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This is FRIDA (v2.1): an introduction to the FRIDA GMD collection

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Abstract. FRIDA is a new contribution to the portfolio of integrated assessment models (IAMs) that address the climate – energy – economy – and society nexus. The FRIDA acronym stands for *Feedback-based knowledge Repository for IntegrateD Assessments*. Naming it a "knowledge repository" signals that the FRIDA model is never finished; it represents the current state of knowledge of the development team at any given time.

FRIDA was developed through the European Horizon project *WorldTrans – Transparent Assessments for Real People* (2022–2026). The journal *Geoscientific Model Development* has given us space to document FRIDA, including its submodules and spin-offs, in a special *GMD collection* (https://gmd.copernicus.org/articles/collection12.html, last access: 18 May 2026). This brief paper is the introduction to the GMD FRIDA collection of papers. The purpose of the introductory paper, written by the project lead on behalf of the consortium, is to provide the conceptual and institutional context for the original model and to make explicit the initial design requirements that guide FRIDA's ongoing development as a living knowledge repository.

FRIDA is implemented as a computationally efficient system-dynamics model and is accompanied by an Interactive Learning Environment. This combination makes it suitable not only for research, but also for education and broader outreach. In particular, FRIDA can be used in interdisciplinary climate science courses to show how individual disciplines (e.g. climatology, economics, demography) are tightly interwoven within the coupled climate–human system, thereby lowering the barrier to entry for users beyond the IAM community.

What sets FRIDA apart from traditional IAMs is its shift from exogenous, narrative-based scenarios to a fully feedback-driven framework, in which human activities and climate change co-evolve within a single system of equations. By explicitly representing these two-way feedbacks, FRIDA accounts for the impacts that climate change has already begun to exert on human systems; without them, projections of the human activities that drive climate change will become increasingly unreliable. Preliminary results suggest that including these feedbacks lead to systematically less optimistic projections than conventional IAM baselines.

1 Introduction (knowledge gaps that FRIDA aims to cover, incl. Shortcomings with scenarios)

Earth's surface temperature depends on the amount of greenhouse gases in the atmosphere – in the absence of any greenhouse gases the average temperature on earth would be a freezing −19 °C, instead of the approximately +15 °C we observe today (Ramanathan and Coakley, 1978). Any radiative change in this system results in a change in atmospheric temperature, an experiment humans have been running for the past 250 years. Access to cheap energy – facilitated by the invention of the steam engine and subsequent methods of extracting energy from fossil fuels – which co-evolved during the Industrial Revolution with accelerating population growth, has greatly disturbed the climate equilibrium. Changes in how we use land areas have also contributed greatly to pushing the climate system out of equilibrium.

For long, climate change was hard to notice. But by now, the world has entered the realm of *dangerous climate change*. In 2024, global average temperature exceeded 1.5 °C above pre-industrial levels for the first time (Bevacqua et al., 2025). While an isolated year above this threshold does not yet mean

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the high ambition goal of the Paris Agreement – to hold global temperature increase well below 2 °C and to pursue efforts to limit it to 1.5 °C on a sustained basis – human-caused climate change is already causing widespread adverse impacts and losses and damages (O'Neill et al., 2022 (IPCC AR6 WGII Chapter 16)), including observed increases in extreme heat, heavy precipitation and drought (Seneviratne et al., 2021 (IPCC AR6 WGI Chapter 11)), indicating that dangerous climate change is already being experienced.

Many questions arise, such as: Is it even possible to combat climate change while still pursuing better lives? What strategies can ensure that mitigation efforts are inclusive and just? Is it perhaps better to focus our efforts on adaptation to the new type of climate rather than trying to prevent climate change?

For as long as the UN has engaged in climate change negotiations, these questions have been on the table, and answers have been sought using a myriad of models and expert negotiation processes. But climate has continued to change. These recognitions – that negotiations still fail and that climate now affects our lives – were strong motivations for introducing a new IAM that explicitly includes diverse climate change impacts on humans. We call this new model FRIDA, with the subtitle *Feedback-based knowledge Repository for IntegrateD Assessments*.

What sets FRIDA apart from traditional IAMs is the shift from exogenous, narrative-based scenarios to a feedback-driven approach, where human activities (that drive climate change), and climate change (that drives impacts, such as reduced labor productivity or financial instability) co-evolve as equal partners within a single system of equations. In other words, FRIDA explicitly accounts for the impacts that climate change has already begun to exert on human systems. Without incorporating these feedbacks, projections of the human activities that drive climate change will become increasingly unreliable.

