptions and enabling the study of climate-finance interactions—including risks of disorderly transitions—absent from mainstream IAMs. Calibration against historical data demonstrates the model's ability to reproduce key macroeconomic developments. A 100,000-member ensemble simulation communicates the uncertainty in projections through 2150 while revealing endogenous constraints on economic activity. We show that without further action to combat climate change, expected climate impacts not only affect economic production, primarily through reduced investment growth and financial fragility, but also government budgets which come under stress owing to the increasing burdens of unemployment and demographic change. By providing a transparent, modifiable platform for simulating monetary, financial, and innovation dynamics under climate constraints, FRIDA v2.1 expands the analytical scope of IAMs and supports richer exploration of transition pathways.

1 Introduction and state of the art

Integrated assessment models (IAMs) are important tools for shaping global climate policy. At the international level, they feature heavily in the IPCC reports (IPCC, 2023) and inform climate negotiations under the UNFCCC (Science in the UNFCCC negotiations, 2025). In the United States, they are used to calculate carbon prices for policy appraisal (Rennert et al., 2022; Stern et al., 2022). In the European Union, model-based evidence of macroeconomic impacts has become a near prerequisite for accepting new climate or energy policy proposals (Pollitt and Mercure, 2018). IAMs' widespread use and growing influence

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have naturally invited scrutiny from the research community, leading to the identification of several limitations. It has been suggested that widening the underlying methodological scope is needed to overcome these limitations (Donges et al., 2021; Keppo et al., 2021; Stern et al., 2022). The FRIDA v2.1 model represents one such effort to broaden the methodological foundations of integrated assessment. The purpose of this paper is to document the economy module built for FRIDA v2.1 and its contributions to addressing some of these limitations, which are described below.

Most IAMs rely on highly aggregated damage functions, translating the complex relationships between temperature increases and economic consequences into a direct reduction in GDP. These functions' empirical foundations are limited because of data constraints, making their parametrisation highly uncertain (Farmer et al., 2015; Pindyck, 2013, 2017). Model outcomes, including policy-relevant optimal emission trajectories and the social cost of carbon estimates, demonstrate extraordinary sensitivity to damage function specifications (Gillingham et al., 2018; Hänsel et al., 2020; Nordhaus, 2019). Furthermore, owing to their aggregate nature, these damage functions operate as statistical black boxes (Pindyck, 2017). This aggregation necessarily compromises the traceability of model assumptions, making it impossible to identify how climate damage disrupts specific macroeconomic systems and sectors. The resulting opacity in model structure constrains researchers' ability to test individual assumptions and validate specific climate damage mechanisms (Elster, 2015; Meadows and Wright, 2008).

Similarly, most IAMs feature heavily aggregated economy modules. Representations of the financial system, notably, are either absent or omit the complex dynamics of credit creation, financial intermediation, and monetary policy, despite substantial literature documenting the financial risks posed by climate change (Battiston et al., 2021a; Pollitt and Mercure, 2018). Researchers have described how climate change and resulting extreme weather events pose risks to the global financial system, ranging from physical damage to financial assets to transition risks from stranded assets (Battiston et al., 2017, 2021b; Lamperti et al., 2019; Mandel et al., 2025). The mounting evidence has made financial and monetary authorities increasingly attentive to climate-related risks (Carney, 2015; Kiley, 2021; NGFS, 2019) and even prompted amendments to financial stability policies (Brunetti et al., 2021; Giuzio et al., 2019), making the inclusion of finance in IAMs timely.

In addition to understanding the vulnerability of financial systems to climate impacts, researchers call for models that are able to explore how global finance is poised to mitigate climate change. Sanders et al. (2022) noted that IAMs without finance leave "a crucial gap" in our ability to conduct macro model-based analyses of climate policy. A disorderly transition—where delayed recognition of climate risk leads to sudden, tardy action—is probable and poses systemic risks. Such a green transition could beget financial instability (Battiston et al., 2017, 2021a; Carattini et al., 2023; Garcia-Jorcano and Sanchis-Marco, 2025; Ojea-Ferreiro et al., 2024). Both Sanders et al. (2022) and Stern et al. (2022) warned that a disorderly transition could involve large and rapid changes in the price of carbon, resulting in sudden changes in asset values, triggering system-wide financial distress. These volatile dynamics are outside the scope of most contemporary IAMs because of their equilibrium assumptions and omission of finance, which leads us to the next IAM limitation: their lack of business cycle dynamics and short-term phenomena with long-term consequences.

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In the most comprehensive treatment of the topic to date, Annicchiarico et al. (2022) noted that integrating business cycles in climate policy analyses represents a frontier area where substantial research gaps remain. Empirical evidence supports the hypothesis that emissions are procyclical (Doda, 2014). This finding indicates that instruments such as a carbon tax may be more effective if adjusted to the business cycle (Annicchiarico et al., 2022). Most contemporary IAMs are ill suited for evaluating the dynamic relationship between business cycles and climate policy (Stern et al., 2022). Adequately modelling these dynamics requires the integration of short-term mechanisms within a modelling framework that has traditionally favoured a long-term perspective (Pollitt and Mercure, 2018).

Neglecting short-term volatile mechanisms has implications beyond policy assessment. For example, extreme climate events can affect both existing economic activities and planned investments (Griffin et al., 2019). This is borne out in the growing body of research documenting the financial impact of climate change, especially in regard to failure rates of investments, leading to increased bankruptcies (Bartsch et al., 2024; Carattini et al., 2023; Feng et al., 2024). These unexpected defaults produce short-term negative employment shocks and drive long-term changes in lending standards, as the financial sector adapts its future growth expectations accordingly, negatively affecting investment and therefore both quantitative growth and qualitative economic development (Dell'Ariccia and Marquez, 2006; Fishman et al., 2024; Lown and Morgan, 2006; Rodano et al., 2018).

A more realistic representation of financial and monetary mechanisms and their dynamics further supports the endogenous modelling of innovation. Stern et al. (2016) emphasised that most IAMs fail to capture the feedback loops in innovation processes, particularly the interactions across the economy that drive institutional and behavioural change. Mercure et al. (2019) extended this critique, showing that outcomes in climate–economy models are vastly different depending on how innovation is represented. They stress that innovation cannot be treated as an exogenous cost-reducing trend, as this approach fails to take into account the disruptive nature of the innovation process and its multiple feedbacks (Antonelli, 2017; Schumpeter, 1934) but should instead be endogenised within a framework that considers financial conditions, policy interventions, and other institutional dynamics—another direct call for economic disaggregation.

To address the highlighted gaps, the economy module built for FRIDA v2.1 rests on the following conceptual foundations: it is built on Schumpeterian theory, it operates in disequilibrium, all growth components are endogenous, and it features a stock-flow consistent financial architecture. These characteristics, elaborated on in Section 2, allow FRIDA v2.1 to analyse the two-way interactions of climate change through a multitude of direct and explicit impacts documented in Section 3. This opens new possibilities for understanding climate–economy interactions and evaluating policy interventions.

FRIDA v2.1, and its novel economic module documented in this paper, aims to contribute to the recent research stream addressing these limitations. One body of work particularly influential for the FRIDA project is the "coupled human and natural systems" (CHANS) modelling approach, which emphasises that human and natural systems are defined by feedbacks, thresholds, nonlinearities, time lags, and emergence and link flows of matter, energy, and information (Alberti et al., 2011; Kramer et al., 2017; Liu et al., 2007). FRIDA v2.1 takes on this approach by disaggregating climate damage functions into multiple categories (see Wells et al. (2025) for a detailed treatment of the biophysical processes behind climate losses and

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damage, as represented in FRIDA v2.1), breaking down aggregate climate impacts into tangible, observable processes that can be empirically parameterised—processes that an aggregate damage function necessarily obscures. FRIDA v2.1's economy module adopts a disaggregated process-based approach to socioeconomic modelling that integrates short-term monetary, financial and innovation dynamics in the analysis.

This documentation paper is structured as follows. Section 2 expands on the module's key conceptual foundations by establishing the theoretical rationale underlying model design choices and its attending limitations. Section 3 provides a detailed description of the module's structure across seven interconnected submodules, complete with stock and flow diagrams. Section 4 describes the calibration methodology and our protocol for the treatment of uncertainty. Section 5 presents simulation results demonstrating the model's performance against historical data and projection confidence intervals that explicitly communicate the project's inherent uncertainty. Section 6 concludes the paper with a run-through of contributions and a discussion of future applications.

2 Analytical aims and conceptual foundations

FRIDA v2.1 is a multipurpose model for climate–economy analyses and policy experimentation. Its analytical aims are to close feedback loops across human, economic, and climate systems in a process-based manner and to identify the most essential feedback processes in a climate context (Schoenberg et al., 2025b). These aims require certain considerations in the development of the model. The first consideration is the representation of multiple climate impact pathways affecting specific economic processes and actors, rather than a single aggregate damage function. The second consideration is the need to include finance and monetary mechanisms of climate damage and adaptation. The third consideration is the need to capture emergent dynamics from interactions between short-term dynamics with long-term consequences, such as financial fragility, and long-term dynamics susceptible to short-term disruption, such as innovation. The fourth consideration is to endogenously model aspects of human behavioural change relevant to the climate context. The final and fifth consideration is to enable fully endogenous simulation of all of these components without the assumption of an exogenous "social decision maker" driving investment and mitigation choices.

To achieve these analytical aims and satisfy the related requirements, the economy module of FRIDA v2.1 has been developed as a Schumpeterian disequilibrium model of endogenous growth (Antonelli, 2017; Dosi et al., 2010; Schumpeter, 1939). The Schumpeterian framework provides a consistent understanding of financial and innovation dynamics. It operates in disequilibrium to enable the analytical integration of short-term and long-term dynamics and their interactions. Growth and innovation are treated as endogenous to evaluate the consequences of climate damage and climate policy for productivity growth and the opportunities offered by productivity growth for mitigation and adaptation purposes. The following paragraphs elaborate on these characteristics in turn.

While it is possible to include financial mechanisms in IAMs on the basis of a real analysis approach (see Adelman & Yeldan (2000) for an exogenous solution), it would have excluded the modelling of endogenous short-term systemic crises with enduring consequences. Owing to the potential relevance of these mechanisms for the analysis of the economic consequences of climate change, we opted to integrate them within the context of a monetary, stock-flow-consistent (SFC) approach, as suggested by Pollitt and Mercure (2018). We further adopted Keppo et al.'s (2021) recommendations to track debt accumulation, borrowing capacity, and interest rates to assess the potential disruptive effects of climate risks and transitions. This has the further benefit of enabling FRIDA to evaluate the inflationary consequences of both climate damage and climate policy.

To represent disequilibrium dynamics, the classical aggregate production function is replaced by a dynamic circular income flow framework, depicting a disaggregated ensemble of firms, owners and workers (Schumpeter, 1934). Eschewing the equilibrium approach and its inbuilt assumptions is required in light of the idiosyncrasies affecting the economic analysis of climate change. The significant uncertainty affecting climate change dynamics, the global nature of the problem, and its complex social and distributional aspects imply significant associated market failures (Stern et al., 2022). Even if market instruments could work perfectly, these instruments are either in their infancy or simply missing (Stern, 2022). While methodologically convenient, equilibrium assumptions are inconsistent with the defining characteristics of the analytical issue at stake. Since the process-based methodology adopted for FRIDA 2.1 allows for the construction of disequilibrium models (Cavana, 2021), we developed FRIDA 2.1 accordingly.

