

Response to Referee #1 Report

Dear Reviewer and Editor,

We thank the Reviewer for taking the time to review our manuscript, and for the constructive feedback. We are grateful for the positive remarks regarding the conceptual motivation and quality of the manuscript and the constructive criticism we received.

We acknowledge, first and foremost, that the original manuscript overstated the model's empirical performance with respect to historical business cycles. Language such as "reproduces major economic downturns" created expectations that neither the figures nor the model support. Upon reflection, we recognize that this framing was misaligned with the model's actual purpose and design intent. FRIDA was never designed to predict or precisely replicate historical business cycles. Its purpose is to serve as a transparent, process-based platform for the exploration of possible scenarios and policy experimentation within a climate-economy context.

Based on the Reviewers comments, we have substantially corrected these claims throughout. This makes it clearer that the contribution is more of a "conceptual integration rather than an empirically validated cycle-generating macro module", just as the Reviewer has pointed out. The precise changes are detailed below. We believe that the revised manuscript presents a significantly more accurate and transparent account of what the model does, what it does not do, and why. Below is a point-by-point response to the Reviewers, along with the revisions we have made to address the feedback.

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

Summary

The manuscript presents an ambitious attempt to embed a Schumpeterian, stock-flow consistent, disequilibrium macro-economy within an integrated assessment modeling (IAM) framework. The conceptual motivation is strong: IAMs typically lack explicit financial dynamics, innovation processes, and macro-economic instability. The authors aim to fill this gap by developing a macro module capable of generating endogenous cycles, downturns, and financial stress.

However, the manuscript's central empirical claim, that the model reproduces major historical downturns and macroeconomic cycles, is not supported by the evidence presented. Figures 5-7, which are intended to demonstrate the model's empirical validity, instead reveal substantial mismatches with observed data. These discrepancies raise fundamental questions about the model's suitability for long-run IAM applications, especially given the extensive literature showing the inherent difficulty of predicting business cycles even a few years ahead.

1. Scientific Significance

The conceptual ambition is high, and the integration of Schumpeterian innovation and stock-flow consistent (SFC) accounting into an IAM is potentially valuable. However, the claimed contribution (capturing macroeconomic cycles and major downturns) is not demonstrated.

We appreciate this assessment and agree that the original manuscript incorrectly described the model's empirical performance with respect to historical business cycles. In particular, we accept that language such as "reproduces major economic downturns" created expectations inconsistent with the model's design and results. We have undertaken a thorough revision of claims throughout the manuscript to bring them into alignment with the model's original design intent, as understood by the Reviewer: a macro module capable of generating endogenous cycles, downturns, and financial stress within an Integrated Assessment Model structure, not point-accurate empirical cycle replication and prediction.

In the revised manuscript, we have substantially revised the introduction and all relevant sections to be transparent about the model's aims—explaining what it does and does not do. The model's primary contribution, as now clarified, lies in its structural integration of Schumpeterian innovation dynamics, stock-flow consistent finance, and disequilibrium macroeconomics within an IAM framework. The model structure is novel among IAMs of comparable scope and enables the analysis of climate-finance interactions, transition risks, and policy feedbacks that are absent from mainstream models.

A key clarification—that receives more space in the revised manuscript—concerns the nature of the business cycles present in FRIDA. The model generates endogenous oscillations as a consequence of the interaction between innovation and finance. In a Schumpeterian framework, innovation inherently begets cyclical dynamics. These oscillations are further augmented by the interactions between innovation and finance. A model that featured Schumpeterian innovation and financial dynamics without producing cycles would be theoretically inconsistent. These oscillations emerged from our attempt at the most parsimonious implementation of Schumpeterian economic theory—as we expected.