The collection of FRIDA papers in Geoscientific Model Development documents the development of FRIDA from its origins in 2023–2026 within the European Horizon project "WorldTrans – Transparent Assessments for Real People" (covering FRIDA version 2.1 and FRIDA v3), as well as the envisaged evolution in future versions. At the time of writing, FRIDA 2.1 is the official version.

2 Requirement for FRIDA

During the framing phase of the WorldTrans project in 2022 the team discussed at length how to design a model that would produce credible and relevant results for all three working groups of the IPCC, that would be able to advise on the European Green deal (to obtain climate neutrality by 2050, leaving no one behind) and which would be useable and useful for non-expert users. We came up with the following list of requirements:

- **Take advantage of conservation laws to constrain the model**. This involves including the carbon, heat and water cycles.
- **Begin with a non-regional model**. By building a global, rather than a regionally segregated, model, the model output remains simpler to analyze, due to the reduced number of degrees of freedom (which is large already on the global scale). The result is increased transparency and a better chance at building intuition and insights.
- **Balanced representation of climate and humans**. This means focusing on the minimum detail necessary to capture the important interconnections between subsystems.
- **Complete treatment of climate change forcing**. This means to include the main greenhouse gases (CO_2, CH_4, N_2O and HFCs) and the main cooling aerosol agent (SO_2), and to account for the effect of other climate forcers, such as those associated with land use change. It also means to model the sectors that create the greenhouse gas emissions (transport sector, energy production, land use and agriculture, chemical industries, cement production and waste). And it means considering the underlying economic system and demography that creates changes in those sectors.
- **Complete treatment of climate-driven feedback**. This implies taking into account, quantitatively, how climate affects (mostly damages) these sectors and the underlying economy and demography.
- **Complete treatment of uncertainty**. This implies keeping the computing speed low, to allow for large ensemble runs.
- **Include human needs, desires and behavior**. This means that (modelled) people can have an impact on the system, by changing behavior with respect to, for instance, dietary and mobility choices. This implies a departure from describing humans as purely theoretical economic beings maximizing profit or utility.
- **A dynamic representation of the economy**. This means to model the economy as a system that moves forward in time and acts and reacts to its surroundings, just like we model the rest of the system.
- **Modular organization of the model**. This is a requirement that improves the transparency of the model.
- **Familiar external levers**. To generate change in the system we include the possibility of acting as a decision maker within the various modules of the model (for instance within government, or within the financial or energy sector).

- **An accompanying toolbox for users of the model**. Since every model, even the simplest, is hard to interpret, we have developed a set of tools to aid the use of the model, aimed at our three user groups: (1) the *decision-maker* who would normally use IAM-based analysis to inform decisions about climate action. An important use context for the decision maker is the European Green Deal; (2) a *scientist*, say, a typical IPCC author who needs improved information flows and shared understanding of the system links and feedbacks between physical climate, the social and environmental impacts of climate change, adaptation responses, and mitigation efforts; and (3) the *engaged citizen* who is concerned about the climate challenge, but lacks the knowledge needed to engage in and catalyze a deeper societal discussion on the topic.

3 Design of FRIDA

FRIDA is built using the tools of System Dynamics (see e.g., Forrester, 1961; Sterman, 2000). This approach facilitates, at relative ease, the inclusion of very different disciplines and their methods, ranging from the laws of nature to empirical relationships, direct observations and co-created knowledge. Central to the approach are feedback and delay perspectives, which highlight the complex and oftentimes circular interactions between system components that endogenously generate behavior, making it a suitable approach to coupling the natural climate system with the many aspects of human life that can affect – and are affected by – climate. FRIDA is divided into seven modules: Climate, Human behavior, Land use and Agriculture, Energy, Economy, Resources and Demography (Fig. 1). All these interlinkages within and between the modules collectively create the complex dynamics of the system. This is what make it is easy to state that "everything is connected to everything", but comparably difficult to explain how.