Endogenous growth is a requirement for any model aiming to provide a viable environment for policy analysis. The Schumpeterian approach to the analysis of growth focuses on the role played by innovative investments in expanding the potential production frontier. This enables us to endogenise both the processes of growth through accumulation and the processes of growth achieved through qualitative changes in the use of economic resources. Furthermore, Schumpeterian analysis stresses the potential short-term negative effects induced by innovative efforts (Aghion et al., 2012, 2014; Quatraro, 2016; Schumpeter, 1939), thus introducing an additional analytical dimension expanding policy analysis beyond the traditional contraposition of growth and environmental sustainability. This is in line with FRIDA's primary object of analysis: A system-wide process of transition, successful or otherwise, towards more sustainable development pathways brought about by increasing climate-related constraints. This is an inherently innovative process, implying qualitative, potentially disruptive change on a global scale involving both private and public agents. Consequently, the Schumpeterian framework, focused on innovation and qualitative development, private and public, including both positive and negative consequences, is an appropriate theoretical instrument for the work at hand (Antonelli, 2017; Schumpeter, 1942).

As a consequence of this approach, FRIDA features endogenous, emerging economic cycles, a unique feature among current IAMs with similar scopes. Business cycles have been a key counterpart of microlevel innovation dynamics in Schumpeterian theory since its inception (Schumpeter, 1939), and their role has been confirmed by more recent research broadly in the same tradition (Aghion et al., 2012). FRIDA's business cycles arise endogenously because of the systemic interactions between investments focused on quantitative accumulation and qualitative exploration. While the dynamic is ultimately nested in the real level of production, key parts of the related systemic loop involve financial dynamics and aggregate financial actors.

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The result is a flexible framework able to portray a wide spectrum of effective policies, thus broadening the scope of potential use of FRIDA. An example of this flexibility is provided by the fact that since Schumpeterian theory extends beyond pure market economies (Schumpeter, 1942), it is able to support the analysis of alternative institutional configurations, such as those that would be theoretically required by a post-growth scenario (Jackson, 2021). Second, Schumpeterian models are inherently fragile and are aimed at analysing both physiological and pathological macroeconomic oscillations (Schumpeter, 1939). This feature is necessary for evaluating the full extent of the potential role played by monetary and financial mechanisms in a climate change context.

While the economy module of FRIDA v2.1 addresses some limitations of current IAMs, it also shares others and introduces new trade-offs inherent to its disequilibrium approach. Its global aggregation will mask local climate impacts, preventing differentiated, locally targeted policy experimentation. Our model also contains uncertainties, as we lack perfect information about the system under study—a reality for all the models of this scope—but rather than obscuring it, FRIDA v2.1 places uncertainty quantification at the forefront of its methodology, as detailed in Section 4. Our disequilibrium approach presents two distinct challenges in this regard. First, the historical calibration data reflect both endogenous dynamics and exogenous shocks (such as pandemics and wars) that lie outside FRIDA v2.1's scope. During calibration, the model unavoidably attempts to reproduce the full amplitude of historical fluctuations using only its endogenous mechanisms—a trade-off we accept to capture financial and monetary mechanisms. However, our uncertainty protocol partially mitigates this limitation by presenting results as confidence intervals rather than single-line projections (see Sections 4 and 5). Second, disequilibrium decreases, although it does not eliminate, our ability to identify optimal policy sets because of the lack of utility maximisation assumptions. Considering that this is a significant limitation of most IAMs (Ackerman et al., 2009), we believe that this trade-off is acceptable in light of the significant gains in terms of scope and realism described above.

3 Model structure and submodules

Parts of the model description in this section draw on the Horizon Europe WorldTrans project report D2.5 (Callegari and Grimeland, 2025), which documents an earlier version of the FRIDA economy module. The Economy module is one of seven modules in FRIDA v2.1 and represents the global economy. All internal processes are simulated in nominal terms, which is consistent with the module's monetary framework (real GDP is calculated by adjusting for inflation in the GDP submodule, as described in Section 3.6). It receives inputs from the Climate, Land Use and Agriculture, Demographics, and Energy modules and provides outputs to the Demographics, Resources, Energy and Behavioural Change modules. A schematic representation of these interactions is provided in Fig. 1. While embedded in FRIDA, the Economy module can also function independently as a stand-alone macroeconomic model of growth under exogenous environmental constraints. To explain the high-level interactions between all the modules and how the Economy module influences the rest of the model, see Schoenberg et al. (2025b).

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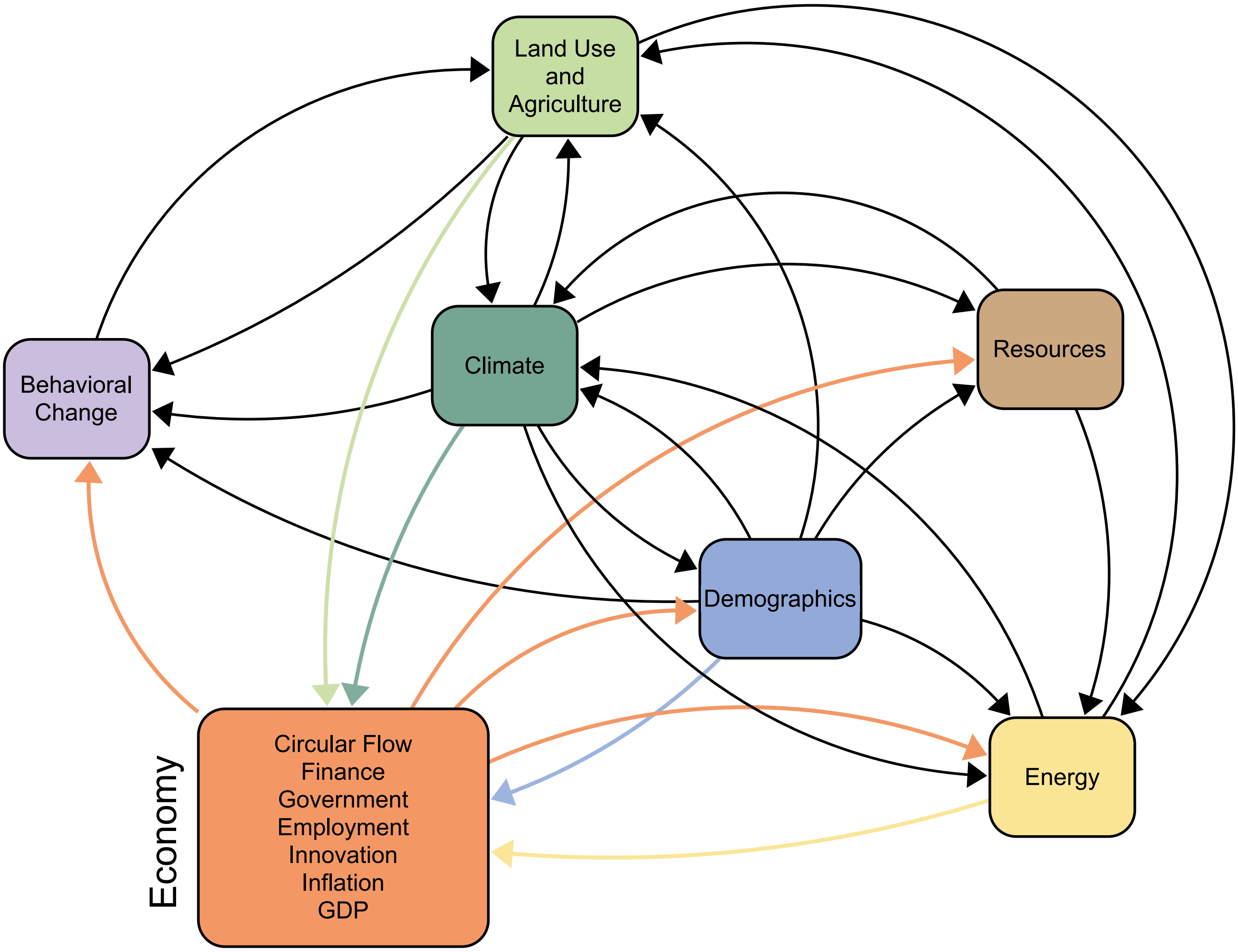

Figure 1: The seven high-level modules comprising the FRIDA model, the connections between them, and the Economy module's component submodules.

The Economy module includes 761 equations, of which 33 are state variables. It replicates data sourced for the period 1980–2023, covering the key macroeconomic indicators GDP, investment, consumption, government expenditure, the government debt-to-GDP ratio, inflation, unemployment, and wages. These time series were sourced from the World Bank, IMF, OECD, WID, and ILO, ensuring consistency and reliability (see Appendix A for the specific payoff elements and dataset references).

The internal structure of the Economy module consists of the seven submodules listed in the Economy module box in Fig. 1, each representing distinct but highly interconnected processes. This section documents the processes represented within each of them and how they interact. First, the Circular Flow submodule is described, followed by the Finance, Innovation, Government, and Employment submodules, and finally the GDP and Inflation submodules.

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3.1 Circular Flow

The Circular Flow submodule is used to simulate the processes of production and consumption and represents the behaviour of two aggregate agents: households and firms. Fig. 2 showcases the submodule's main stocks and the flows between them. The processes represented in the government, employment, and finance modules greatly affect the circular flow but are modelled separately for conceptual clarity; the details of these mechanisms are covered in the sections corresponding to their respective submodules.

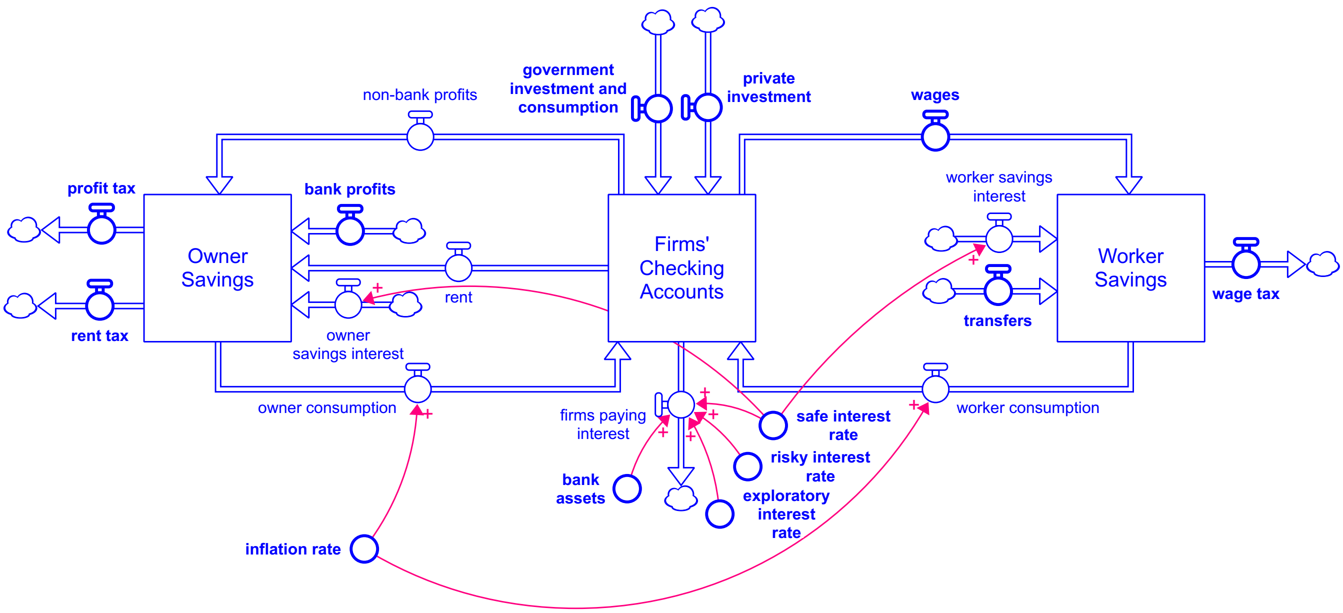

Figure 2: A simplified stock and flow diagram of the Circular Flow submodule. Bold elements receive input from elsewhere in the model.