However, we now make explicit that the Schumpeterian cycles featured in FRIDA represent only a single endogenous component of the complex phenomenon that is the actual, observable business cycle. Real-world business cycles arise from a multiple, interacting endogenous and exogenous drivers that lie outside the model's scope. Because FRIDA captures only the Schumpeterian innovation-finance driver, it has no pretense at either reproducing historical business cycles in their full complexity, or predicting future highs and lows. What the model is designed for is the exploration of how Schumpeterian economic dynamics, including some oscillatory dynamics, interact with other model mechanisms, particularly climate impacts, financial fragility, and policy levers.

We have undergone a language audit to change all instances implying cycle prediction and replication, replacing it with language such as:

"The simulation results show that the model produces dynamics broadly consistent with observed macroeconomic patterns over the calibration period 1980–2023, and generates plausible projections through 2150."

Moreover, we have thoroughly revised Section 2 to include the following paragraph that explains the nature of the models economic cycles within a new dedicated limitations section (2.3):

“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.”

Section 4, which presents the simulation and uncertainty methodology, have also been edited and expanded with clarifications regarding the model's fit to data, and how to interpret figure 6 in light of its oscillations:

“The single-run EMB run, as shown in Fig. 5, 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. 5a and 5b) and are particularly prominent in the unemployment rate (Fig. 5k) and the labour share of GDP (Fig. 5h). 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.”

- Figure 5 shows that the model fails to reproduce the 2009 and 2015 downturns, despite these being among the most significant macroeconomic shocks of the past decades.
- The unemployment simulation moves in the opposite direction of observed unemployment in several periods.

The Reviewer is correct that the model does not reproduce the 2009 or 2015 downturns, nor the associated unemployment movements. These events were significantly affected by mechanisms outside FRIDA's current scope. Since the model does not include the specific shocks and other endogenous mechanisms behind the 2009 and 2015 downturns, the model cycle inevitably differs from the historical record. Even if FRIDA were somehow able to replicate past business cycle data, it would still in no way possess any predictive power, as such replication would be more coincidental than substantial. We acknowledge that the original explanation provided in Section 4 was insufficiently prominent and substantially undermined by overstated claims earlier in the text.

We believe that the three revisions described above address these concerns. They include, (1) language audit and edits, (2) clarification of the model's intent and limitations in the revised section 2, and (3) expanded discussion of figure 6 (previously 5).

- The simulated labor share lies outside the historical range for 1980-2000.

We appreciate the reviewer raising this point, and we wish to clarify a factual matter regarding the data. The labour statistics used for calibration are sourced from the ILO, the source that provided us with the broadest and most complete source of employment data for the relevant level of aggregation, which provides data for this indicator only from 2004 onwards. The period 1980–2000, as referenced by the Reviewer, does not have historical data available in our source. To clarify this for readers, we have expanded Section 4 in the revised manuscript to explain the availability of data and temporal coverage:

“The temporal coverage of the historical data series varies. The labour share of GDP for instance, sourced from the ILO, begins in 2004, which accounts for the absence of observed data before that year in Fig. 6g and h.”

- Figure 6 shows no meaningful cyclical behavior, only trend-like projections with wide confidence intervals.
- Figure 7 shows cycles only in the sense that the confidence interval is extremely wide; the median itself exhibits a downward drift.

We agree with the Reviewer that several panels in Figures 6 and 7 appear to show only trend-like projections or wide confidence intervals rather than cyclical behaviour. This is an artefact of the ensemble presentation method, not an absence of cycles in the model. As noted in the original manuscript (lines 550–552), individual ensemble members exhibit oscillatory behaviour, but because the 100,000 members oscillate asynchronously due to the different parameter values—with different phases, amplitudes, and timing—the median and confidence intervals smooth these oscillations out. The wide confidence intervals reflect genuine

uncertainty in long-run projections, which we consider an honest and informative feature of the ensemble methodology, not a deficiency.

We want to reiterate that precise model fit, for the purpose of obtaining precise parameter values or otherwise, was never the intention of the model, nor is it appropriate given the model's scope. The purpose of the model is to provide a transparent, process-based platform for exploration of possible scenarios and policy experimentation. The ensemble is designed to communicate the range of plausible futures rather than a single deterministic projection—a commitment to uncertainty quantification that we believe is a strength, particularly given the well-documented problems with overly precise long-run economic forecasts which the reviewer has highlighted. We do agree with the Reviewer that the current Figures, especially unsupported by specific explanations, are misleading, a limitation that should be addressed.