In FRIDA, climate impacts are modelled as recognizable processes, such as the assessment of climate risk made by financial institutions, changes in demand for animal food products because of personal norms driven by climate risk perception, changes in demand for energy as a consequence of changing temperature; changes in labor productivity, changes in water use for irrigation, and so forth. To determine which impacts to include, the starting point was IPCC WGII AR6's assessment of literature on climate impacts and risks (Pörtner et al., 2022). Decisions were based on three criteria: (1) applicability to the [global] scope of FRIDA; (2) the expected global magnitude of the effect as agreed upon in the extant literature; (3) when the scope and magnitude of the impact was not agreed upon in the literature, was there enough data present in the literature to reproduce at least one pre-existing global study with wide uncertainty parameters? In addition, we added some climate impacts that are of relevance to the scope of FRIDA yet not included in the IPCC assessment. Details on the implementation of climate drivers and impacts in FRIDA are documented in Wells et al. (2026a) and Ramme et al. (2025). A graphical representation of the implementation of climate effects and impacts in FRIDAv2.1 is given in Fig. 2.

To build each module of FRIDA, the team entered an iterative cycle of mapping essential feedback loops, selecting equations and theoretical frameworks from scientific literature and developing novel "expert-supplied functional forms" when literature is insufficient, as documented in Schoenberg et al. (2025). Examples include:

- **Laws of Nature**: The model embodies the laws of nature within its Climate module, representing the Earth's radiation balance, carbon cycle, and water cycle. Specific examples include the three-layer energy balance model (simulating heat exchange between ocean layers) and the carbonate chemistry system in the ocean (Wells et al., 2026b; Schoenberg et al., 2025).
- **Leading Theoretical Frameworks**:
  - The Economy module uses a monetary model of production, consumption, and finance based on Schumpeterian dynamics of innovation and creative destruction (Schumpeter, 1942; Aghion and Howitt, 1992, 2009) to simulate the dynamic circular flow of income (Grimeland et al., 2026; Schoenberg et al., 2025).
  - The Behavioral Change module is conceptualized using the Motivation–Agency–Past Behaviour (MAP) meta-theoretical framework (van Valkengoed et al., 2025), which integrates motivational drivers, enabling conditions, and behavioural path dependence (Rajah et al., 2025; Schoenberg et al., 2025).
  - Population changes in the demography module are modeled as a continuous cohorting system (Eberlein et al., 2012), using "conveyors" to represent the physical dynamics of aging and age-specific mortality rates (Schoenberg et al., 2025).
- **Expert-Supplied functional Forms**: When established literature is insufficient for certain feedback loops, the team uses "expert-supplied functional forms" that are dimensionally consistent and behaviorally logical under extreme conditions. For example, energy infrastructure damage by climate is modeled as a power law function of the global temperature anomaly, representing how extreme warming increases the decay rate of capital. Climate impact on crop yields is modelled as a complex functional form that is linear in CO_2 concentration and quadratic in absolute temperature, capturing the antagonistic relationship between CO_2 fertilization and heat stress (Wells et al., 2026a; Schoenberg et al., 2025).

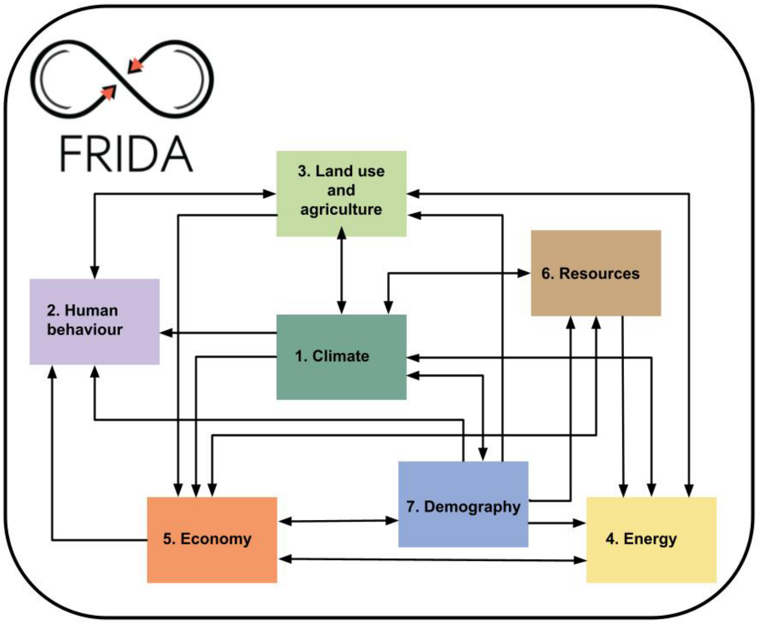

Figure 1. The modules and interlinkages in FRIDA V2.1. All modules except the climate module are collectively referred to as the "anthropogenic" modules of FRIDA. Note, however, that the "Land Use and Agriculture" module contains information about both nature and agriculture.

