

Response to Referee #2 Report

This is an impressive SD work worth celebrating. A strong incrementation for similar integrated models. My main comments are about the presentation and positioning of the model so it can be of use for policymakers, industry and academia.

We thank the Reviewer for the kind words and the constructive feedback on the manuscript. Below is a point-by-point response to the Reviewer's feedback, and the revisions to the manuscript it prompted.

1. Please elaborate in the Introduction or appendix clearly contrasting this economy module with previous versions and other climate–finance/ SFC macro–climate models. Ideally, a small table is desired that lists key dimensions (finance, business cycles, innovation treatment, damage representation, uncertainty) and shows what is new or improved in FRIDA v2.1 relative to those models

We agree that a comparison helps situate the contribution and thank the Reviewer for the idea. We have made a table contrasting FRIDA v2.1's economy module with a small set of comparable climate–finance and stock-flow consistent macro–climate models across the dimensions suggested by the Reviewer, and placed it in an Appendix (please see Appendix C in the revised manuscript), accompanied by a short explanation referring to the Appendix in the introduction:

“Table C1 in Appendix C provides an overview of IAMs with similar aims, alongside the classical DICE model for reference. While other models address some of the research gaps described above, they typically concentrate on the economy in isolation. FRIDA v2.1 stands out by including a similar level of detail in the other domains of the human–earth system (Schoenberg et al., 2025), and is one of only two models with fully endogenous innovation.”

2. Section 2 mixes motivations, theory, and trade-offs - I would focus a section per each.

We agree, and we have implemented this restructuring. Section 2 now opens with a subsection on the model's analytical aims, followed by a subsection on its conceptual foundations covering the Schumpeterian, disequilibrium, and stock-flow consistent commitments, and concludes with a dedicated subsection on limitations. The limitations subsection identifies three primary issues (geographic aggregation, optimal-policy identification under disequilibrium, and the calibration consequences of the endogenous oscillations) followed by a closing paragraph on uncertainty quantification. The separation clarifies the logical flow of the section and the distinction between the model's positive contributions and its acknowledged limitations. Due to the length of Section 2, we've

omitted showing the actual changes from this response letter. Please see the revised manuscript for the restructured Section 2.

3. In my opinion, the model is hard to make sense for a policy maker as it is now. It scares with complexity, and does not involve the user into the experiments. Also model description is quite static (looks like a validation - that you did the job good), at the same time misses holding the hand of the reader - so you can navigable the readership towards detailed reading, not skimming.

We agree with the Reviewer that writing can be difficult inaccessible to the reader in places. To improve the manuscript we implement the Reviewer's specific suggestions, listed below.

4. You can possibly add a more detailed "model roadmap" at the start of Sec. 3: a one-paragraph overview of each submodule (Circular Flow, Finance, Innovation, Government, Employment, GDP/Inflation) and a one-sentence statement of its main role in the overall feedback structure

We have added a roadmap paragraph at the start of Section 3. The paragraph introduces the seven submodules in the order in which they are documented and gives, for each, a short statement of its role in the module's feedback structure. The roadmap prepares the reader to anticipate how the submodules interact before encountering them in detail.

"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. Before turning to the detailed documentation, we provide a brief description of the seven submodules and their roles in the module's feedback structure. The Circular Flow submodule simulates firms' production and households' consumption. The Finance submodule mediates private investment affecting the flow of funds in and out of the circular flow, employment levels and interest rates. The Innovation submodule, together with the Finance submodule, governs R&D orientation and exploratory lending, determining the productivity growth that drives long-term economic development while displacing existing investments and workers in the short term. The Government submodule sets fiscal and monetary policy, with tax revenue, transfers, public debt, and the policy rate responding to conditions elsewhere in the economy. The Employment submodule translates investment flows into labour demand, wage formation, and unemployment, feeding back into consumption and government transfers. The GDP and Inflation submodules aggregate these flows into nominal and real output and determine the price level, which in turn affects consumption, wages, and the policy rate. This section documents the processes represented within each of these

submodules and how they interact in more detail. First, the Circular Flow submodule is described, followed by the Finance, Innovation, Government, and Employment submodules, and finally the GDP and Inflation submodules.”