To address the Reviewer's concerns directly, we have expanded the discussion in Section 5 regarding the apparent absence of oscillations in some of the ensemble figures:

“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.”

Given these issues, the manuscript does not yet demonstrate a substantial advance in modeling science for IAMs. Many existing IAMs can reproduce long-run trends; the novelty claimed here is not supported by the results.

We hope that the revisions detailed above, together with the other changes described below, would help addressing this concern and ensure that FRIDA's contribution is properly presented.

2. Scientific Quality

The modeling framework is internally coherent, but the empirical validation is insufficient and, in some cases, contradictory to the claims.

2.1. Mismatch between claims and results

The manuscript repeatedly asserts that the model “reproduces major downturns” and “captures macroeconomic cycles.” However:

- The model does not reproduce the 2009 or 2015 downturns.
- The unemployment dynamics are counterfactual.
- The labor share simulation is systematically misaligned with historical data.
- No cycle-focused diagnostics (e.g., year-on-year changes, HP-filtered cycles, turning-point analysis) are provided.

Please see the above discussion and revisions under point 1. We fully accept that the original framing was incorrect and have thoroughly modified it in the revised manuscript. Regarding the absence of cycle-focused diagnostics, we appreciate the suggestion and have given it due consideration. Considering our revised and clarified position that the model does not aim to reproduce or predict historical business cycles, such diagnostics would impose an evaluation criterion misaligned with the model's purpose. The model's endogenous oscillations arise from Schumpeterian innovation–finance interactions and represent one theoretical driver of business cycles among many. Applying turning-point analysis or HP-filtered cycle comparisons would implicitly benchmark the model against the DSGE standard of historical cycle replication and prediction that it does not aspire to. We have, however, ensured that the revised manuscript is transparent about this scope, so that readers can evaluate the model on terms appropriate to its design.

2.2. Lack of engagement with DSGE and macro-forecasting literature

There is a large body of work such as DSGE, VAR, and macro-forecasting studies, demonstrating that:

- Business cycles are extremely difficult to predict, even 1-3 years ahead.
- Models that match long-run trends often fail to match short-run dynamics.
- Predicting cycles over 50-100 years is not considered feasible in the macroeconomics literature.

The manuscript needs to acknowledge these fundamental limitations, and justify why this model should be able to do what DSGE models cannot.

We are in complete agreement with all the points raised by the Reviewer here had the motivation behind the model been similar to that of DSGE-, VAR-, and macro-forecasting studies. Several of revisions to the manuscript explained above explains how we have repositioned the paper conceptually and clarified its scope based on the Reviewers feedback. Importantly, we do not claim that FRIDA can do what DSGE models cannot. Rather, our revised framing makes clear that FRIDA occupies a fundamentally different methodological position. The model does not attempt to forecast or predict business cycles. Its Schumpeterian oscillations emerge from the model's structural interactions between innovation and finance—they are a theoretical and demonstrated consequence of the framework, and should not be presented as a forecasting output. The question FRIDA addresses is not “when will the next recession occur?”, it is rather a framework for exploring how endogenous innovation–finance-

driven oscillations interact with climate impacts, financial fragility, and policy interventions within an integrated assessment framework.

To further situate our model and contribution within the landscape of Integrated Assessment, we have included a model comparison table (see Appendix C in the revised manuscript). It compares our work with a small set of comparable climate–finance and stock-flow consistent macro-climate models. We hope that this table and the various edits detailed elsewhere would suffice to clarify and properly limit the scope of our work.

2.3. Implications for IAMs

For IAMs, the question is whether this macro block provides reliable, policy-relevant dynamics. Given the weak empirical performance, it is unclear whether the model adds value beyond simpler trend-based representations.

