

This is FRIDA

V2: Submitted April 22, 2026

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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**By naming it a “knowledge repository” **signals**we signal that the FRIDA model is never finished; it represents the current state of knowledge of the development team at any given time. **We aim to continually integrate new scientific findings to keep the FRIDA up to date.**

FRIDA **was developed through**comes with a learning environment that, together with, the model's low computational cost, makes it a useful tool for education. It can be used in the classroom setting in interdisciplinary climate science courses and will allow students to understand how their discipline is intricately woven into the rest of the climate science disciplines. This feature set makes FRIDA accessible to a wider range of users than just researchers and scientists. Our aim is to lower the barrier to entry of using this model so that even lay people are able to use the model to build an understanding of the interconnectedness of climate and humans. Additionally, the low computational burden allows for uncertainty exploration by varying model parameters.

In this collection of papers in the Geoscientific Model Development (GMD) journal we intend to document the developments of FRIDA, from its origin in the years 2023-2026 within 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.

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26 in a special GMD Collection¹. This ” (FRIDA version 2.1 and FRIDA V3); and (hopefully) future versions
27 that the spirited (and growing) development team will hopefully ensure. The intention of this brief paper is the
28 introduction to the GMD FRIDA collection of papers. The purpose of the introductory paper, written
29 by the project lead on behalf of the consortium, is to provide the conceptual and institutional
30 contextextual framework for the original model, and to make explicitexplicitly state the initial
31 designoriginal requirements that guide FRIDA’s ongoing development as a living knowledge
32 repository.

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

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

46

47 **1 Introduction**

48 Governance of nations, businesses, international organizations and private lives alike are made difficult by the
49 fact that the world has entered the realm of *dangerous climate change*. Earth’s surface temperature depends
50 on the amount of greenhouse gases in the atmosphere - in the absence of any greenhouse gases the
51 average temperature on earth would be a freezing -19 °C, instead of the approximately + 15 °C we
52 observe today (Ramanathan and Coakley, 1978). Any radiative change in this system results in a
53 change in atmospheric temperature, an experiment humans have been running for the past 250 years.
54 Access to cheap energy—facilitated by the invention of the steam engine and subsequent methods of
55 extracting energy from fossil fuels—which co-evolved during the Industrial Revolution with

¹ <https://gmd.copernicus.org/articles/collection12.html>
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56 accelerating population growth, has greatly disturbed the climate equilibrium. Changes in how we use
57 land areas have also contributed greatly to pushing the climate system out of equilibrium.

58 For long, climate change was hard to notice. But by now, the world has entered the realm of
59 dangerous climate change. In 2024, global average temperature exceeded 1.5 °C above pre-industrial
60 levels for the first time (Bevacqua et al., 2025). While an isolated year above this threshold does not
61 yet mean the high ambition goal of the Paris Agreement — to hold global temperature increase well
62 below 2 °C and to pursue efforts to limit it to 1.5 °C on a sustained basis — human-caused climate
63 change is already causing widespread adverse impacts and losses and damages (O'Neill et al., 2022
64 (IPCC AR6 WGII Chapter 16)), including observed increases in extreme heat, heavy precipitation and
65 drought (Seneviratne et al., 2021 (IPCC AR6 WGI Chapter 11)), indicating that dangerous climate
66 change is already being experienced. — has been breached, many dangerous impacts of climate change are
67 already observed, such as extreme heat, floods, droughts and wildfires.

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

72 For as long as the UN has engaged in climate change negotiations, these questions have been on the
73 table, and answers have been sought using a myriad of models and expert negotiation processes.

74 But during this time, climate has continued to change. These recognitions —, to the extent, that
75 negotiations still fail and that climate now affects our lives — were strong motivations for introducing
76 a new IAM that explicitly includes diverse the impacts of climate change impacts on humans. We call
77 this new model FRIDA, with the subtitle *Feedback-based knowledge Repository for IntegrateD*
78 *Assessments.* can be felt, physically, all around the globe (IPCC, 2022).