5. Please consider explicitly reference the main equations/variables from simplified stock-and-flow diagrams (Figures 2–5) in the text (e.g. “as shown in Fig. 3, the risk premium depends on X)

We have added in-text references to select variables shown in Figures 2 through 5 throughout Section 3. The description of each submodule’s mechanisms now points the reader to the corresponding diagram, reducing the difficulty of mapping prose descriptions onto the figures unaided. Examples of these additions include:

“This variable, shown in figure 2, represents all the deposit accounts for all the world's firms.”

“Finally, global climate change, represented by increases in surface temperature anomaly (STA), further increases risk and is shown in Fig. 3 as an input to the failure rate.”

“Government expenditure, excluding interest payments on outstanding debt, shown as “public expenditure not including interest payments” in Fig. 4, 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 working-age population is divided into three stocks shown in Fig. 5: nonactive, unemployed, and employed.”

6. Elaboration of results is the weakest point of the paper. Given the complexity of the model, please consider adding the key schematic that highlights just the key feedback loops (e.g., climate → productivity → employment → transfers → debt → risk premium) - that would greatly help readers who would like to use findings from the study.

We have given this suggestion careful consideration. A rigorous treatment of FRIDA’s feedback structure is the subject of a separate forthcoming paper based on the Loops-That-Matter analytical method, where the relevant loops can be ranked and discussed with the analytical apparatus they require. Including a reduced schematic in the present manuscript would either pre-empt that work or risk presenting a diagram without the analytical grounding the forthcoming treatment provides. Given the already considerable length of this documentation paper, we believe its scope is best preserved by leaving the Loops-That-Matter analysis to the dedicated paper. We have addressed the underlying concern by expanding the discussion of the results in Section 5 in a way that connects

results to the underlying structure more thoroughly, as described in our response to comment 9.

7. Please be clear on the shortcomings and elaborate limitations with more detail. Its currently unclear for me which aspects of the historical series are deliberately not reproduced apart from mentioning 2009, 2020 pandemic. Missing what range of crises this is acceptable for the model's intended use as an exploratory tool? Say we have pandemic every 5 years from now - what time range of the model would still be feasible for use? Moreover, I would be surprised if model covered all business cycles related to innovation the model reproduces. Say the AI that is embedded at the large scale in the society? scarcity of rare earth? Potential wars and conflicts?

This concern overlaps with the issues raised by Reviewer 1 regarding the model's empirical performance and the framing of its cyclical dynamics. The revised manuscript addresses both Reviewers' concerns together through major revisions and expanded discussions of limitations across Sections 2, 4, 5, and 6. Section 2 now contains a dedicated subsection on limitations that identifies the three principal trade-offs of the chosen approach, including the calibration consequences of representing only one driver of business cycle behaviour. The discussion makes clear that real-world business cycles arise from multiple endogenous and exogenous drivers that lie outside the model's scope, including pandemics, wars and conflicts, technological progress, and resource scarcities of the kind the Reviewer mentions. The model's endogenous oscillations should be read as illustrating the qualitative behaviour of a single structural mechanism, the Schumpeterian innovation/finance nexus, rather than predicting the timing or amplitude of future actual cycles. Sections 4 and 6 elaborate on these points in the context of the calibration and interpretation of results.

The most relevant new passage is from the revised Section 2, under the limitations subsection:

"The third limitation arises from the model's endogenous business cycles. As a consequence of its Schumpeterian foundations (Schumpeter, 1939), FRIDA v2.1 features emergent business cycles from the interaction between innovation and finance, a relatively unique feature among current IAMs of comparable scope. While the dynamic is ultimately nested in production dynamics, their magnitude and timing are affected by financial dynamics and aggregate financial actors. The cycles featured in the model, however, are significantly different from actual business cycles. The former are produced by a single, endogenous driver, namely the performance of innovative activities in a market economy, while the latter are complex phenomena driven by multiple endogenous and exogenous drivers, and

their interactions (Ramey, 2016). The representation of realistic business cycles lie outside the model's scope. The model is therefore unable to either accurately reproduce specific historical cycles, or forecast the timing and amplitude of future ones. The model's cycles should be read as illustrating the qualitative behaviour of one structural mechanism, rather than as point predictions of macroeconomic activity. Their purpose, instead, is to enable the analysis of climate change, and climate-related policies, with innovation-related endogenous business cycle dynamics."