Household money flows are disaggregated into those originating from the labour supply aspect and those related to the ownership aspect of households, following established practices in stock-flow consistent modelling of a monetary economy (Godley and Lavoie, 2007). All income related to ownership flows into owner savings, while labour income flows into worker savings, thereby tracking the mechanisms affecting the flow and accumulation of different income streams separately. A percentage of both the owners' and workers' net income is spent on consumption. Additional costs of ownership stemming from climate change in the form of costs related to retreating from sea level rise (SLR) are included in owner consumption (see Ramme et al. (2025) for documentation of FRIDA's Sea Level Rise Impacts and Adaptation module). The remaining income after consumption accumulates as savings, represented by two stocks, owner savings and worker savings, and conceptualised as checking accounts in the aggregate banking system, representing aggregate deposits from owner and worker incomes, respectively.

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The percentage of income spent on consumption is calculated using the same method for workers and owners but parameterised differently under the assumption that a larger share of worker income is spent immediately, while a larger share of owner income is saved. This is because asset-based income by and large tends to be allocated to long-term savings goals, including retirement, while a higher portion of income from labour tends to be spent on day-to-day expenses (Carroll et al., 2017). The level of consumption of both groups is determined by the relationship between income and each group's dynamic savings goal. This savings goal, which represents a desired level of savings relative to income, adjusts gradually over time as each group's financial situation changes. When income increases, both groups revise their savings target upwards after a delay, reflecting a gradual reassessment of their wealth (Jappelli and Pistaferri, 2010). With a similar lag, the savings goal adjusts downwards with reductions in aggregate income. The consumption decision follows a rule where a fraction of each group's income, minus the shortfall between their current savings and their target savings level, is spent on consumption—with a hard floor to prevent households from having unrealistically low consumption levels under extreme conditions (Andreyeva et al., 2010). Inflation has an immediate effect on the consumption of both groups; as prices change, net of the negative impact of additional unemployment, consumption increases in an attempt to maintain the same standard of living (Burke and Ozdagli, 2023).

The consumption expenditure of each group flows into a third state variable, the firms' checking accounts. This variable represents all the deposit accounts for all the world's firms. The income streams that flow from firms checking accounts to households consist of wages, rent, and profits. The processes that determine the cost of wages and rent are modelled in the Employment submodule and discussed in Section 3.5. Together, wages and rent represent the compensation received by households in exchange for their contribution of productive services to the production process. These payments are drawn from the firms' checking accounts. Profits consist of the residual firm income after all the required payments have been made by firms. They are distributed to owners gradually as firms manage outflows to maintain the required working capital (Larkin et al., 2017).

We represent government transfers (welfare payments) as contributing to the worker subset of household income. The process for determining government transfers is modelled in the government module and discussed in Section 3.4. The savings of both workers and owners receive interest from the banks through a process described in the Finance submodule (Section 3.2). Bank profits are represented separately from the profits already discussed. Bank profits are not drawn from the firms' checking accounts because banks are modelled separately from general firms. This process is explained in Section 3.2. Moreover, wages, profits and rent are taxed, creating revenue for the public sector, which is used in the Government submodule (Section 3.4.).

The circular flow, as explained thus far, cannot grow on its own. Income would circulate between firms and households, leading to a stable equilibrium as savings goals are met (Schumpeter, 1934). Growth is achieved through private investments originating in the Finance submodule (Section 3.2.), which lends money to firms, enabling them to increase the scale of their productive activities. Firms pay interest on these loans depending on the risk level as determined by the Finance submodule (Section 3.2). A second potential source of growth of the circular flow is government expenditures; when

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government expenditures exceed tax revenues, they increase the general income level, although the increase may be purely nominal depending on productivity growth and the amount of slack present in the economy. These government expenditures are determined in the Government submodule (Section 3.4). The next section describes the Finance module—how it mediates private investment and enables growth.

3.2 Finance

The Finance submodule is modelled as a single aggregate financial intermediary. It simulates mechanisms governing private investment, credit creation, allocation of resources to exploratory investments, and risk management. Key concepts include loans, which are classified as performing[1], nonperforming, safe or exploratory, lending standards, which represent banks' attitudes towards lending risk, and defaults, which arise from the eventual failure to repay nonperforming loans.

[1] As shorthand, performing and nonperforming loans are represented in the model and Fig. 3 as "Good Loans" and "Bad Loans," respectively.

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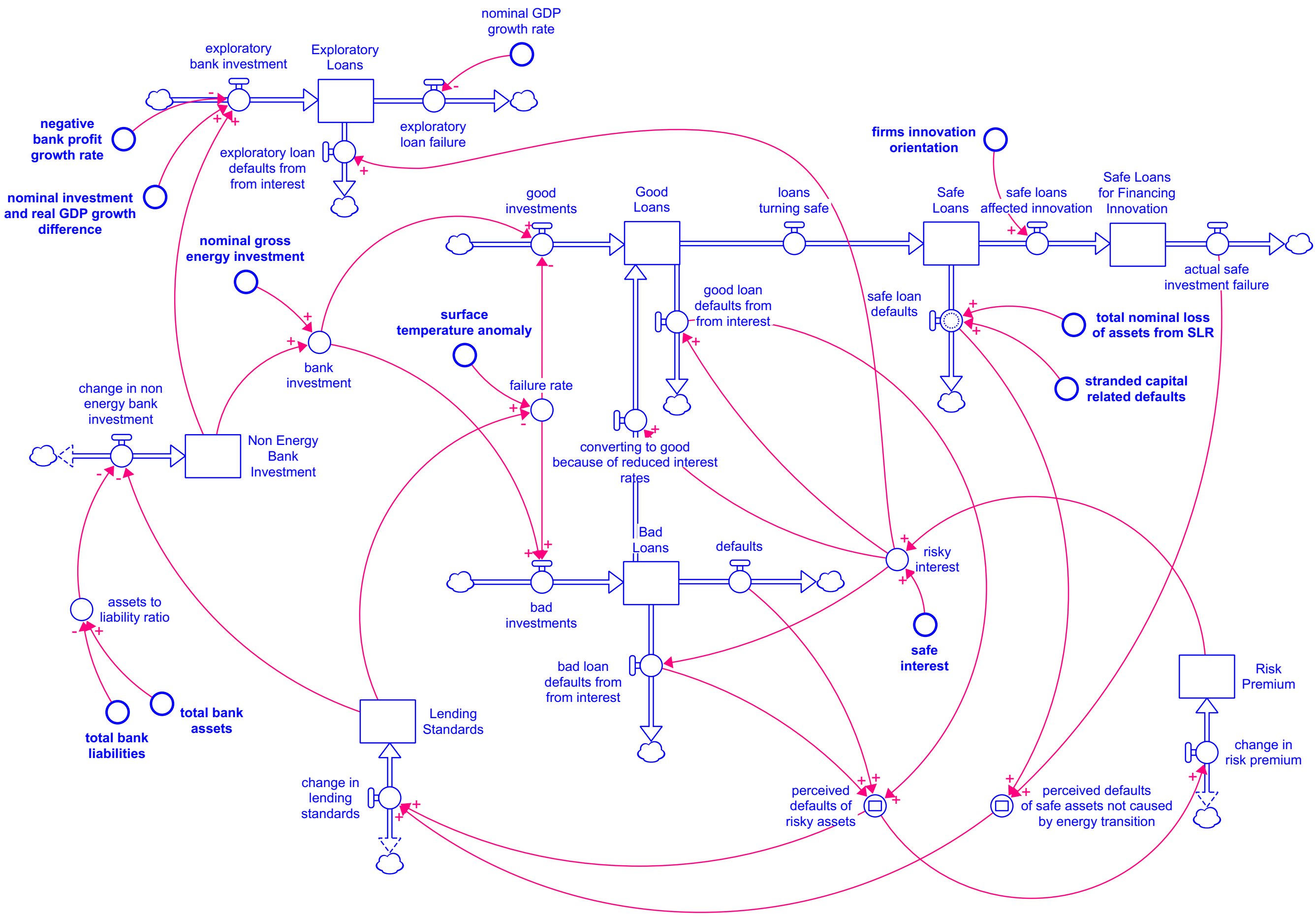

Figure 3: A simplified stock and flow diagram of the finance sector. Bold elements receive input from elsewhere in the model.

3.2.1 Bank profits, solvency, and government intervention

275 Households' accumulation of savings and the banking sector's profit incentives drive the issuance of loans, as banks attempt to generate a sufficient amount of interest-paying assets to remunerate deposits and distribute profits, a monetary rendition of the savings/investments nexus (Bernanke and Blinder, 1988). The issuance of loans expands both sides of the banking sector's balance sheet: when banks extend credit, it increases their assets in the form of loans and creates new liabilities in the form of additional deposits held by firms (McLeay et al., 2014)[2]. This mechanism injects new money into firms, from where it
280 circulates between households' and firms' deposit accounts through the remuneration of productive services and consumption. The difference between accumulated loans in the Finance module and the accumulated deposits in the Circular Flow constitutes the banks' equity.

[2] FRIDA v2.1 does not model consumption credit.

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The amount of profits distributed by banks to owners in the Circular Flow submodule (Section 3.1) is a fraction of the total equity and is dynamically adjusted on the basis of the annual growth rate of equity. Declining (rising) equity puts downwards (upwards) pressure on bank profit distribution (Menicucci and Paolucci, 2016). Bank profits flow into the circular flow as an income stream. If the bank asset-to-liability ratio falls below an exogenous threshold, we simulate bailout policies through which the government intervenes and provides solvency support, subsidising the banking sector to ensure financial stability (Gup, 2003).

3.2.2 Investment, lending and loan classification

The banking sector aims to generate profits. To do so, they need to generate performing loans, expanding their balance sheets in the process. The banks' desire to expand their asset base is modelled as a long-term historical reference of the past rate of growth in loan volume (Rodano et al., 2018), adjusted for their equity target—a ratio of assets to liabilities below a desired threshold that puts upwards pressure on the banks' desired investment growth rate, and vice versa. The preponderance of bank lending is governed by mechanisms interior to the Finance submodule, but those investments pertaining to energy are determined by FRIDA's energy module, as documented in Schoenberg et al. (2025b).

This quantitative expansion drive is tempered by the desire to minimise the origination of nonperforming loans. The primary instrument to achieve this aim is the screening of potential borrowers and investment opportunities, represented by lending standards. Lending standards are represented as a relative index adjusted over time in response to the default rate (see Section 3.2.3 for sources of loan failure) and past lending standards (Fishman et al., 2024; Lown and Morgan, 2006). If the rate of loan creation exceeds the economy's growth potential, loan quality deteriorates, leading to increased defaults (Kraft and Jankov, 2005). As the rate of defaults relative to the size of the loan portfolio increases, lending standards increase, which reduces lending growth, and vice versa (Gjeçi et al., 2023).

In the model, we classify new loans as "performing", "nonperforming", or "exploratory" at issuance and accumulate them into distinct state variables. "Exploratory" loans stand for funding of innovative projects with the possibility of contributing to productivity growth. The origination of exploratory loans is modelled separately from that of conventional performing and nonperforming loans and is described together with innovation and productivity in Section 3.3.

Owing to information asymmetry, banks do not know which new loans are going to be nonperforming, but they do know that some of them will. Consequently, the banks consider all new lending as risky and apply risk premia to newly originated loans (Liao et al., 2009) (see Section 3.4.2 for interest rate formation). As these risky loans mature, nonperforming loans default and are written off as losses for the bank. On the other hand, performing loans are reclassified over time as safe assets. Once a loan has been demonstrated to be safe, a risk premium is no longer applied. Exploratory loans, however, maintain their risk premium.