79 These recognitions — that climate now affects our lives, and the failure thus far to mitigate climate change — were
80 strong motivations for introducing a new integrated assessment model that explicitly includes diverse climate
81 change impacts on humans. We call this new model FRIDA, with the subtitle *Feedback-based knowledge*
82 *Repository for IntegrateD Assessments.* ~~The journal *Geoscientific Model Development* has given us space~~
83 ~~to document FRIDA, including its submodules and spin-offs, in a special *GMD Collection*.~~ What sets
84 FRIDA apart from traditional IAMs is the shift from exogenous, narrative-based scenarios to a
85 feedback-driven approach, where human activities (that drive climate change), and climate change
86 (that drives impacts, such as reduced labor productivity or financial instability) co-evolve as equal
87 partners within a single system of equations. In other words, FRIDA explicitly accounts for the

[2 - https://gmd.copernicus.org/articles/collection12.html](https://gmd.copernicus.org/articles/collection12.html)

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88 impacts that climate change has already begun to exert on human systems. Without incorporating these
89 feedbacks, projections of the human activities that drive climate change will become increasingly
90 unreliable.

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

95 2 Requirement for FRIDA

96 The first version of FRIDA (V2.1) is documented in Schoenberg et al. (2025).

97 FRIDA is built using the tools of system dynamics to integrate and couple the natural climate system and aspects
98 of human life that can affect – and are affected by – climate. These include population growth, energy and food
99 demand, investment strategies, damage to infrastructure and government budgets. FRIDA explicitly models
100 human behavior (Rajah et al., 2025) and simulates the impact of climate change on numerous processes, such as
101 crop yield, energy production, infrastructure, changes in livelihood in low-lying areas, uncertainties in the
102 financial sector, and mortality due to climate extremes (Wells et al., 2025a). Human activities in turn alter
103 climate by emitting greenhouse gases and aerosols, and by transforming land surfaces, changing albedo,
104 managing water resources, and reshaping biogeochemical cycles, all of which modify the Earth’s energy balance
105 and the climate system.

106 With FRIDA we can investigate ways to minimize climate change and at the same time meet human needs
107 within a framework that allows us to identify barriers and leverage points towards change.

108 FRIDA is modular, facilitating future expansions into other aspects of life on planet Earth, such as a more
109 complete treatment of the biosphere.

110 FRIDA is a global model, intended to build intuition and provide insights of a general nature. As the model
111 matures it will be possible to develop non-global versions, for instance, country-specific versions of FRIDA.
112 One would in that case most likely link the “country” FRIDA to a “rest of the world” FRIDA, to allow for
113 movement (of goods, people, policies etc.) in and out of the country in question.

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114 This brief introductory paper is the introduction to the GMD FRIDA collection of papers. So, here is the
115 background for FRIDA.

116 2-Original model requirements

117 During the framing phase of the WorldTrans project in 2022 the team we discussed at length how to we
118 could design a model that would produce credible and relevant results for all three working groups of
119 the IPCC, that would be able to advice on the European Green deal (to obtain climate neutrality by
120 2050, leaving no one behind) and which would be useable and useful for non-expert users. We came
121 up with the following list of requirements:

- 122 1. **Take advantage of conservation laws to constrain the model.** This involves including the
123 full carbon, heat and water cycle.
- 124 2. **Begin with a non-regional model.** By building a global, rather than a regionally segregated
125 model, the model output remains simpler to analyze, due to the reduced number degrees of
126 freedom (which is large already on the global scale). The result is increased transparency and
127 a better chance at building intuition and insights.
- 128 3. **Balanced representation of climate and humans.** This means focusing on the minimum
129 detail necessary to capture the important interconnections between subsystems.
- 130 4. **Complete treatment of climate change forcing.** This means to include the main greenhouse
131 gases (CO₂, CH₄, N₂O and HFCs) and the main cooling aerosol agent (SO₂), and to account
132 for the effect of other climate forcers, such as those associated with land use change. It also
133 means to model the sectors that create the greenhouse gas emissions (transport sector, energy
134 production, land use and agriculture, chemical industries, cement production and waste). And
135 it means to consider the underlying economic system and demography that creates changes in
136 those sectors.
- 137 5. **Complete treatment of climate-driven feedback.** This implies taking into account,
138 quantitatively, how climate affects (mostly damages) these sectors and the underlying
139 economy and demography.
- 140 6. **Complete treatment of uncertainty.** This implies keeping the computing speed low, to allow
141 for large ensemble runs. We obtain this by requirement no. 1 to build a non-regional model.
- 142 7. **Include human needs, desires and behavior.** This means that (modelled) people can have an
143 impact on the system, by changing behavior, with respect to, for instance, dietary and mobility
144 choices. This means that we can impose requirements on wealth distribution, energy consumption
145 and so forth. Furthermore, it implies a departure from describing humans as purely theoretical
146 economic beings maximizing profit or utility.