In Sections 4 we write:

"The single-run EMB run, as shown in Fig. 6, presents the model's behaviour over the 1980–2023 calibration period, with simulated trajectories whose general level and variability are broadly consistent with the observed data. Notable features of these results include the model's ability to produce business cycle fluctuations, which are visible in the changing slope of GDP (Fig. 6a and 6b) and are particularly prominent in the unemployment rate (Fig. 6k) and the labour share of GDP (Fig. 6h). These cycles arise from the interaction of innovation and finance described in Sections 3.2 and 3.3, and should not be interpreted as replicating specific historical downturns. Their amplitude and frequency are broadly consistent with observed macroeconomic variability, but their phase does not align perfectly with particular historical economic events, since FRIDA does not include shocks exogenous to the processes described in Section 3. 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."

Finally, we add the following paragraph in Section 6:

"[The] 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. The resulting calibration should therefore not be interpreted as a replication of specific historical episodes, and the endogenous oscillations the model generates do not, and are not intended to, align perfectly in phase with observed business cycles."

8. The current contribution is vague for a policy maker to take an action. Suggest adding one illustrative figure showing the distribution (histogram) of a key outcome (e.g. real GDP in 2100) to make the probabilistic reading more concrete. Make sure the that is improved so readers have an interactive tool to play with.

We appreciate the suggestion regarding the histogram and agree wholeheartedly that it would aid interpretation of results. We have added a histogram showing the distribution of real GDP for seleveted years across the 100,000-member ensemble, together with the 67% and 95% confidence bounds and the best-fit single run for reference:

“

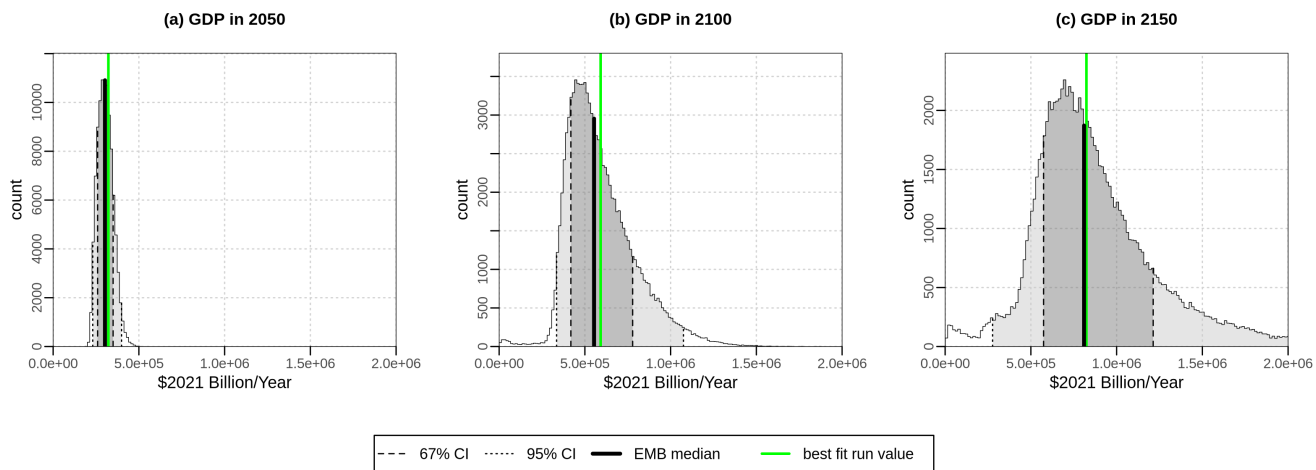


Figure 7: Histogram of the distribution of real GDP in 2021\$ across the 100,000 ensemble members in the years 2050 (a), 2100 (b), and 2150 (c). The black solid line shows the median, darker shaded areas show the 67% confidence intervals, and lighter shaded areas show the 95% confidence intervals. The green line indicates the value of the calibrated best fit estimate in these years.”

And we expanded the first paragraph of Section 5 to describe the new figure:

“Fig. 7 shows the distribution of the ensemble members results for real GDP in selected years. As the runs progress the spread increases, exhibiting a fat tail. The ensemble median remains close to the calibrated best fit throughout the simulation period. This is a result of the uncertainty procedure varying the parameters symmetrically around the calibrated values. In the following figures the best fit run is not explicitly shown. It is treated as merely one of the ensemble members.”