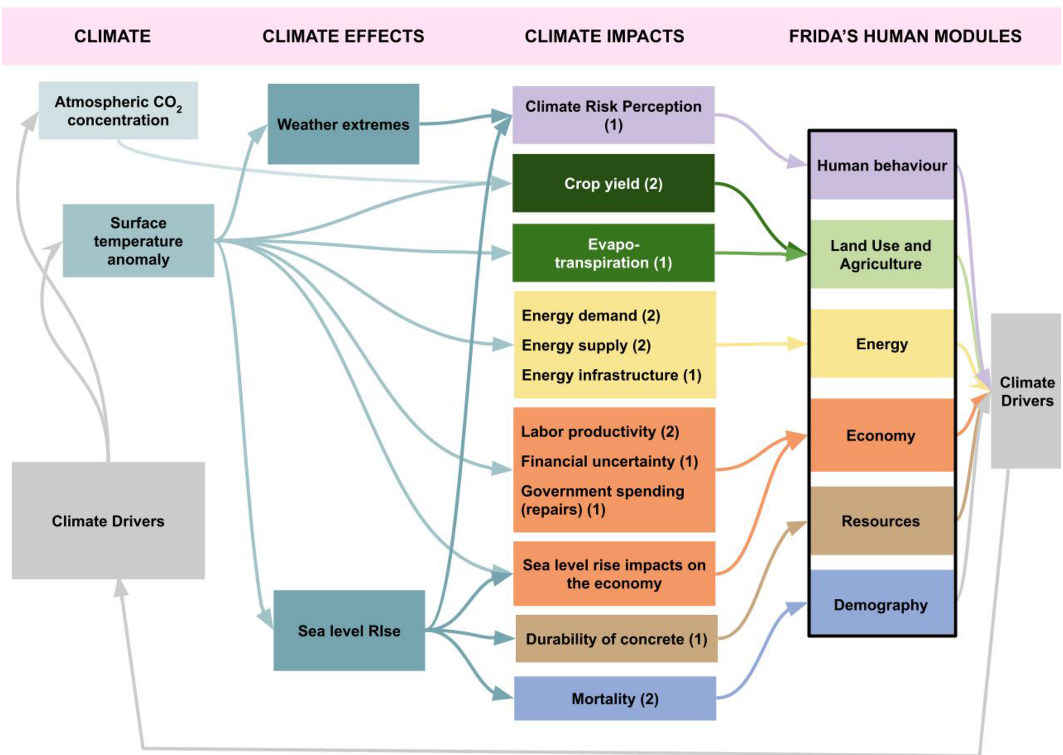

Figure 2. A schematic overview of the climate drivers and impacts in FRIDA V2.1, from climate change to the anthropogenic modules.

The calibration process of FRIDA happens in two steps: First, a partial calibration is made within each module, and then the full model is calibrated. During the latter process, the parameter estimates and uncertainty ranges that cannot with confidence be found in the literature – more than 800 parameters – are determined through calibration against historical data (1980–2023), using climate and socio-economic variables such as global GDP and its growth rate, inflation, investment, population, working age population, radiative forcing, energy use and so forth (158 time series in total). These serve as targets that the model should reproduce. Each uncertain parameter is given an initial uncertainty range by the team. Using those ranges, a 100 000-member Sobol sequence (Sobol, 1967; Saltelli et al., 2008) global sensitivity ensemble is run with the full model. The purpose of this analysis is twofold: (1) As a vehicle for calibration, by exploring the joint parameter space and selecting subsets that match historical time series, and (2) as a tool to quantify uncertainty and importance, showing how different parameters drive variability in model outcomes. Each variable from each model run is reported as the ensemble median – and 67 % and 95 % confidence intervals – over the horizon $\sim$ 2020–2150. Details are laid out in Schoenberg et al. (2025).

4 FRIDA's Endogenous Model Behaviour

A useful feature of a nearly all-inclusive model like FRIDA is that it does not require external forcing for future projections. The processes that are deemed important for the problem, i.e. within the scope of the model, exist inside the model. This is contrary to a typical Earth System Model and many process-based Integrated Assessment Models, which require external forcing to run (the former: for example, greenhouse gas emissions; the latter: for example, population growth). We call FRIDA's "free", or "unforced", or "endogenous" run the "*Endogenous Model Behavior*" (EMB) run. In the EMB run, all the change comes entirely from its internal feedback structure. The run is "free" because, after starting, all changes are driven solely by the model's internal mechanisms. It is "endogenous" because every variable that changes does so because of the model's own dynamics. And the results are tied to reality in the sense that where possible, the governing equations are based on science, and the parameterizations are arrived at through calibration with observations.