The proportion of new conventional loans classified as nonperforming at origination is determined by the "failure rate". The failure rate has a calibrated baseline, reflecting normal liquidity conditions with well-functioning financial markets, and is dynamically adjusted on the basis of economic and climatic conditions (World Bank, 2023e). Higher lending standards

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lead to stricter screening of investment opportunities, reducing the failure rate as banks allocate credit more selectively (Lown and Morgan, 2006; van der Veer and Hoeberichts, 2016). Conversely, looser lending standards increase the failure rate as riskier investments are pursued (Dell'Ariccia and Marquez, 2006; Rodano et al., 2018). Additionally, when the growth rate of annual investment volume exceeds GDP growth, the failure rate also increases. This occurs because investment expands faster than the economy is able to generate profitable investment opportunities (Beck et al., 2015; Kraft and Jankov, 2005). Finally, global climate change, represented by increases in surface temperature anomaly (STA), further increases risk: as global temperatures increase above preindustrial levels, extreme weather events increase the probability of new investments failing (Dietz et al., 2016; Feng et al., 2024; Mandel et al., 2025).

3.2.3 Sources of loan failure

While all nonperforming loans eventually default—except for those that may be reclassified as performing as a result of improved liquidity conditions—all other classes of loans (performing, nonperforming, and exploratory) can also fail under specific conditions. In addition to conventional nonperforming loans failing, there are four other causes of defaults: interest rate hikes can cause failures across every loan class, safe loans can also fail because of SLR, or R&D-driven innovation, and exploratory loans can be made vulnerable and fail from GDP deceleration.

Sudden changes in interest rates (see Section 3.4.2 for interest rate formation) directly impact loan performance. Interest rate cuts can make a share of nonperforming loans become performing by alleviating liquidity constraints (Bhandari and Weiss, 1993; Minsky, 2008). On the other hand, interest hikes increase debt servicing costs and can lead to failures across all loan classes, including safe loans, as they become too expensive to sustain (Adrian and Shin, 2008).

Higher sea levels increase the severity of floods, creating losses and damage in coastal areas in the absence of adaptation (see Ramme et al. (2025) for documentation of FRIDA's Sea Level Rise Impacts and Adaptation module). These losses and damages can strain even otherwise sound businesses, preventing them from servicing their loans and causing loan failures from the bank's perspective.

R&D-driven innovation, which renders a portion of existing investments obsolete (Diamond, 2006; Schumpeter, 1934, 1942), will cause further loan failure. The value of the total number of safe loans issued by firms reflects the value of their productive assets. A portion of these assets is allocated to exploratory uses (R&D). The extent to which firms allocate these assets to R&D depends on their innovation orientation, which is determined in the Innovation submodule (Section 3.3). While R&D activities improve economy-wide productivity—as described in Section 3.3—the obsolescence it creates causes a share of safe loans to fail over time as new technologies diffuse and gradually displace previous techniques (Chinloy et al., 2020).

Finally, while exploratory loans can also fail from interest hikes, they mainly fail because of GDP deceleration. This reflects the effect of liquidity constraints on high-risk innovative ventures (Brown et al., 2009; García-Quevedo et al., 2018).

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3.3 Innovation and productivity

Following our Schumpeterian approach, we identify innovative investments from both incumbents and new entrants as a primary driver of long-term economic growth (Wong et al., 2005), structural change (Quatraro, 2016), and a disruptive process—reflecting creative destruction (Schumpeter, 1942). While the endogenous innovation process is spread across the various submodules, it is presented here under a single heading. This section describes the two classes of innovative investments and their disruptive effects, how they translate into potential productivity growth, and how climate impacts affect realised labour productivity.

Innovative investments in new market entrants are funded through exploratory lending. Such lending generates new investment opportunities, particularly in periods of high investment activity relative to growth potential—i.e., when the growth rate of nominal investment exceeds real GDP growth, exploratory lending increases (Gompers et al., 2008; Mendi, 2024; Nanda and Rhodes-Kropf, 2013). This reflects situations where credit expansion is not matched by real economic output growth, prompting the funding of innovative ventures that might open new avenues for additional profit. Conversely, a decline in the growth rate of annual bank profits places downwards pressure on exploration, as banks become less willing to take on more risk (Ahmad, 2021). Thus, exploratory loans fluctuate based on both financial and macroeconomic conditions.

Innovative investment by incumbents constitutes R&D activities and is represented as the reallocation of existing private assets, with implications for defaults in the finance module as described in Section 3.2.3. The driver of R&D activities and the resulting asset reallocations is located in their own Innovation submodule. Therein, the firm's innovation orientation increases (decreases) as a reaction to low (high) profit rates, thereby fluctuating with the business cycle (López-García et al., 2013; Mendi, 2024). The firms' orientation towards innovation is represented as an index. When the growth in firms' cash reserves slows down, firms rapidly become more inclined to innovate, reflecting an increased urgency to explore new potential revenue streams. Conversely, as cash reserves grow, this orientation declines gradually, indicating a preference for stability and risk aversion over uncertain R&D investments.

Productivity growth in the model arises from these innovative activities—exploratory loans and firm R&D activities (Hasan and Tucci, 2010; Kortum and Lerner, 1998)—and is simulated in the Employment submodule (Section 3.5). The values of both exploratory loans and safe loans failing due to innovation are expressed as shares of GDP to enable direct comparison. On the basis of these normalised values, productivity growth is calculated, weighting the contribution of exploratory loans more heavily to reflect their higher transformational potential (Acemoglu and Cao, 2015). After a time delay, realised productivity materialises, reflecting the time required for innovation to diffuse and yield economic benefits (Meade and Islam, 2006).

Finally, realised labour productivity is determined by reducing labour productivity on the basis of climate impacts. As the STA increases, labour productivity declines on the basis of the degree of exposure (Dasgupta et al., 2021). High-exposure labour, such as strenuous activity performed in the open, is the most affected. Low-exposure labour, such as work in not climate-controlled but shaded areas, is less affected. No exposure labour, such as work in a climate-controlled office setting,

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is not affected. To determine the allocation of global labour to these exposure classes over time, we model the development of the three main economic sectors: agriculture, industry and services. For each of the sectors, we specify the share of high exposure, low exposure, and no exposure work and, thereby, the impact of climate change on labour productivity in each sector. Agriculture is the most susceptible to climate impacts, followed by industry, while workers in the service sector are less affected. The overall impact on labour productivity is then the average across sectors weighted by their share of the global economy. These shares are a function of GDP, reflecting the transition from agriculture to industry and services observed with higher economic output (Alvarez-Cuadrado and Poschke, 2011).

3.4 Government

The Government submodule simulates fiscal and monetary policy, modelling the world's governments and central banks as aggregate agents responsible for managing tax revenue allocation, government debt dynamics, and the interest rate. Tax revenues collected from households and industry are redistributed through public investment, consumption, and transfers. Total government expenditure levels adjusted in response to the public debt-to-GDP ratio.

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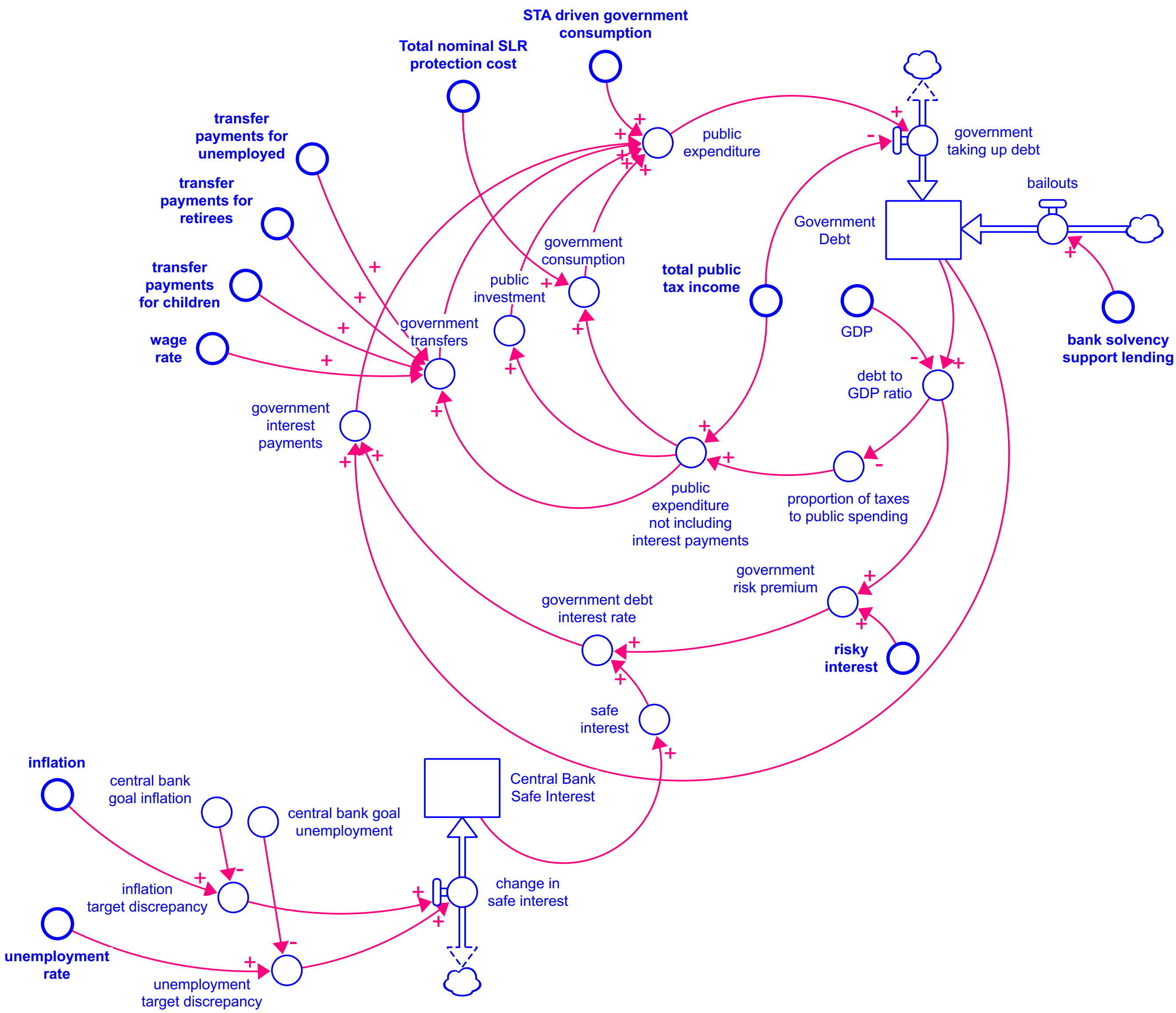

395 **Figure 4: A simplified stock and flow diagram of the Government submodule. Bold elements receive inputs from elsewhere in the model.**

3.4.1 Government revenue, expenditure and debt

Government expenditure, excluding interest payments on outstanding debt, is determined as a percentage of total tax income, which is levied on the flows of wages, profits, and rents (Narayan and Narayan, 2006; Ram, 1988). The percentage of tax income spent adjusts dynamically on the basis of the governments' fiscal stance, measured by the debt-to-GDP ratio. This ratio imposes constraints on the government's expenditure relative to its tax-derived income: when the ratio is less than 1, spending

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exceeds tax revenue. However, as the ratio increases above 1, expenditure gradually decreases, eventually reaching a lower bound as the debt burden increases (Bohn, 1998; Ghosh et al., 2013).

