

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