The significance of the EMB run is twofold: (1) it gives insights into how the system would evolve into the future without further policy changes or other external forcing, and (2) it gives us a base run to compare all forced runs to. By "forced runs" we mean experiments during which external levers are pulled, or forcings or parameters are altered.

5 Using FRIDA

FRIDA is designed as an intuition builder, not as a source of precise future projections with fine regional granularity and sectoral detail. It is possible to run experiments on one's desktop in minutes. To do so one can adjust a lever or parameter at any time during the model run and see what happens. To set up experiments with FRIDA the team developed a few guiding principles (see the appendix) and a wide range of external levers that can be pulled to run experiments (the original set is documented in Schoenberg et al., 2025).

To facilitate the learning process, the FRIDA model is accompanied by an Interactive Learning Environment (ILE) (Mustafa, 2025). The ILE combines guided demonstrations with an interactive dashboard which can be used to investigate how the model responds to interventions. Dynamic visualizations illustrate the consequences of decisions across time scales. The user manipulates parameters through interactive levers, observe responses across more than 225 variables, and compare results with the EMB run as well as with predetermined "goals" for each experiment). The visualization framework highlights trade-offs, sensitivities, and unintended consequences, illustrating how even simple interventions can produce complex outcomes. The hypothesis is that by lowering technical and conceptual barriers, the platform extends beyond research applications to engage students, educators, and lay users. This makes the ILE well suited for interdisciplinary teaching, where students can see how their own discipline, whether economics, environmental science, or engineering, is interwoven with other domains in shaping climate futures.

6 Comparisons with other projections

FRIDA projections have been compared to the five Shared Socioeconomic Pathways: SSP1 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5 (Fossil-fueled Development) (O'Neill et al., 2017). In this comparison, Schoenberg et al. (2025) find that SSP1-, SSP2-, and SSP5-Baseline are overly optimistic regarding future economic growth, while SSP3- and SSP4-Baseline align more closely with FRIDA's ensemble behavior. The reason is the structural difference: FRIDA represents the climate–human system as a fully coupled, feedback-rich system, rather than treating many climate-to-human effects as exogenous, omitted, or highly aggregated. In conventional IAMs, much of the climate-damage literature has focused on aggregate GDP losses in top-down assessments (Howard and Sterner, 2017), often through highly aggregated damage functions that have been criticized as empirically weak and "black box" in nature (Pindyck, 2017). FRIDA instead replaces this with a more disaggregated, process-based representation of impacts (Grimeland et al., 2026; Wells et al., 2026a).

What this means in practice is that FRIDA allows climate damages to feed back onto the drivers of future growth. In the economy module, expected climate impacts reduce economic production primarily through reduced investment growth and financial fragility, while government budgets come under increasing stress from unemployment and demographic change; in some simulations, these combined pressures can even halt growth altogether (Grimeland et al., 2026). Unlike standard IAM baselines, FRIDA therefore does not assume that high GDP growth can continue largely unaffected in a warming world. Rajah et al. (2025) further show that, when behaviour is endogenized, future food and animal-product demand is lower than in the standard GDP-driven approach, producing slightly lower emissions and a somewhat cooler baseline climate. Ramme et al. (2025) likewise show that adding coastal feedbacks can generate non-linear damage patterns, including peak-and-decline storm-surge damages driven by endogenous retreat and reduced coastal investment. Wells et al. (2026b) add that even the climate module differs from standard simple-climate emulators because FRIDA-Clim uses a process-based carbon cycle within the coupled framework. Overall, the FRIDA papers therefore suggest not just a different set of numbers, but a systematically less optimistic future outlook, because once feedbacks from climate damages, finance, behaviour, and adaptation constraints are internalized, future growth paths become lower, more fragile, and less consistent with the high-growth baselines commonly used in conventional IAM exercises (Schoenberg et al., 2025; Grimeland et al., 2026; Rajah et al., 2025; Ramme et al., 2025; Wells et al., 2026a, b).