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147 8.● **A dynamic representation of the economy.** This means to model the economy as a system
148 that moves forward in time and acts and reacts to its surroundings, just like we model the rest
149 of the system.

150 9.● **Modular organization of the model.** This is a requirement that improves the transparency of
151 the model.

152 10.● **Familiar external levers.** To generate change in the system we include the possibility
153 of acting as a decision maker within the various modules of the model (for instance within
154 government, or within the financial or energy sector)

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

165 12. **Indices of the state of the system.** Based on variables interior to the model we include well-known
166 indicators that describe the state of the system at every point in time during the simulations, both with
167 respect to nature and humans.

169 2.1 Scope of model

170 The processes we have chosen to represent in FRIDA are determined by the main purposes of 3. Design
171 of FRIDA

172 FRIDA is built using the tools of System Dynamics (see e.g., Forrester 1961, Sterman 2000). This
173 approach facilitates, at relative ease, the inclusion of very different disciplines and their methods,
174 ranging from the laws of nature to empirical relationships, direct observations and co-created
175 knowledge. Central to the approach are feedback and delay perspectives, which highlight the complex
176 and oftentimes circular interactions between system components that endogenously generate behavior.

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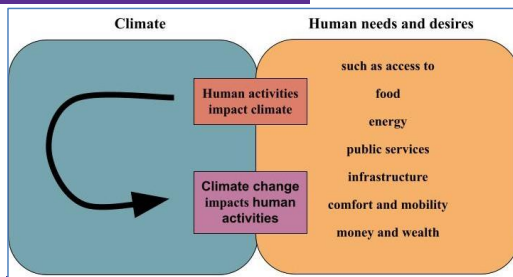
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177 making it a suitable approach to coupling the natural system to produce numerically consistent results for IPCC
 178 Working Groups I-III and to provide advice on the European Green deal. We include the spheres we live in and
 179 interact with — land, oceans, atmosphere, cryosphere, anthroposphere. The model includes what are understood to
 180 be the largest anthropogenic forcings of climate system with the many aspects change, and the most important
 181 impacts of climate change on humans. Fig. 1 shows, schematically, how we perceive climate change and humans
 182 to be interrelated within the model. The needs and desires highlighted in the figure are of a generic nature, but
 183 they map fairly directly into sectors of human life that can affect — and each are affected/impacted by —
 184 and/or contribute to, anthropogenic climate change.



185
 186 **Figure 1: Schematic representation of the scope of FRIDA: The interconnectedness of climate and human needs and**
 187 **desires.**

188
 189
 190 Though the model time resolution in FRIDA is 1/4 of a year, we do not aim to reproduce processes of shorter
 191 timescales than 5-10 years. Finally, our model simulations start in 1980 and typically end in 2150 (Fig. 2). Thus,
 192 any internal variability in the climate system on timescales longer than ca. 100 years² are ignored.

²—such as slow-changing climate variations caused by astronomical or geological changes.