This is an important question, and we are grateful to the Reviewer for pressing it. We believe the answer is yes, but we recognise that our original manuscript did not make the case clearly enough—precisely because the overstated business cycle claims distracted from the model’s actual contributions.

The value FRIDA adds beyond simpler trend-based IAMs is not in cycle prediction, but in the structural richness of its economic architecture. Specifically, FRIDA’s economy module enables the study of: (1) climate–finance interactions, including how rising temperatures increase investment failure rates and affect lending standards, credit conditions, and financial fragility; (2) the fiscal consequences of climate impacts, as rising unemployment and demographic change drive transfer payments and public debt dynamics; (3) the potential for disorderly transitions, where delayed climate action triggers sudden asset revaluations and systemic financial stress; and (4) the interaction between innovation, disruption, productivity and climate. None of these mechanisms are available in trend-based IAMs, and their inclusion responds directly to the calls made by Sanders et al. (2022), Stern et al. (2022), Pollitt and Mercure (2018), and Keppo et al. (2021) for expanded IAM methodological scope.

The endogenous oscillations, while not calibrated to specific historical episodes, play an analytical role: they allow the model to explore how economic volatility—arising from the structural interaction of innovation and finance—amplifies or dampens climate impacts and policy effects. For example, we observe connections between cycle amplitude and surface temperature anomaly, that provide insight into how climate change may affect economic stability through finance. The question is not whether these specific cycles will occur, but whether the structural connections that produce them are analytically informative. We believe that they are, and that the revised manuscript makes this case more explicitly.

3. Presentation Quality

The manuscript is generally well written, but the presentation of results is not balanced. A more transparent discussion of model limitations would strengthen the manuscript.

We appreciate this feedback and agree that the original presentation was not sufficiently balanced. The revised manuscript includes a substantially expanded discussion of limitations, both in Section 2 (where the conceptual foundations and scope are established) and in Sections 4 and 5 (where results are presented and discussed), as discussed above.

The extensive edits and expanded discussions in Sections 2, 4 and 5 are described above. In addition, Section 6 (the conclusion) was also expanded to elaborate and reiterate on the limitations:

“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. 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.”

Moreover, we took this opportunity to expand the new limitations subsection within Section 2 by discussing the limitations that arise from eschewing utility maximisation assumptions common to mainstream IAMs in favour of our Schumpeterian disequilibrium approach:

“The second limitation concerns optimal policy identification. Without utility maximisation assumptions, our disequilibrium framework restricts our ability to identify optimal policy set. While many IAMs are designed for this purpose, (Ackerman et al., 2009) note that the resulting optima are highly sensitive to assumptions regarding discounting, technological change, and uncertainty. We therefore trade the ability to derive formally optimal policies for an approach that avoids conditioning policy analysis on these contested assumptions. Considering our aims, and the scope afforded by our approach, we consider this trade-off acceptable.”

4. Improvements

To move toward publication, the authors would need to:

1. Reassess the claim of capturing cycles, given the DSGE literature and the model's performance.

As detailed above, all claims regarding cycle capture have been thoroughly revised. The model is now presented as generating endogenous Schumpeterian oscillations—a structural feature of the framework—rather than as reproducing or predicting observed business cycles.

2. Provide rigorous cycle-focused validation (year-on-year changes, filtered cycles, turning-point analysis).

As discussed above, we respectfully suggest that cycle-focused validation diagnostics such as HP-filtered cycles and turning-point analysis would presuppose an objective—historical cycle replication—that the revised manuscript no longer claims. Applying such diagnostics would impose an evaluation standard that is not aligned with the model’s design intent. We believe that our revised framing makes this scope sufficiently clear, allowing readers to evaluate the model on appropriate terms.

3. Discuss why the model misses major downturns and what this implies for long-run projections.

The revised manuscript provides an expanded and more prominent explanation of why the model’s endogenous dynamics do not align with specific historical episodes (absence of exogenous shocks, representation of only one endogenous cycle-generating mechanism, etc.), and) and discusses the implications for interpreting long-run ensemble projections.