7 Outlook

FRIDA was conceived as a transparent, modular, and flexible integrated assessment framework designed to connect climate dynamics with the multiple facets of human activity that both drive and are affected by climate change. By framing FRIDA as a "knowledge repository" rather than a static model, we emphasize its role as a platform that can be continually updated with new scientific insights, policy needs, and empirical data.

IPCC AR6 WGII Summary for Policymakers (Pörtner et al., 2022) identifies one of the central challenges of climate change as the growing complexity of impacts and risks: multiple hazards interact with non-climatic stressors, producing compounding and cascading risks that are increasingly difficult to manage across sectors and regions. The present version of FRIDA (which at the time of writing is v2.1) demonstrates that it is possible to integrate climate forcing, human behavior, land use, energy, resources, demography, and the economy into a single, fully coupled system, making it possible to capture cascading socioeconomic risks and systemic feedbacks. Because changes in one sector propagate through the entire system with realistic lags and feedbacks, FRIDA is particularly well positioned to explore risks of systemic destabilization, identify leverage points, and illuminate co-benefits and trade-offs of mitigation and adaptation strategies.

A central advantage of FRIDA is its suitability for running a wide range of experiments. Its low computational cost enables users to explore thousands of alternative futures, whether testing hypothetical "what if" scenarios, assessing the effectiveness of different policy levers, or comparing model behavior across versions and against other frameworks. The EMB provides a powerful baseline for these explorations: it isolates the dynamics generated purely by the model's internal feedback structure, allowing users to distinguish between outcomes that emerge from past actions already "baked into the system" and those that result from external interventions.

Importantly, not all of our original requirements have yet been met: equity dimensions, certain social and health impacts, and systematic treatment of biodiversity remain outside the current scope of the model. Nevertheless, the framework is designed to facilitate such extensions.

In sum, FRIDA provides a novel contribution to the family of integrated assessment approaches: it is computationally light, transparent in design, open to interdisciplinary collaboration, and accessible to both expert and non-expert users. We see FRIDA as a living platform that will grow with the scientific community, and as an instrument to help society confront the complex and cascading challenges of climate change in the decades ahead.

Appendix A: Best practices for running experiments: Type of research question vs. type of experiment

There are many kinds of experiments one may wish to run with FRIDA. How to set up each experiment depends partly on the research questions one attempts to answer. We have identified four types of research questions that require their own type of experiments in FRIDA:

> **Research question type 1**: *What happens to the system if we introduce this or that change (structure or policy) to the model sometime in the future?* For instance: what happens if we introduce a global carbon tax in 2030, or a new central bank target for inflation in 2040, or a moratorium on the extraction of fossil fuels in 2050? This type of experiment is easy to perform: one changes the relevant lever, or parameter, or flux in the relevant year and compares the EMB run to the experimental run. These are hypothetical "what if"-type questions.

> **Research question type 2**: *What would have happened to the system if this or that change (to structure or policy) was introduced in past times?* For instance: what would the system have looked like if the carbon tax had

been implemented in 1990. In this case the experiment is made the same way as in the previous case, except that the change is introduced to the calibration period, so we compare a factual and a counterfactual system (the EMB run vs. the experimental run). This can be applied both to policy changes (i.e. carbon taxes) as well as system structure, i.e. including or not including a feedback or a physical process. These are hypothetical "what if"-type questions.

Research question type 3: *How does the impact of introducing a change in FRIDA compare to a similar change in another model?* For instance: how would FRIDA and model *X* compare in their response to a moratorium on fossil fuels in 2050? This comparison is straightforward, one must simply make sure that the introduction is of the same magnitude and speed, and that it is initiated at the same point in time.

Research question type 4: *What is the difference between models at various levels of maturity?* Specifically, what was the impact of including this or that process/feedback in an upgrade of FRIDA? For instance: what is the impact of using complex vs. simple feedbacks from climate to the human side? Or: what are the impacts of the improvements made to FRIDA 2.1, compared to FRIDA 1.0? In this case we compare two different models, for instance FRIDA 1 and FRIDA 2, or FRIDA 2 and FRIDA2simpleClimateFeedbacks. It must be recognized that the impacts of the differences between the two models will spill over to the entire system, i.e. the impacts will be system-wide, so the interpretation of these impacts will be complex. This approach is to be used for analysis of model differences, not for hypothetical what-if questions like the ones in number 1 and 2. This approach is extremely labor intensive, because it requires full model recalibration, so it should be used sparingly.