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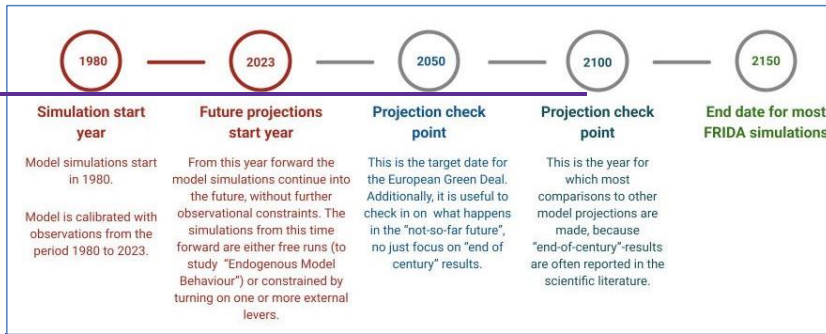


Figure 2: Schematic representation of the scope of FRIDA: The timeline for the FRIDA simulations.

3 Approach

FRIDA consists of a set of ordinary differential equations, written in the language 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 so 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.

We use the laws of nature and well-established empirical relationships to derive as many equations in the model as possible. For relationships where we have less established knowledge, we still use the best available knowledge to generate the structure, but we set wide parameter ranges so that we may report the uncertainty inherent in our projections. As a part of behavioral validation, we calibrate the model to historical observations from 1980 to the present (the "historical simulation period"; at the time of writing, this period is divided into 1980-2023), keeping track of the uncertainty that is inherent in the model's calibration.

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209 FRIDA's structure is validated by experts who understand how different parts of the system that are represented
210 in the model function in reality. The calibration, validation, and uncertainty measurement procedures are
211 described in detail in Schoenberg et al., (2025).

212 As mentioned, FRIDA is designed as an intuition builder, not as a source of precise future projections with fine
213 regional granularity and sectoral detail. But there is another advantage of the relative simplicity of the model,
214 namely the possibility of running large ensembles for uncertainty analysis. To assess the uncertainty space of a
215 FRIDA setup, we typically run several hundred thousand simulations.

216 4. FRIDA's Modular Framework

217 FRIDA presently consists of seven modules: Climate, Human behavior, Land use and Agriculture,
218 Energy, Economy, Resources and Demography (Fig. 3). In addition to improving the transparency of the
219 model, the modular framework allows development of the scientific basis for each module in parallel.
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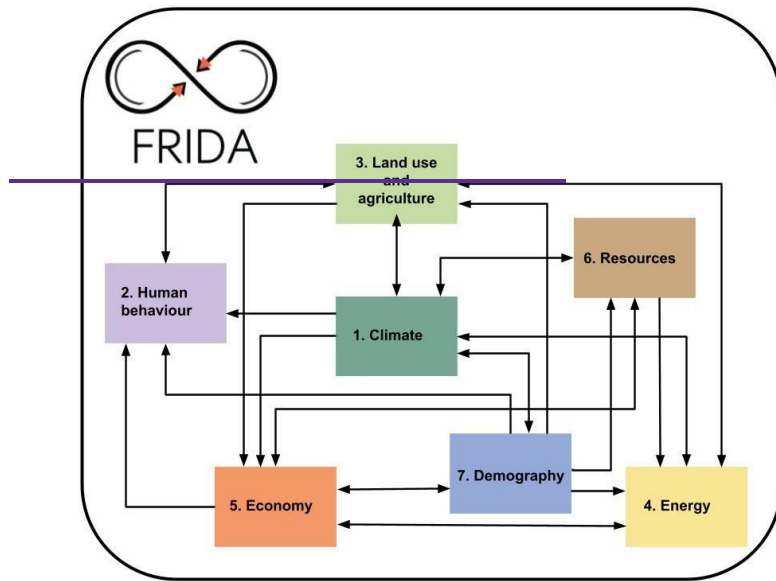


Figure 3: The modules and interlinkages in FRIDA V2.1.

We refer to all modules except the climate module as the “anthropogenic” modules of FRIDA. Note, however, that the “Land Use and Agriculture” module contains information about both nature and agriculture.