4. Clarify the intended use case: is the model meant to capture cycles, or long-run structural trends?

The revised manuscript clarifies that the model is designed to provide a structurally rich, process-based platform for climate–economy analysis and policy experimentation. It is not designed to capture historical business cycles or produce long-run trend forecasts in isolation. Rather, it integrates short-term dynamics (innovation, finance, employment) with long-term processes (productivity growth, demographic change, climate impacts) to study their mutual interactions under uncertainty. The endogenous oscillations are a theoretically motivated feature that enables the exploration of how economic volatility interacts with climate constraints and policy choices—not a forecasting tool.

5. Consider reframing the contribution as a conceptual integration rather than an empirically validated cycle-generating macro module.

We accept this recommendation and have implemented it. The revised manuscript frames the model’s contribution in terms of its novel structural architecture—the integration of Schumpeterian innovation, stock-flow consistent finance, and disequilibrium macroeconomics within an IAM—and the analytical possibilities this opens, rather than as an empirically validated cycle-generating module. The empirical calibration is presented as demonstrating that the model produces dynamics broadly consistent with historical macroeconomic patterns, sufficient for its intended purpose as an exploratory and experimental platform, without claiming point-accuracy in cycle replication.

We hope that these revisions address the Reviewer’s concerns satisfactorily. We are grateful for the constructive engagement, which has substantially improved the manuscript’s clarity, transparency, and self-awareness regarding its scope and limitations. We believe the revised

manuscript now presents an honest account of the model's capabilities and analytical value, and we look forward to the Reviewer's further assessment.

Sincerely,

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

Response to Referee #3 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:

“

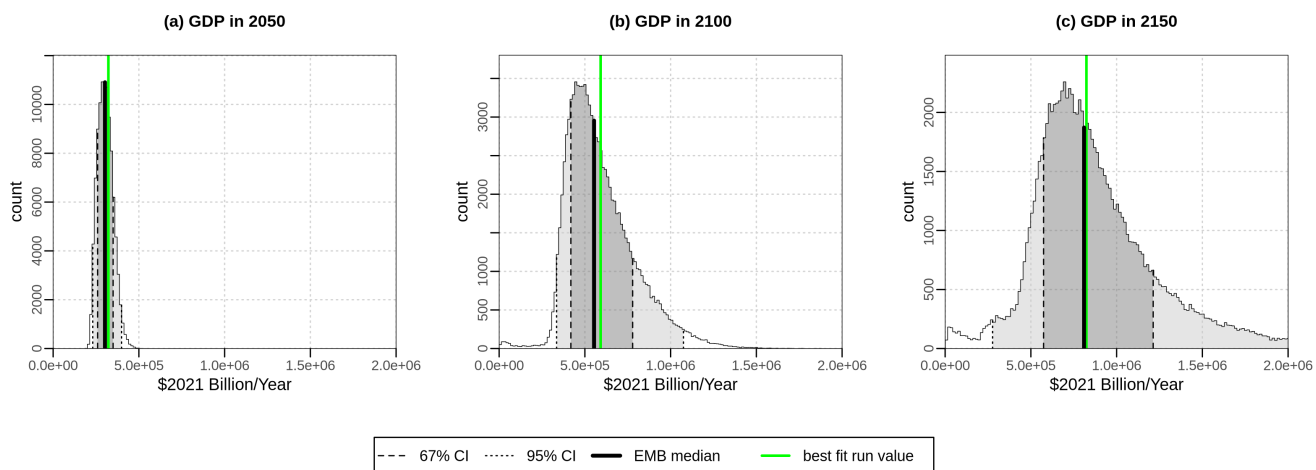


Figure 7: Histogram of the distribution of real GDP in 2021\$ across the 100,000 ensemble members in the years 2050 (a), 2100 (b), and 2150 (c). The black solid line shows the median, darker shaded areas show the 67% confidence intervals, and lighter shaded areas show the 95% confidence intervals. The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