Code and data availability. This paper is an overview of the FRIDA collection and does not introduce new simulations or datasets. Code and data availability for FRIDA v2.1 and specific experiments are documented in the companion model-description and application papers in the collection.

Competing interests. The author has declared that there are no competing interests.

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References

Aghion, P. and Howitt, P.: A model of growth through creative destruction, Econometrica, 60, 323–351, https://doi.org/10.2307/2951599 1992.

Aghion, P. and Howitt, P.: The economics of growth, MIT Press, Cambridge, MA, USA, 518 pp., ISBN 978-0-262-01263-8, 2009.

Bevacqua, E., Schleussner, C.-F., and Zscheischler, J.: A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit, Nat. Clim. Change, 15, 262–265, https://doi.org/10.1038/s41558-025-02246-9, 2025.

Eberlein, R. L., Thompson, J. P., and Matchar, D. B.: Chronological aging in continuous time, in: Proceedings of the 30th International Conference of the System Dynamics Society, 22–26 July 2012, St. Gallen, Switzerland, System Dynamics Society, https://proceedings.systemdynamics.org/2012/proceed/papers/P1064.pdf (last access: 18 May 2026), 2012.

Forrester, J. W.: Industrial dynamics, MIT Press, Cambridge, MA, USA, 464 pp., ISBN 978-0-262-06003-5, 1961.

Grimeland, M. B., Blanz, B., Schoenberg, W., and Callegari, B.: Schumpeterian disaggregation and integrated assessment: An endogenous, stock-flow consistent economy in disequilibrium for FRIDA v2.1, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-6342, 2026.

Howard, P. H. and Sterner, T.: Few and not so far between: A meta-analysis of climate damage estimates, Environ. Resour. Econ., 68, 197–225, https://doi.org/10.1007/s10640-017-0166-z, 2017.

Mustafa, M.: From complexity to clarity: Designing and evaluating an interactive learning environment for human–climate system exploration using FRIDA, Master's thesis, University of Bergen, Bergen, Norway, BORA – University of Bergen Open Research Archive, https://hdl.handle.net/11250/3215620 (last access: 18 May 2026), 2025.

O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., and Solecki, W.: The roads ahead:

Narratives for shared socioeconomic pathways describing world futures in the 21st century, Glob. Environ. Change, 42, 169–180, https://doi.org/10.1016/j.gloenvcha.2015.01.004, 2017.

O'Neill, B., van Aalst, M., Zaiton Ibrahim, Z., Berrang Ford, L., Bhadwal, S., Buhaug, H., Diaz, D., Frieler, K., Garschagen, M., Magnan, A., Midgley, G., Mirzabaev, A., Thomas, A., and Warren, R.: Key risks across sectors and regions, in: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 2411–2538, https://doi.org/10.1017/9781009325844.025, 2022.

Pindyck, R. S.: The use and misuse of models for climate policy, Rev. Environ. Econ. Policy, 11, 100–114, https://doi.org/10.1093/reep/rew012, 2017.

Pörtner, H.-O., Roberts, D. C., Adams, H., Adelekan, I., Adler, C., Adrian, R., Aldunce, P., Ali, E., Ara Begum, R., Bednar-Friedl, B., Bezner Kerr, R., Biesbroek, R., Birkmann, J., Bowen, K., Caretta, M. A., Carnicer, J., Castellanos, E., Cheong, T. S., Chow, W., Cissé, G., Clayton, S., Constable, A., Cooley, S. R., Costello, M. J., Craig, M., Cramer, W., Dawson, R., Dodman, D., Efitre, J., Garschagen, M., Gilmore, E. A., Glavovic, B. C., Gutzler, D., Haasnoot, M., Harper, S., Hasegawa, T., Hayward, B., Hicke, J. A., Hirabayashi, Y., Huang, C., Kalaba, K., Kiessling, W., Kitoh, A., Lasco, R., Lawrence, J., Lemos, M. F., Lempert, R., Lennard, C., Ley, D., Lissner, T., Liu, Q., Liwenga, E., Lluch-Cota, S., Löschke, S., Lucatello, S., Luo, Y., Mackey, B., Mintenbeck, K., Mirzabaev, A., Möller, V., Moncassim Vale, M., Morecroft, M. D., Mortsch, L., Mukherji, A., Mustonen, T., Mycoo, M., Nalau, J., New, M., Okem, A., Ometto, J. P., O'Neill, B., Pandey, R., Parmesan, C., Pelling, M., Pinho, P. F., Pinnegar, J., Poloczanska, E. S., Prakash, A., Preston, B., Racault, M.-F., Reckien, D., Revi, A., Rose, S. K., Schipper, E. L. F., Schmidt, D. N., Schoeman, D., Shaw, R., Simpson, N. P., Singh, C., Solecki, W., Stringer, L., Totin, E., Trisos, C. H., Trisurat, Y., van Aalst, M., Viner, D., Wairiu, M., Warren, R., Wester, P., Wrathall, D., and Zaiton Ibrahim, Z.: Technical summary, in: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, 37–118, https://doi.org/10.1017/9781009325844.002, 2022.