1) One can change or expand FRIDA, if new information is published, or if the scope of the model (Figs. 1 and 2) were to be changed. One such expansion could be to include “biosphere” as its own module, allowing FRIDA to respond to issues raised by the Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services (IPBES), complementing the present focus on IPCC. One might wish to address the sustainable development goals in the 2030 Agenda for Sustainable Development. Both these topics are partly covered in FRIDA, but not systematically. The main focus of FRIDA has from the start been to systematically and holistically address the human activities that cause anthropogenic climate change and the ways that anthropogenic climate change impact humans.

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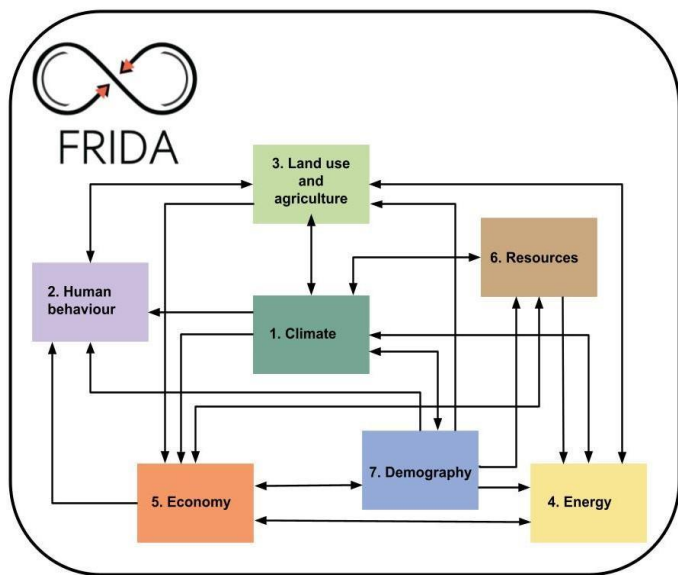
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234 Note that there are as many linkages between the various anthropogenic modules of FRIDA as there are between
 235 the climate module and the anthropogenic modules. All these interlinkages within and between the
 236 modules collectively create the complex dynamics of the system. This is what makes, and they are the
 237 reason, it is easy to state that say, “everything is connected to everything”, but comparably
 238 difficult/terribly hard to explain/understand how.

239 **5. Drivers of climate change**

240 ~~Earth’s surface temperature depends on the amount of greenhouse gases in the atmosphere – in the~~
 241 ~~absence of any greenhouse gases the average temperature on earth would be a freezing –19 °C, instead~~
 242 ~~of the approximately –15 °C we observe today (Ramanathan and Coakley, 1978). Any radiative~~
 243 ~~change in this system results in a change in atmospheric temperature~~



244 **Figure 1:** The modules and interlinkages in FRIDA V2.1. All modules except the climate module are
 245 collectively referred to as the “anthropogenic” modules of FRIDA. Note, however, that the “Land Use and
 246 Agriculture” module contains information about both nature and agriculture.
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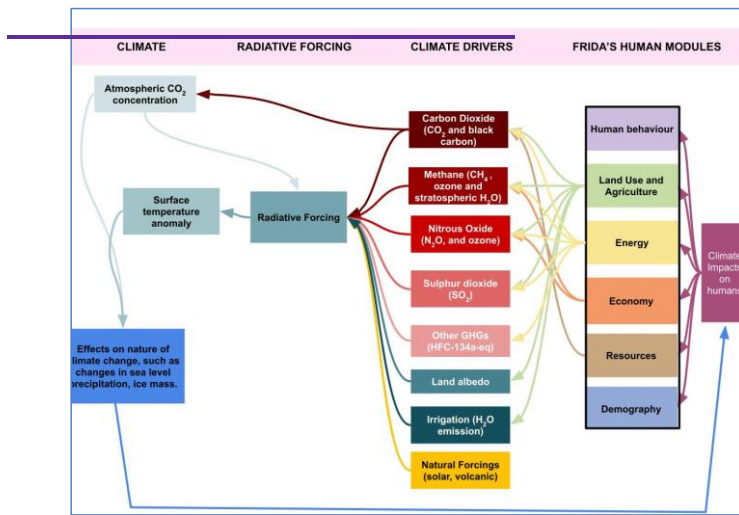
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248 In FRIDA, climate impacts are .The climate system is, however, continually trying to achieve an equilibrium
 249 state, in which the incoming solar radiation is ultimately balanced by the outgoing thermal radiation of the Earth.
 250 Minor shocks to the climate system, such as volcano outbursts, take a year or two to recover from, whereas large
 251 shocks may take millions of years. After the end of the last ice age, approximately 10,000 years ago, the Earth
 252 entered into an unusual state of quasi-equilibrium, with just minor long term drift and temporary periods of
 253 short-term fluctuations. It was during this climatically stable period that the development of agriculture and the
 254 establishment of states took place.