The government is able to spend more of its income. The resulting deficit leads to the issuance of public debt from the government sector to the banking sector (Fang et al., 2025). It is important to note that we do not include nonbank holdings of government debt since the current version of the model lacks aggregated wealth portfolio management dynamics. Government expenditures are modelled as the sum of investment, consumption, interest payments and transfer payments. In addition to deficits created via these regular spending and taxation processes, we model a second process for creating government debt, which is the additional government debt directly issued to stabilise the financial system should the banks be insolvent, effectively "bailing them out". Interest on outstanding government debt, including a risk premium (see Section 3.4.2 for interest rate formation), is assumed to always be paid, regardless of fiscal constraints. While this assumption ignores the empirical reality of defaulting sovereigns (Beers and Mavalwalla, 2017), the implementation of the latter is incompatible with the globally aggregate nature of the model.

After interest payments are accounted for, government expenditure is allocated across investment, consumption, and transfers. The proportion of government expenditures directed to transfers is endogenised and adjusts dynamically with demographic changes and unemployment. FRIDA's Demographics module (see Schoenberg et al. (2025b) for documentation) divides the global population into age cohorts, allowing the tracking of children and retirees to determine the cost of transfers to those cohorts. Welfare for the unemployed considers the number of unemployed individuals determined in the Employment module described in Section 3.5. The cost of the transfer payment per individual and each type of transfer—child support, pensions, and unemployment welfare—is adjusted with changes in the average wage rate with a delay (OECD, 2025). This ensures that transfers are adjusted for inflation in line with wages. Being partly driven by changes in unemployment, transfers are countercyclical (Chrysanthakopoulos et al., 2025). The remaining budgeted funds after transfers are then divided between investment and consumption. The allocation is dynamically adjusted in response to increases in STA; as climate-related losses and damage increase, consumption becomes a larger share of total expenditures to accommodate increased climate-driven repairs and maintenance (Qiao et al., 2015).

3.4.2 Central banking, the policy rate, and risk premia

The central banks are modelled as a single, aggregate agent and are tasked with keeping inflation and unemployment near their respective targets by adjusting the policy rate. Specifically, they aim for 2% inflation and 5% unemployment (Solow and Taylor, 1998). When inflation exceeds 2%, the policy rate is pushed upwards to slow growth in the price level, whereas inflation below 2% will push the rate down to stimulate investment (Clarida et al., 1998). Unemployment follows the same logic, but in reverse: if unemployment falls below 5%, it will increase the rate to mitigate excessive wage growth, whereas unemployment above 5% will decrease the rate to stimulate labour demand. These adjustments to the policy rate occur gradually, with greater weight given to inflation than unemployment (Cukierman and Lippi, 1999).

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The private-sector average safe interest rate is derived as a moving average of the policy rate. The average private sector's risky interest is set above the safe rate by adding a risk premium to it. This premium changes dynamically to reflect the banks' perceived risk profile, which is proxied by the default rate of loans relative to the total number of risky loans. As defaults increase in the Finance submodule (Section 3.2.3), the risk premium increases, making new loans more expensive (Huljak et al., 2022). Conversely, lower default rates reduce the risk premium, easing borrowing conditions (Fishman et al., 2024).

The interest rate on government debt is similarly derived from a moving average of the policy rate, reflecting the composite nature of government debt duration (Dembiermont et al., 2015). It also includes a dynamically adjusted with a dynamic risk premium. When the debt-to-GDP ratio is at or below one, no extra risk premium is charged. When the ratio exceeds one, government debt is perceived to be riskier, and additional interest is charged in proportion to how much the ratio surpasses unity (Ardagna et al., 2007; Jacobs et al., 2020).

3.5 Employment

The Employment submodule simulates how the global working-age population transitions between nonactive, unemployed, and employed and how wage rates respond to changing labour market conditions. Also included within this submodule is our representation of labour productivity. Dynamics in this submodule are driven by public and private investment flows—originating in the Government (Section 3.4) and Finance (Section 3.2) submodules, respectively, as well as inflation, from the Inflation submodule (Section 3.6.). This submodule also integrates productivity gains related to "creative destruction", where innovation from the Finance and Innovation submodules (Section 3.2. and 3.3, respectively) render existing processes obsolete but boost economy-wide productivity, with implications for worker displacement. This section details how these forces—labour supply and demand, wage formation, innovation and productivity—together shape global employment outcomes in the model.

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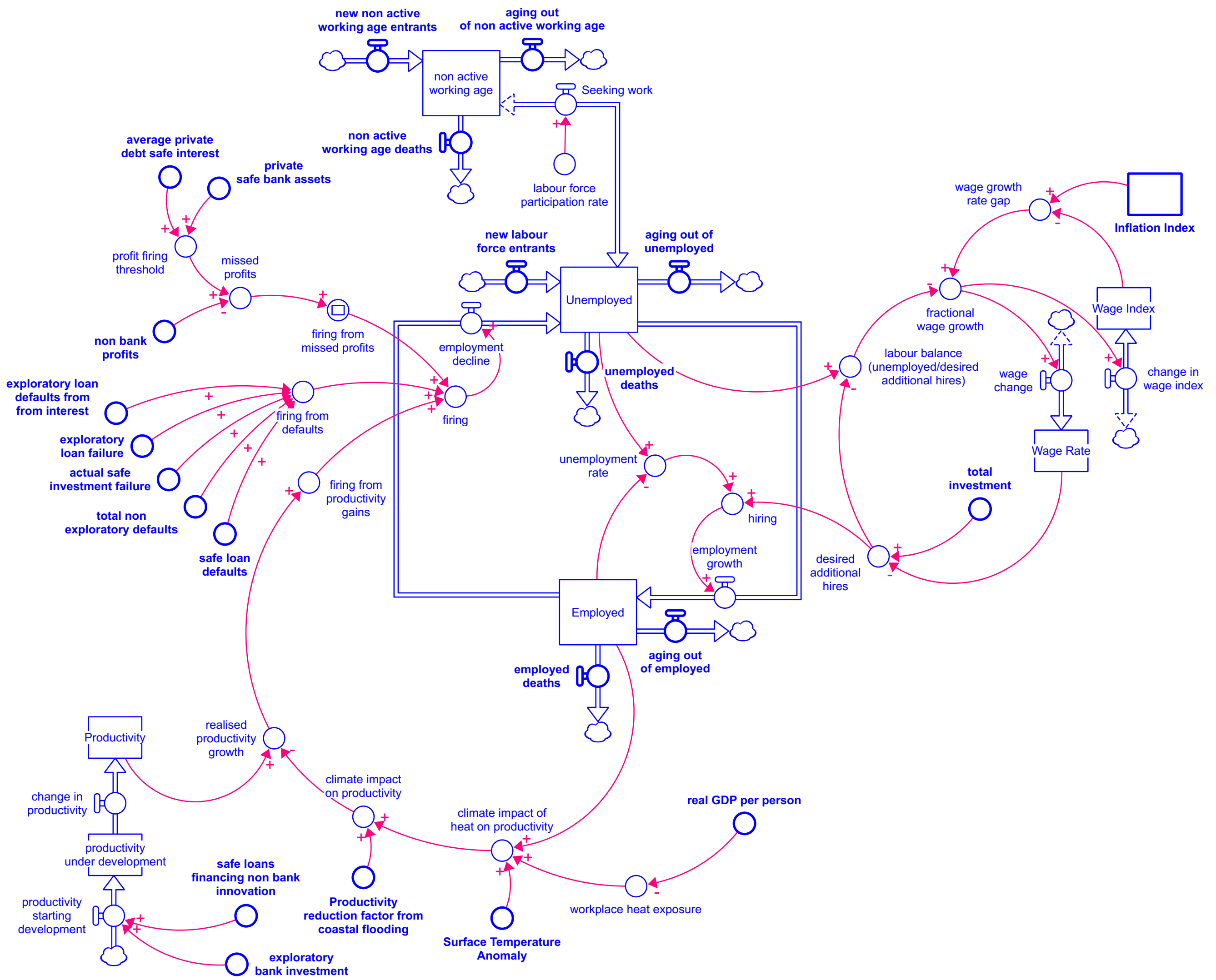

Figure 5: A simplified stock and flow diagram of the Employment submodule. Bold elements receive input from elsewhere in the model.

3.5.1 Labour and the wage rate

The working-age population, as represented in the Employment submodule, consists of people between the ages of 15 and 65. People ageing in or out or dying are modelled in the Demographics module (see Schoenberg et al. (2025b) for documentation). The working-age population is divided into three state variables: nonactive, unemployed, and employed. The nonactive represents those of working age who cannot, or will not, seek work. Historically, approximately 35% of the working-age population has been in this category (ILO, 2024b). Hence, the model maintains a share of the working-age population in this

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category, with some allowance for variation during calibration given data uncertainties. The unemployed and the employed make up the labour force. Hiring and firing depend on the labour demand and wage dynamics.

Firms' labour demand stems from public and private investment, as determined in the Government and Finance submodules, respectively, calibrated as a fraction of total investment divided by the average wage rate (ILO, 2024). The time required to hire new employees depends on the unemployment rate; as it declines, it becomes increasingly difficult to match vacancies with qualified workers (Mortensen and Nagypál, 2007).

The average wage rate responds asymmetrically to changes in the ratio of labour supply to labour demand: if the ratio falls below one, wages rise, whereas if it rises above one, wages decline at a lower rate, reflecting the relative "stickiness" of wages (Ehrlich and Montes, 2024; Grigsby et al., 2021). Additionally, if inflation (Section 3.6) outpaces nominal wage growth, the resulting purchasing power loss exerts upwards pressure on wages (Kahn, 1984). However, firms adjust wages with a lag to reflect real-world negotiation delays and the impact of existing contracts (Grigsby et al., 2021).

Firing moves workers from the employed to the unemployed category. Firing occurs for three reasons. The first reason is that defaults in the Finance submodule (Section 3.2.3) lead to layoffs proportional to the defaulted amount relative to the cost of labour. The second reason is that missed profits drop below a threshold tied to the average rate of interest on private debt (Section 3.4.2). The missed profits prompt firms to compensate by reducing their payroll (Coucke et al., 2007). The third reason is that productivity growth (Section 3.3) displaces portions of the employed over time, with delays reflecting the time it takes for new technologies and techniques to diffuse and result in firings (Feldmann, 2013; Quatraro, 2016).

3.6 GDP and inflation

GDP in this model is calculated in its own submodule using a nominal expenditure approach, summing the final purchase price of public and private consumption and investment. Owing to the global nature of the model, international trade cancels out and is therefore not included. Private and public investments originate in the Finance and Government submodules, respectively (Sections 3.2 and 4.4). Private and public consumption originate in the Circular Flow (Section 3.1) and Government (Section 3.4) submodules, respectively. To derive real GDP in constant 2021 dollars, the model applies an inflation index calculated in the Inflation submodule described in detail below, ensuring comparability across simulation runs.

Inflation is calculated on the basis of two components: excessive income growth and input shocks (Auer et al., 2019; Deniz et al., 2016; Lim and Sek, 2015). Both components can be positive or negative, but inflationary pressures have an outsized effect compared with deflationary pressures, reflecting stickiness in price levels (Altonji and Devereux, 1999). Income growth leads to inflation when the combination of private income (from the Circular Flow submodule in Section 3.1.) and annual government deficit spending (from the Government submodule Section 3.4.) grows faster than economic expansion potential, proxied by productivity and employment growth, referring to qualitative development and quantitative growth, respectively (Hasan and Tucci, 2010). This imbalance places upwards pressure on the price level. The input-shock components of inflation originate outside the core Economy module—specifically from the Energy and Land Use and Agriculture modules (see Schoenberg et al. (2025b) for documentation). When demand exceeds supply in animal products and crops, it adds to

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inflation. The opposite has a deflationary effect. Other pressures arise from the growth rates of fertiliser use, cropland, and grazing land and the marginal cost of energy. Changes in these growth rates exacerbate scarcity, driving up input costs and triggering cost-push inflation. Furthermore, they proxy all historical input-shock inflation, and their inflationary contribution is weighted accordingly, capturing the impact of scarcity on real growth (Parker, 2017).