9. I would argue there is a need to explain the story by binding variables to macro outcomes and the need for interventions, e.g.: higher STA → higher failure rates → investment slowdown → higher unemployment → more transfers → higher debt → higher risk premia → further slowdown.

We agree that the manuscript could benefit from more narrative around the results, connecting them to them to the model structure. To address this concern, we have expanded the discussion in Section 5 in key places. As explained in our response to point 6, a forthcoming publication will delve deeper into the feedback structure of FRIDA .

We add the following new passages in Section 5:

“The investment slowdown originates in the Finance submodule (Section 3.2), where the rising STA increases the failure rate on new loans. The result is higher lending standards and risk premia, which together dampen private investment and income growth.”

“The default rate itself is climate-sensitive: rising STA increases defaults on new loans, and the resulting defaults sustain the risk premium even as the safe interest rate falls. The widening gap between the safe and risky rates is therefore a direct channel through which climate impacts are transmitted to the cost of investment finance.”

“Transfers are designed to be countercyclical in the model: the share of expenditure directed to transfers adjusts with the number of unemployed and with the child and retiree cohorts, so a rising unemployment rate and a rapidly ageing population both enlarge public spending.”

10. Consider adding a short comparison of results using the best-fit parameter set vs the median of the ensemble, to illustrate the role of uncertainty and what can be done to improve the outcome

We agree that the role of uncertainty will be better communicated by expanding the nature of the median run vs the best-fit run. Our expanded discussion of the ensemble’s apparent smoothness, prepared in response to Reviewer 1’s comments on Figures 6 and 7, addresses what a side-by-side comparison between the best-fit run and the ensemble median would illustrate. The best-fit run is a single trajectory generated under one specific parameterisation, while the ensemble median is the cross-member median at each point in time across 100,000 trajectories whose parameterisations differ. Since individual ensemble members oscillate with different periods, amplitudes, and phases, the median is necessarily smoother than any single member, including the best-fit run. The histogram introduced in response to comment 8 marks the best-fit value within the distribution, allowing readers to see how it sits relative to the ensemble without dedicating an additional comparative figure to it. We hope this combination addresses the Reviewer’s underlying concern about the role of uncertainty in interpreting the results.

The expanded paragraph in Section 5 reads as follows:

“[...] 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, especially Fig. 7, display relatively smooth trajectories as they show statistical measures of the asynchronous oscillatory behaviour across ensemble members. The smoothness is therefore a property of the ensemble statistics rather than of the model dynamics. Each member oscillates, but members differ in the period, amplitude, and phase of their cycles because they are generated under different parameterisations. When the median is taken across members at each point in time, peaks in some members coincide with troughs in others, flattening it. The same characteristic widens the confidence intervals, since the spread reflects both projection uncertainty and the different cycle phases across the ensemble.”

11. Ensure terms such as “safe loans”, “exploratory loans”, “performing/nonperforming loans”, and “risk premium” are defined once and used consistently. Same with other terms that have synonyms in the paper.

We have audited the manuscript for consistent use of these and related key terms, ensuring that these terms are defined where appropriate and used consistently.

12. For Figures 6–8 please consider explicitly stating in each caption what the lines and shaded areas represent (median, 67%, 95%).

The captions for Figures 6, 7, and 8 now state explicitly that solid lines show the ensemble median, darker shaded areas show the 67% confidence intervals, and lighter shaded areas show the 95% confidence intervals. The same convention is applied across all three figures for consistency:

“Figure 7: Nominal and real GDP and their components across the 100,000-member ensemble. Solid lines show the median, darker shaded areas show the 67% confidence intervals, and lighter shaded areas show the 95% confidence intervals.”

“Figure 8: Key variables of the Finance submodule across the 100,000-member ensemble. Solid lines show the median, darker shaded areas show the 67% confidence intervals, and lighter shaded areas show the 95% confidence intervals.”

“Figure 9: Changes in labour productivity, unemployment rate, government debt to GDP, and the share of government expenditure spent on transfers across the 100,000-member ensemble. Solid lines show the median, darker shaded areas show the 67% confidence intervals, and lighter shaded areas show the 95% confidence intervals.”

Good luck with the revision, I hope my comments will make the paper stronger

Sincerely,

Martin B. Grimeland, Benjamin Blanz, William Schoenberg, and Beniamino Callegari