255 But, for the past 250 years, humans have been pushing the climate system out of equilibrium. The access to
 256 cheap energy, facilitated by the invention of the steam engine and all the subsequent methods to extract energy
 257 from fossil sources, co-evolving during the industrial revolution with huge population growth, has disturbed the
 258 climate equilibrium greatly. Changes in how we use land areas have also contributed greatly to pushing the
 259 climate system out of equilibrium (Fig. 4). Details on how the climate system is modelled in FRIDA are
 260 documented in Wells et al. 2025A and Ramme et al., 2025.

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262

263 **Figure 4: A schematic flow chart of climate change drivers, from the anthropogenic modules in FRIDA to the climate**
264 **module.**

265 **6. Effects and impacts of climate change**

266 The change in atmospheric CO₂ concentration and other climate forcings—and subsequent change in atmospheric
267 temperature—have numerous effects on nature: ice melts, ocean heats up, the sea rises; there are droughts,
268 changes in precipitation patterns, heat waves, wildfires and so forth. We refer to changes in nature caused by
269 anthropogenic climate change as “climate effects”.

270 We use a different nomenclature for the effects of climate change on the human side of the system, i.e. in the
271 anthropogenic modules of FRIDA. We refer to these changes as “climate impacts”.

272 In FRIDA we model climate impacts as recognizable processes, such as the assessment of climate risk
273 made by financial institutions, changes in demand for animal food products because of personal
274 norms driven by climate risk perception, changes in demand for energy as a consequence of changing
275 temperature; changes in labor productivity, changes in water use for irrigation, and so forth. To
276 determine which to name a few.

277 In implementing climate impacts to include in FRIDA v2.1, the starting point was IPCC WGII AR6’s
278 considered the assessment of the literature on climate impacts and risks made by IPCC WGII AR6,
279 summarized in the Technical Summary of the report (Pörtner et al., 2022). Decisions were on what impacts to
280 include was based on three criteria: 1) applicability to the [global] scope of FRIDA; 2) the expected
281 global magnitude of the effect as agreed upon in the extant literature; 3) when the scope and
282 magnitude of the impact was not agreed upon in the literature, was there enough data present in the
283 literature to reproduce at least one pre-existing global study with wide uncertainty parameters? In
284 addition, we have added to FRIDA some climate impacts that are of relevance to the scope of FRIDA
285 yet not included in the IPCC assessment. Details on the implementation of climate drivers and
286 impacts in FRIDA are documented in Wells et al. 2026a and Ramme et al., 2025.

287 To date we have implemented 16 climate impacts that directly drive the behavior of the human system plus six
288 that drive behavior indirectly through impacts on land. This is in addition to all the feedbacks within the climate