4 Integration, calibration and uncertainty

FRIDA is implemented in Stella Architect 3.8 and simulated over a time horizon spanning 1980–2150. The integration method used to simulate the model is fourth-order Runga-Kutta (RK4) with a timestep of $1/8^{th}$ of a year. A multistep protocol was developed for estimating parameter value ranges and presenting results in such a way as to communicate the range of possible outcomes given the input uncertainty rather than a single outcome (Schoenberg et al., 2025b).

The first step of the protocol is calibration using Powell's BOBYQA algorithm (Powell, 2009). Parameter inputs whose values, or value uncertainty ranges, could not be sourced from the data or literature were given wide uncertainty ranges on the basis of the outcomes created at the most extreme potential values for the parameter. The calibration involved varying the inputs within their individual uncertainty ranges to minimise the squared error between historical data and simulated data for 16 payoff elements for the period 1980–2023. This first step produced the best-fit single-term endogenous model behaviour (EMB) shown in Fig. 5 for a selection of 12 key performance indicators plotted against historical reference data. All historical datasets used for these payoff elements—including the reference series plotted in Fig. 5—are publicly available and listed in Appendix A where the original data sources are cited.

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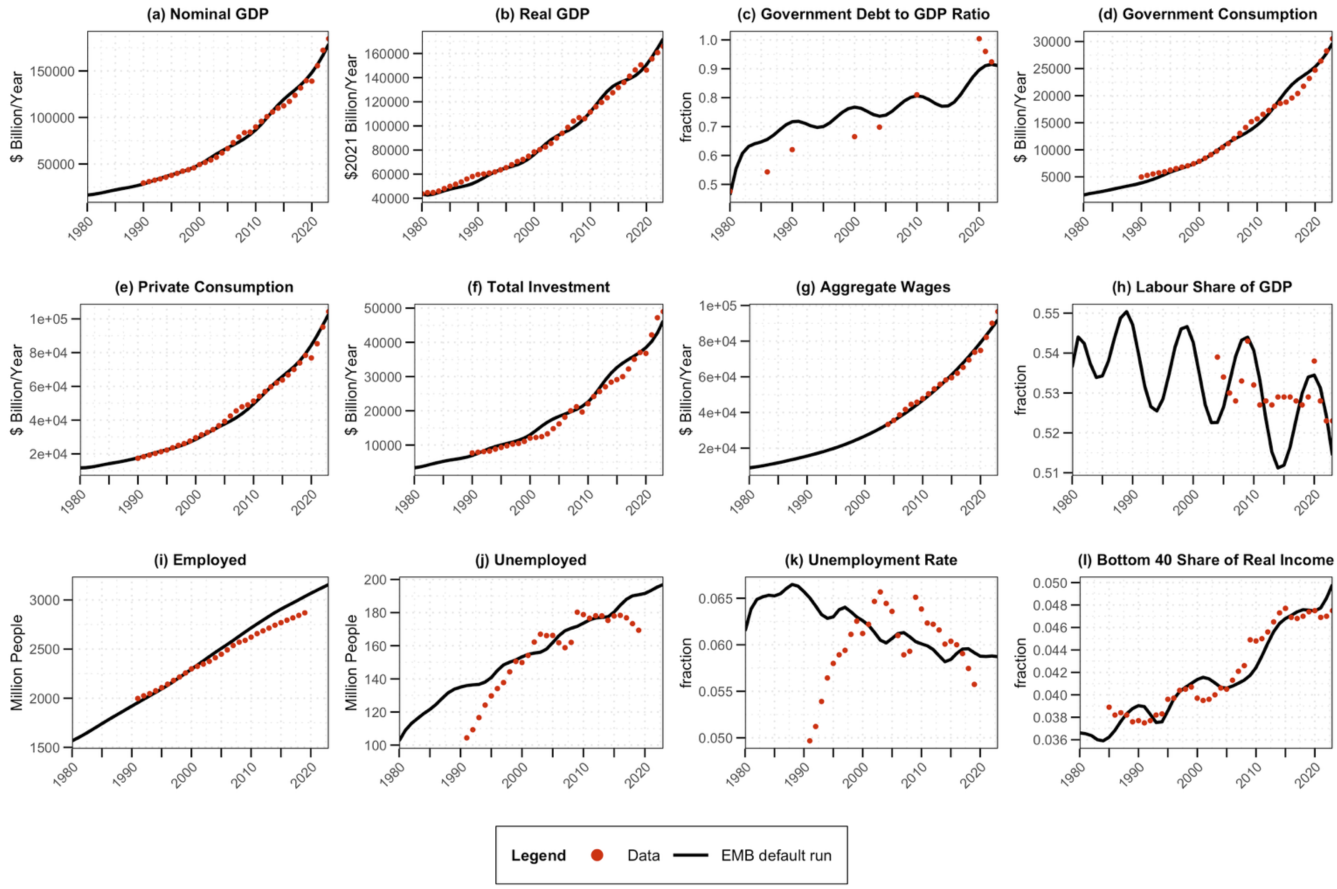

Figure 5: Best fit FRIDA results for key macroeconomic indicators against observed data.

The single-run EMB run, as shown in Fig. 5, demonstrates FRIDA's ability to reproduce key macroeconomic dynamics over the 1980–2023 historical simulation period. Notable features of these results include the model's ability to capture business cycle fluctuations, which are visible in the changing slope of GDP (Fig. 5a and 5b) and are particularly prominent in the unemployment rate (Fig. 5k) and the labour share of GDP (Fig. 5h). The model successfully reproduces major economic downturns, although the amplitudes of some shocks differ from historical observations. For the historical period, FRIDA does not include shocks exogenous to the processes described above. This explains the absence of effects of the 2020 pandemic, 2009 banking crisis and similar events in the model results. For the historical period, the model does not include discrete policy changes, and endogenous policy changes are continuous. These deviations are consistent with FRIDA's design philosophy: rather than aiming for perfect replication of historical events driven by exogenous shocks, the model generates endogenous oscillations through the feedback processes within and across economic sectors.

The second step of the protocol involves exploring the possibility space, arising from the parameter uncertainty ranges. This is done in two steps. In the first step, the parameters are constrained to their likely ranges. The likely range is defined as the interval within which a parameter can be varied, while the likelihood of the model's output remaining above the

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1/1000th of the best fit likelihood obtained during calibration. These ranges are then symmetrised within the originally provided widest possible bounds. This approach ensured that samples were distributed evenly around the default parameter set while still covering the regions with the highest likelihood. The resulting parameter bounds are documented in Appendix B.

On the basis of these ranges, we conduct a 100,000-member global sensitivity analysis (Saltelli, 2008) using Sobol sequence sampling (Sobol' and Levitan, 1999). This technique produces a set of sample points aimed at efficiently sampling the high-dimensional parameter space of the model. This method is needed because the high number of parameters to be sampled makes more systematic sampling computationally infeasible. The model is then run for each sample point, i.e., a set of parameter values, to produce the ensemble presented as the result of the model. As a result, the ensemble runs are not weighted by their likelihood, yet they can still be understood probabilistically: the resulting bounds highlight the regions of the output space that the ensemble most frequently explored, providing a probability-based interpretation conditioned on our sampling approach. It should be noted, however, that these confidence bounds are wider than they would be if likelihood weighting had been applied. While the sample is not weighted by likelihood, the spread captures a wide range of plausible system behaviours. The ensemble median, along with the 67% and 95% confidence intervals, are reported in Section 5.

This protocol reflects the project's commitment to openly communicating uncertainty, and it also underscores FRIDA's nature as an exploratory model: the goal is not to provide point predictions but to test the robustness of insights across a meaningful uncertainty space. Presenting single-line projections would understate the range of potential futures and could mislead stakeholders about the model's precision.

5 Simulation results

This section evaluates the model behaviour of the FRIDA v2.1 Economy module over a simulation time horizon spanning 2020–2150. The results are based on the 100,000-member ensemble run derived from the simulation protocol described in Section 4. Figs. 6 to 8 present the baseline results of the 100,000-member ensemble runs for key macroeconomic indicators. The full infrastructure and data to run this or alternative scenario ensembles is linked in the code and data availability statement. While Fig. 5 above demonstrates FRIDA's ability to reproduce historical data series, here, we show the projected future economic trajectories under uncertainty. The figures show the medians and 67% and 95% confidence intervals of the 100,000 ensemble projections. While individual ensemble members have the oscillatory behaviour discussed above, the figures display relatively smooth trajectories as they show statistical measures of the asynchronous oscillatory behaviour across ensemble members.

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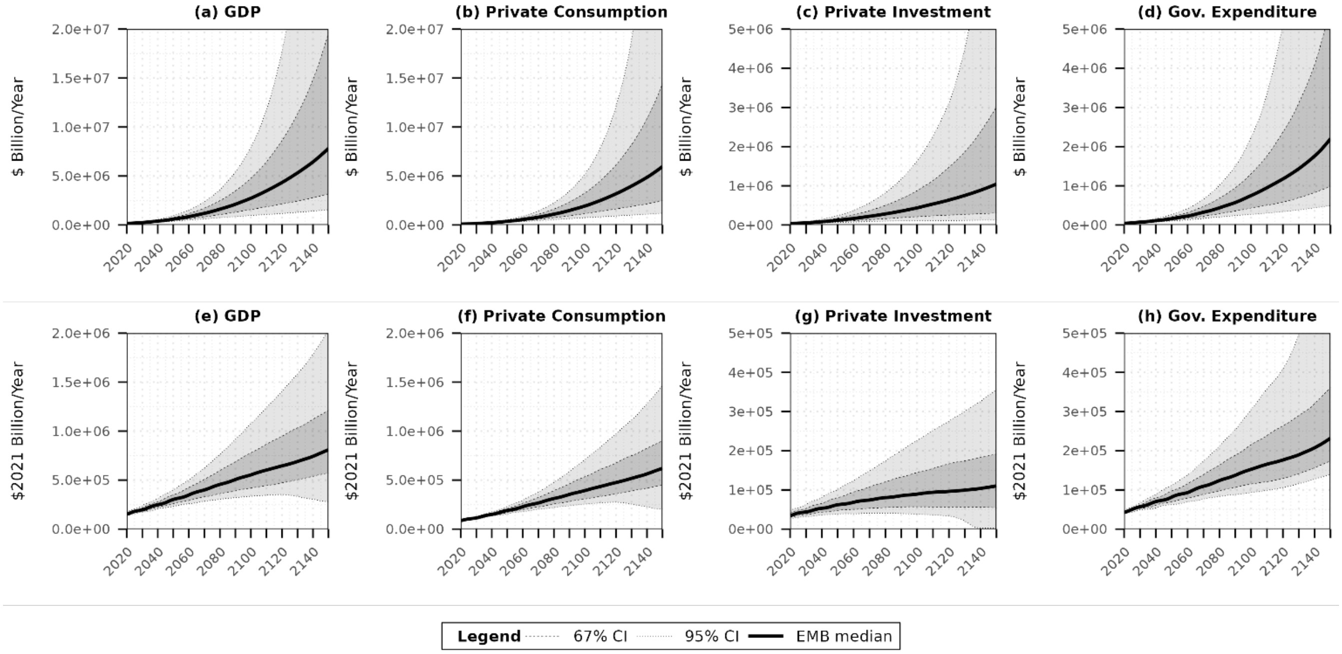

Figure 6: Median and 67% and 95% confidence intervals of the 100,000-member ensemble for nominal and real GDP and its components.