Rajah, J. K., Blanz, B., Kopainsky, B., and Schoenberg, W.: An endogenous modelling framework of dietary behavioural change in the fully coupled human-climate FRIDA v2.1 model, Geosci. Model Dev., 18, 5997–6022, https://doi.org/10.5194/gmd-18-5997-2025, 2025.

Ramanathan, V. and Coakley, J. A.: Climate modeling through radiative-convective models, Rev. Geophys., 16, 465–489, https://doi.org/10.1029/RG016i004p00465, 1978.

Ramme, L., Blanz, B., Wells, C., Wong, T. E., Schoenberg, W., Smith, C., and Li, C.: Feedback-based sea level rise impact modelling for integrated assessment models with FRISIAv1.0, Geosci. Model Dev., 18, 10017–10052, https://doi.org/10.5194/gmd-18-10017-2025, 2025.

Saltelli, A., Tarantola, S., Campolongo, F., and Ratto, M.: Global Sensitivity Analysis: The Primer, John Wiley & Sons, Chichester, UK, 304 pp., https://doi.org/10.1002/9780470725184, 2008.

Schoenberg, W., Blanz, B., Rajah, J. K., Callegari, B., Wells, C., Breier, J., Grimeland, M. B., Lindqvist, A. N., Ramme, L., Smith, C., Li, C., Mashhadi, S., Muralidhar, A., and Mauritzen, C.: An overview of FRIDA v2.1: a feedback-based, fully coupled, global integrated assessment model of climate and humans, Geosci. Model Dev., 18, 8047–8069, https://doi.org/10.5194/gmd-18-8047-2025, 2025.

Schumpeter, J. A.: Capitalism, socialism and democracy, Harper & Brothers, New York, NY, USA, OCLC: 30488029, 1942.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., and Zhou, B.: Weather and climate extreme events in a changing climate, in: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., and Zhou, B., Cambridge University Press, Cambridge, UK and New York, NY, USA, 1513–1766, https://doi.org/10.1017/9781009157896.013, 2021.

Sobol, I. M.: On the distribution of points in a cube and the approximate evaluation of integrals, USSR Comput. Math. Math. Phys., 7, 86–112, https://doi.org/10.1016/0041-5553(67)90144-9, 1967.

Sterman, J. D.: Business dynamics: Systems thinking and modeling for a complex world, McGraw-Hill, New York, NY, USA, 982 pp., ISBN 978-0-07-231135-8, 2000.

van Valkengoed, A. M., Perlaviciute, G., and Steg, L.: Representing the drivers of lifestyle change in integrated assessment models: Introducing the Motivation, Agency, and Past Behaviour (MAP) framework, Environ. Res. Commun., 7, 032001, https://doi.org/10.1088/2515-7620/adb9bf, 2025.

Wells, C. D., Blanz, B., Ramme, L., Breier, J., Callegari, B., Muralidhar, A., Rajah, J. K., Lindqvist, A. N., Eriksson, A. E., Schoenberg, W. A., Köberle, A. C., Wang-Erlandsson, L., Mauritzen, C., Grimeland, M. B., and Smith, C.: The representation of climate impacts in the FRIDAv2.1 Integrated Assessment Model, Geosci. Model Dev., 19, 1229–1260, https://doi.org/10.5194/gmd-19-1229-2026, 2026a.

Wells, C. D., Ramme, L., Smith, C., Breier, J., Muralidhar, A., Li, C., Gjermundsen, A., Schoenberg, W. A., Blanz, B., and Mauritzen, C.: FRIDA-Clim v1.0.1: a simple climate model with process-based carbon cycle used in the integrated assessment model FRIDAv2.1, Geosci. Model Dev., 19, 1429–1453, https://doi.org/10.5194/gmd-19-1429-2026, 2026b.