Fig. 6 shows GDP and its components in both nominal and real terms (constant 2021$). In nominal terms, private consumption (Fig. 6b), private investment (Fig. 6c), government expenditure (Fig. 6d), and, hence, GDP (Fig. 6a) increase exponentially, which is consistent with historical patterns. Much of this growth, however, is due to inflation (Fig. 7a). Nonetheless, most ensemble members also exhibit continuing growth in real GDP (Fig. 6e) until the end of the simulation time horizon, albeit not exponentially. Private consumption (Fig. 6f) is the largest component of GDP and the main driver of the long-term upwards trend in GDP. The decline in the median growth rate around the end of the century is due to a decline in the growth of private consumption and investment (Fig. 6f and 6g). This slowdown is partly compensated by an increase in government expenditures, including public investments (Fig. 6h). This is in turn driven by increases in government transfers, described below. However, there are ensemble members within the 95% confidence interval that exhibit negative growth in real terms (nominal growth remains positive), reflecting ensemble members whose parameterisations specify the strongest climate damage consistent with historical data when combined with uncertainty in other areas of the economic system.

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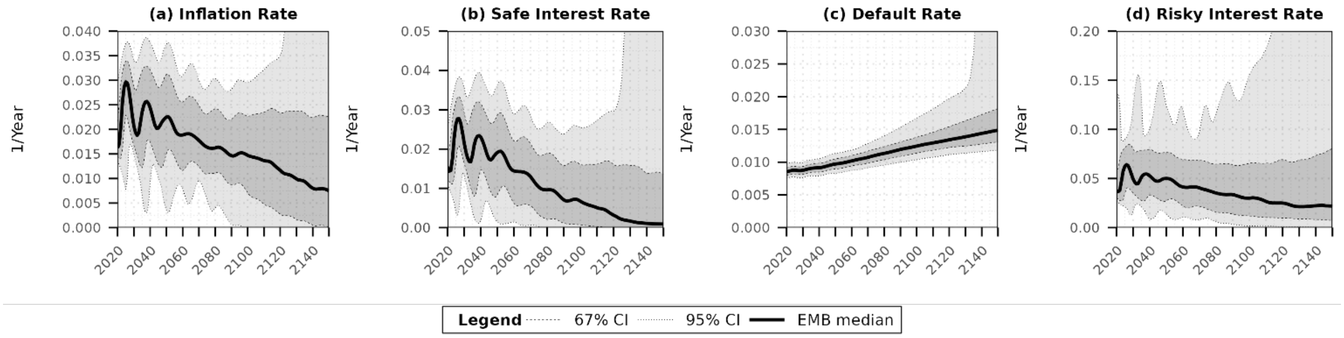

Figure 7: Median and 67% and 95% confidence intervals of the 100,000-member ensemble for key variables of the Finance submodule.

The inflation rate (Fig. 7a), starting from historical levels, declines over time. As a consequence, the central bank safe interest (Fig. 7b) rate is reduced (see Section 3.4.2). Without quantitative easing measures (not currently implemented in FRIDA), the central bank is not able to maintain the inflation rate at the target of 2%, with the safe interest rate near the zero lower bound towards the end of the simulation time horizon. Interest rates paid by private investors (Fig. 7d) do not decline as strongly as the safe interest rate does because of the risk of defaults (Fig. 7c) perceived by banks, driving a risk premium between safe and risky interest rates (see Section 3.2).

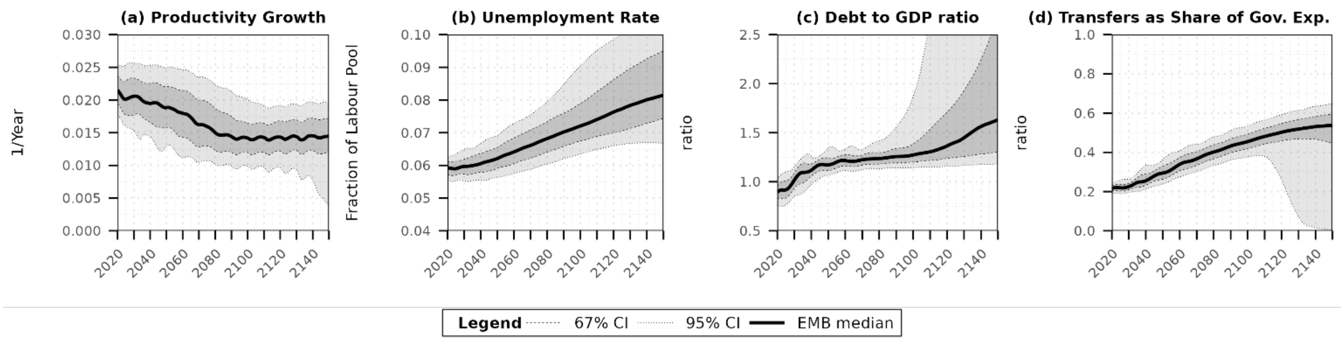

Figure 8: Median and 67% and 95% confidence intervals of the 100,000-member ensemble for changes in labour productivity, unemployment rate, government debt to GDP, and share of government expenditure spent on transfers.

A share of private investment (Fig. 6c) flows into research and development with the potential to increase productivity. Fig. 8a shows the effect of these exploratory investments on changing economy-wide productivity (see Section 3.3). Increases in productivity increase GDP but also contribute to redundancies among workers, contributing to an increasing unemployment rate. The unemployment rate is further affected by demographic contraction around the turn of the century, combined with downwardly sticky wages keeping labour costs relatively high and decreasing the investment growth rate, leading to fewer new job vacancies because of proximately default-driven, but ultimately climate-driven, economic slowdown (see Section 3.2.3). Furthermore, economic volatility causing defaults translates to increased firing due to missed profits, in addition to productivity-driven displacement. These factors combine to reduce the economy's capacity to finance ever-growing

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numbers of workers, as clearly reflected in the growing unemployment rate (Fig. 8b; see Section 3.5). The increasing unemployment together with demographic change (see Schoenberg et al. (2025b)) drives an increase in government expenditure for transfer payments (Fig. 8d). Increasing transfer payments contribute to the government debt-to-GDP ratio (Fig. 8c). Increasing government debt increases government interest rates, further straining the budget, which reduces the government's ability to invest and pay for transfers and other government services.

Taken together, these results show that the FRIDA v2.1 Economy module produces internally consistent long-run macroeconomic dynamics under uncertainty. The widening confidence intervals for the results reflect the substantial uncertainty inherent in long-run economic projection under climate constraints. However, robust patterns do emerge: median nominal aggregates continue to rise, and real activity generally increases but slows towards the end of the century because financial, demographic, and labour-market constraints are sensitive to climate impacts. While median projections suggest a generally growing but decelerating economy, the ensemble intervals expose substantial risk arising from climate impacts on the financial system, which can generate persistent unemployment, increase transfer burdens and public debt, and halt growth.

6 Conclusion

A substantial body of research has identified critical limitations in contemporary IAMs: aggregate damage functions that operate as statistical black boxes, the absence of financial system representation despite mounting evidence of climate-related financial risks, a lack of business cycle dynamics and short-term mechanisms with long-term consequences, and exogenous treatment of innovation. The novel economy module of FRIDA v2.1 documented in this paper addresses these limitations. The module is defined by its institutionally disaggregated structure, which allows for the traceability of specific climate impact and policy pathways through distinct economic sectors and processes. Moreover, it enables the model to leverage more observable economic variables with available time series data, strengthening its empirical foundations beyond the highly uncertain parametrisations of aggregate damage functions.

While FRIDA v2.1 addresses several critical gaps in the IAM literature, it introduces others that are inherent to its approach. Its global aggregation masks local climate impacts, precluding geographically differentiated policy analysis. The disequilibrium framework presents two distinct challenges. First, historical calibration necessarily attempts to reproduce observed fluctuations—including exogenous shocks such as pandemics and wars outside the model's scope—using only endogenous mechanisms, potentially overfitting to historical volatility. Second, the absence of utility maximisation assumptions limits the identification of optimal policy sets. Our ensemble methodology partially addresses these limitations by presenting results as probability distributions rather than point forecasts, explicitly foregrounding the considerable uncertainties inherent to long-run economic projection.

The model's primary contributions lie in its endogenous treatment of economic processes and the inclusion of finance, innovation, and business cycles. FRIDA v2.1 adopts a Schumpeterian disequilibrium framework that explicitly represents the role of the financial sector in both short- and long-term dynamics. This enables the analysis of climate-related financial risks,

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transition funding, and the potential for disorderly transitions to trigger system-wide instability—dynamics that remain largely unexplored in current policy-relevant models. The endogenous representation of innovation, driven by both incumbent R&D activities and the financing of new market entrants, captures the inherently disruptive nature of technological change and its dual role in both promoting productivity growth and displacing existing investments and workers.

The simulation results demonstrate the model's ability to reproduce key macroeconomic dynamics over the historical period 1980–2023 and generate plausible projections through 2150. The ensemble approach, which is based on 100,000 simulation runs, produces widening confidence intervals over time, reflecting the compounding uncertainties as economic systems encroach on planetary boundaries. The median projections show that nominal aggregates increase throughout the simulation, whereas real activity expands more slowly and begins to decelerate as financial, demographic, and climate pressures accumulate. Moreover, the ensemble's more extreme scenarios reveal a substantial risk of economic volatility and even decline under more adverse climate impacts.

Following the historical period, the ensemble also reveals long-run constraints that arise from the model sectors' endogenous connections. Rising surface temperatures gradually weaken firms' ability to sustain investment by increasing failure rates and slowing growth. Moreover, demographic ageing and labour-market pressure increase the share of government spending devoted to transfers. Governments can rely on debt to maintain spending, but doing so increases interest burdens and inflationary pressure, further tightening fiscal conditions. These patterns—deteriorating investment conditions, rising welfare costs, and shrinking discretionary expenditures—emerge directly from the model's feedback structure rather than from imposed assumptions.

These endogenous constraints offer unique realism for policy experimentation with FRIDA v2.1. Climate-transition policy scenarios will operate within and interact with evolving financial, fiscal, and demographic pressures rather than being assessed in isolation. As a result, scenario outcomes reflect genuine trade-offs—for example, between maintaining welfare commitments, funding mitigation and adaptation, and preserving financial stability. By allowing these tensions to arise from the system's internal dynamics, FRIDA v2.1's economy module offers a rich exploration of transition pathways by embedding policy choices within the evolving macro conditions that will ultimately govern their success.

Appendix A: Payoff elements for calibration

Table A1: Calibration payoff elements, with dataset citations and notes

Variable name in source code	Source	Notes
Circular flow submodule		
private_consumption	(World Bank, 2023b, d)	Calculated
Labour_share_of_GDP	(ILO, 2024c)	
bottom_40_share_of_real_income	(WID, 2024)	
Finance submodule		

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total_investment	(World Bank, 2023b, c)	Calculated
government_consumption		
debt_to_gdp_ratio	(Poplawski-Ribeiro et al., 2023)	
Employment submodule		
Employed	(ILO, 2024a)	
Unemployed	(ILO, 2024d)	
Unemployement_rate	(ILO, 2024a, d)	Calculated
annual_aggregate_wages	(ILO, 2024c; World Bank, 2023b)	Calculated
GDP submodule		
nominal_GDP	(World Bank, 2023b)	
real_GDP_in_2021_c$	(World Bank, 2023a)	
nominal_gdp_growth_rate_deviation_from_average_in_calibration_period_summed	(World Bank, 2023b)	Calculated
real_GDP_growth_rate_deviation_from_average_in _calibration_perdiod_summed	(World Bank, 2023a)	Calculated
Inflation submodule		
gdp_difference	n/a	real GDP base year

Appendix B: Uncertain parameters

Table B1: Uncertain parameters with their estimated values and ranges rounded to three decimal places

Name in source code	Value	Min	Max
consumption_habits_adjustment_time	1.464	1.241	1.687
desired_savings_as_multiple_of_profits	12.006	11.989	12.023
desired_savings_as_multiple_of_wages	1.198	1.190	1.205
fraction_of_income_to_consumption	0.750	0.748	0.752
fraction_of_owner_income_to_consumption	0.750	0.747	0.753
initial_firms_checking_accounts	5003.534	4979.060	5028.009
initial_owner_savings	46357.047	46313.514	46400.579
initial_worker_savings	22209.036	22175.118	22242.955
normal_bottom_40_wages	0.116	0.114	0.118
profit_tax_rate	0.335	0.333	0.336
time_for_bottom_40_to_be_affected	2.717	1.328	4.106
time_for_inflation_to_change_consumption	1.000	0.981	1.019

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time_to_consider_desired_savings	2.373	2.308	2.438
time_to_pay_out_profits	2.522	2.511	2.532
time_to_reach_savings_goal	4.981	4.961	5.000
wage_tax_rate	0.213	0.210	0.216
xmiddle	0.743	0.736	0.751
xspeed	14.664	13.704	15.624
yfrom	1.672	1.570	1.774
yto	0.579	0.567	0.591
average_time_private_refinances_debt	3.000	2.772	3.228
bank_desired_asset_to_liability_ratio	1.100	1.099	1.101
bank_reference_formation_time	80.000	66.465	93.535
effect_of_default_rate_on_lending_standards_curvature	4.004	3.912	4.096
effect_of_default_rate_on_lending_standards_range	1.947	1.923	1.972
effect_of_lending_standards_on_failure_rate_curvature	5.915	5.677	6.154
effect_of_lending_standards_on_failure_rate_range	2.950	2.836	3.064
elasticity_of_bankruptcy_rate_on_risk_premium	2.960	2.859	3.061
elasticity_of_desired_bank_growth_rate_to_changes_in_lending_standards	2.983	2.913	3.053
equity_gap_above_min_effect	0.434	0.376	0.492
equity_gap_below_max_effect	3.105	2.409	3.802
equity_gap_effect_max_x_magnitude	0.170	0.152	0.188
equity_ratio_gap_effect_above_exponent	-1.132	-1.265	-1.000
equity_ratio_gap_effect_below_exponent	1.071	1.000	1.142
exploration_effect_midpoint	1.211	1.205	1.217
exploratory_premium	2.000	2.000	2.000
exponential_effect_of_interest_on_defaults	9.049	8.718	9.380
failure_rate_floor	0.002	0.001	0.003
initial_annual_bank_negative_profit_fractional_growth	0.140	0.050	0.230
initial_bad_loans	202.031	200.716	203.346
initial_bank_investment_growth_rate	0.084	0.083	0.084
initial_fraction_of_safe_loans_financing_innovation	0.030	0.027	0.033
initial_fraction_of_safe_loans_that_are_exploratory	0.020	0.017	0.023
initial_good_loans	8240.068	8193.957	8286.179
initial_net_bank_asset_fractional_growth	0.155	0.154	0.156
initial_non_energy_bank_investment	3000.000	2989.476	3010.524
initial_risk_premium	0.028	0.027	0.030
Initial_safe_assets	72569.200	72508.643	72629.757

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loan_maturation_time	11.561	9.000	13.000
max_change_in_failure_rate	0.076	0.073	0.079
max_change_in_lending_standards	0.227	0.224	0.230
max_risk_premium_increase_rate	0.015	0.015	0.015
normal_bank_profit_payment_fraction	1.000	0.993	1.007
normal_exploration_rate	0.037	0.037	0.037
normal_failure_rate	0.037	0.030	0.045
normal_growth_rate_of_GDP_growth_rate	1.000	0.826	1.174
normal_rate_of_converting_safe_loans_to_safe_loans_for_financing_innovation	0.030	0.029	0.031
renegotiation_time	1.000	1.000	1.000
reporting_delay	0.475	0.410	0.550
safe_asset_default_rate_threshold	0.015	0.015	0.015
scale_of_exploratory_loan_failure	7.508	6.016	9.000
sensitivity_of_bank_exploration_to_profit_decline	0.502	0.485	0.519
sensitivity_of_bank_profit_payment_to_net_asset_growth	1.100	1.093	1.107
sensitivity_of_defaults_to_changes_in_risky_interest	11.899	11.436	12.363
sensitivity_of_effect_of_safe_default_rate_on_lending_standards	0.151	0.146	0.156
sensitivity_of_effect_of_sta_on_failure_rate	0.567	0.350	0.850
sensitivity_of_effect_of_stranded_energy_capital_on_other_assets	2.156	1.000	3.313
sensitivity_of_exploratory_loan_failure_to_GDP_growth	1.049	1.008	1.089
sensitivity_of_failure_rate_to_investment_to_gdp_ratio	0.170	0.143	0.198
sensitivity_of_investment_and_GDP_difference	2.217	2.157	2.277
time_for_safe_loans_that_will_fail_to_actually_fail	13.752	13.527	13.977
time_to_change_lending_standards	1.140	1.119	1.162
tolerance_of_the_cap_on_indicated_risk_premium	0.010	0.005	0.015
average_time_government_refinances_debt	7.000	5.977	8.023
averaging_time_to_adjust_tax_based_on_income	2.284	2.219	2.349
baseline_interest	0.020	0.019	0.021
central_bank_adjustment_time	1.500	1.305	1.695
central_bank_interest_rate_reactivity	1.000	0.936	1.064
fraction_of_wages_as_child_transfer_payments	0.082	0.079	0.086
fraction_of_wages_as_pension	0.375	0.336	0.413
fraction_of_wages_as_unemployment_payments	0.250	0.176	0.324
inflation_weight	1.330	1.260	1.400
initial_government_debt	9712.900	8395.455	11030.345
initial_measured_GDP	20970.400	20000.000	21940.800

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initial_safe_interest	0.039	0.038	0.039
initial_smoothed_total_public_tax_income	2635.200	2584.367	2686.033
maximum_effect_of_debt_to_GDP_ratio_on_government_spending	1.245	1.237	1.252
normal_share_of_public_expenditure_available_for_investment_and_consumption_to_consumption	0.835	0.828	0.842
sensitivity_of_banks_gov_debt_risk_perception	0.100	0.050	0.150
sensitivity_of_STA_on_public_consumption	0.071	0.054	0.087
time_for_government_to_change_transfers	5.000	3.123	6.877
time_to_measure_unemployment	1.000	0.905	1.095
unemployment_weight	0.330	0.295	0.365
average_development_completion_time	5.000	4.746	5.254
fraction_of_productivity_gains_translating_to_firing	0.500	0.466	0.534
hiring_to_investment_ratio	0.455	0.450	0.459
initial_productivity_growth	0.026	0.026	0.026
initial_unemployment_rate	0.061	0.060	0.063
Initial_Wage_Rate	5695.751	5680.618	5710.883
labour_force_participation_fixed	63.939	63.615	64.263
max_change_in_fractional_wage_growth	0.069	0.068	0.070
negotiation_effectiveness	1.000	0.643	1.357
productivity_yield_of_exploratory_investment	1.947	1.938	1.957
productivity_yield_of_non_bank_innovation	0.133	0.132	0.134
profit_threshold_multiplier	1.000	0.769	1.231
rent_to_investment_ratio	0.250	0.248	0.252
sensitivity_of_firing_to_profit_discrepancy	0.500	0.250	0.750
sensitivity_of_hiring_to_unemployment_rate	2.290	2.262	2.317
share_of_employment_in_agriculture_intercept	62.902	62.005	63.799
share_of_employment_in_industry_intercept	-2.581	-3.371	-1.791
share_of_employment_in_industry_slope	2.931	2.875	2.987
share_of_employment_in_services_intercept	-30.739	-31.508	-29.970
share_of_employment_in_services_slope	7.498	7.435	7.562
Temperature_effect_on_high_exposure_productivity	-6.133	-7.823	-4.442
Temperature_effect_on_low_exposure_productivity	-2.083	-4.666	0.501
Temperature_squared_effect_on_high_exposure_productivity	-1.062	-1.500	-0.624
Temperature_squared_effect_on_low_exposure_productivity	-1.569	-2.000	-1.139
threshold_unemployment_rate	0.099	0.099	0.100
time_for_defaults_to_affect_firing	1.000	0.500	1.500
time_seeking_employees	1.417	1.391	1.443

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time_to_fire_from_missed_profits	1.000	0.500	1.500
Urgency_with_which_wage_growth_is_demanded	2.000	1.000	3.000
wage_adjustment_negotiation_time	2.000	1.000	2.999
initial_nominal_GDP_growth_rate	0.041	0.039	0.044
initial_real_GDP_growth_rate	0.024	0.007	0.041
Agriculture_share_of_GDP_intercept	3.449	3.017	3.880
agriculture_share_of_GDP_slope	-2.288	-2.570	-2.006
agriculture_share_of_GDP_starting_point_determinant	19.877	19.754	20.000
deflation_adjustment_time	3.825	3.803	3.848
inflation_adjustment_time	1.451	1.401	1.500
initial_animal_products_demand_growth_rate	0.020	0.005	0.035
initial_animal_products_production_growth_rate	0.035	0.020	0.050
initial_crop_demand_growth_rate	0.020	0.005	0.035
initial_crop_supply_growth_rate	0.020	0.005	0.035
initial_employed_growth	-0.015	-0.016	-0.014
initial_energy_demand_growth_rate	0.020	0.019	0.021
initial_energy_supply_growth_rate	0.020	0.019	0.021
initial_growth_rate_in_cropland	0.003	0.000	0.006
initial_growth_rate_in_grazing_land	0.001	0.000	0.002
initial_income_growth_rate	0.020	0.019	0.021
initial_inflation_index	0.383	0.382	0.384
initial_inflation_rate	0.061	0.061	0.062
time_to_measure_growth_rate	2.000	1.500	2.500
weight_of_cropland_inflation_contribution	0.094	0.066	0.123
weight_of_fertilizer_used_per_unit_of_crop_production	0.018	0.001	0.035
weight_of_grazing_land_inflation_contribution	0.054	0.001	0.108
weight_of_irrigation_water_used_per_unit_of_crop_production_inflation_contribution	0.050	0.036	0.064
weight_of_marginal_energy_cost_inflation	0.812	0.791	0.833
reference_cash_reserve_growth_rate	0.049	0.042	0.056
sensitivity_of_effect_of_cash_reserve_growth_rate_on_firms_innovation_orientation	-0.114	-0.156	-0.073
time_for_firms_to_adjust_innovation_orientation	3.005	2.000	4.009

Code and data availability. FRIDA is released as a free and open-source model on GitHub https://github.com/metno/WorldTransFRIDA. The specific version used for this manuscript, including the calibration data set for the complete model, is available on Zenodo https://doi.org/10.5281/zenodo.15310859 (Schoenberg et al., 2025a). The R code used to produce all figures in this manuscript is also available on Zenodo https://zenodo.org/records/18419262. The full infrastructure to run scenario ensembles with FRIDA is hosted on GitHub https://github.com/BenjaminBlanz/WorldTransFrida-Uncertainty. EMB ensemble data is available https://zenodo.org/records/15396799 (Schoenberg, 2025).

Author contributions. Conceptualisation: BC, MBG, WS. Data curation: MBG, BC, BB. Formal analysis: MBG, BB, BC, WS. Investigation: MBG, WS, BC, BB. Methodology: MBG, BC, WS, BB. Software: MBG, WS, BB. Supervision: WS, BC. Visualization: MBG, BB, WS. Writing - original draft: MBG. Writing - review and editing: BC, BB, WS, MBG.

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