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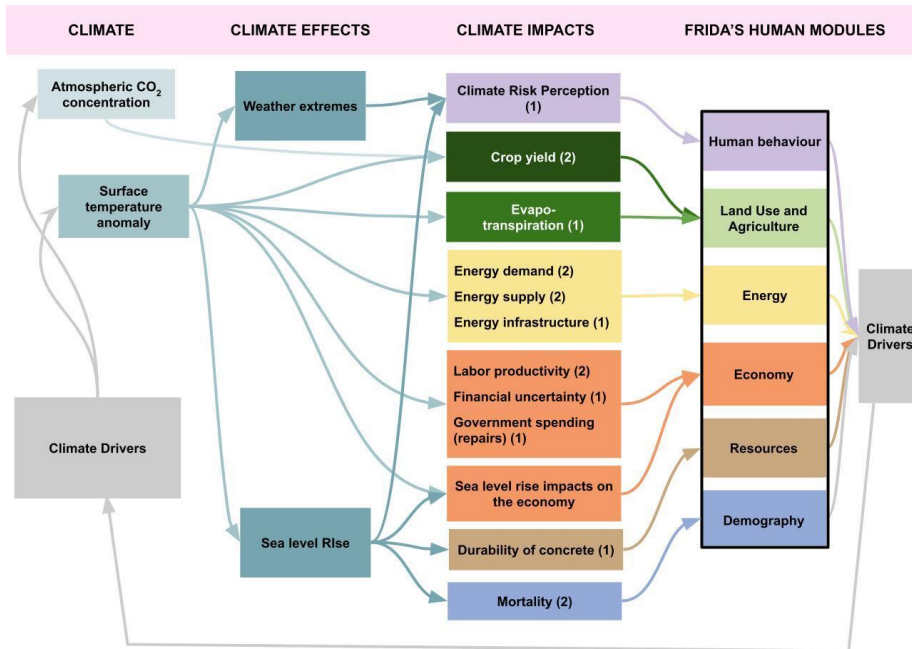
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289 system itself. A graphical representation of the implementation of climate effects and impacts in
 290 FRIDAv2.1 is given in Fig. 25.

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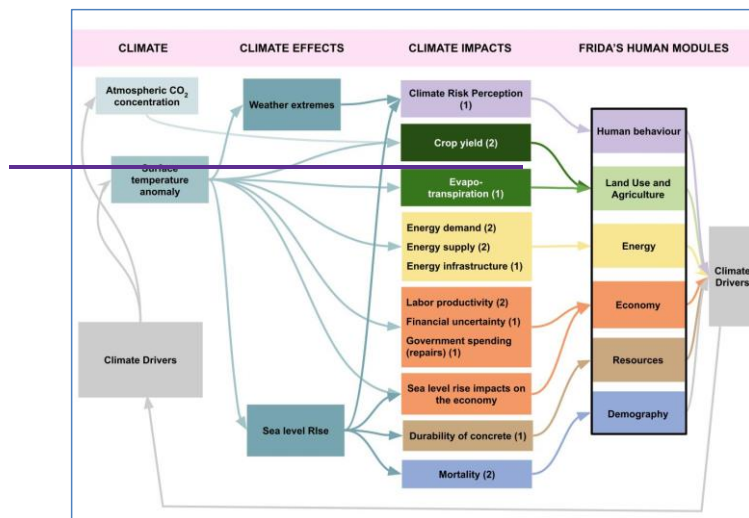
291
 292 The climate module in FRIDA is documented in Wells et al., 2025A. Details on the treatment of sea level rise in
 293 FRIDA is documented in Ramme et al., 2025. Finally, the details on how the climate effects and impacts are
 294 implemented in FRIDA are documented in Wells et al. 2025B.

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296
297 **Figure 25:** A schematic overview of the climate drivers and impacts in FRIDA V2.1, from climate change to the
298 anthropogenic modules.

299
300 To build each module of FRIDA, the team entered an iterative cycle of mapping essential feedback
301 loops, selecting equations and theoretical frameworks from scientific literature and developing novel
302 "expert-supplied functional forms" when literature is insufficient, as documented in Schoenberg et
303 al., 2025. Examples include:

- 304 ● **Laws of Nature:** The model embodies the laws of nature within its Climate module,
305 representing the Earth's radiation balance, carbon cycle, and water cycle. Specific examples
306 include the three-layer energy balance model (simulating heat exchange between ocean layers)
307 and the carbonate chemistry system in the ocean (Wells et al., 2026b, Schoenberg et al., 2025)
- 308 ● **Leading Theoretical Frameworks:**
 - 309 ○ The Economy module uses a monetary model of production, consumption, and
310 finance based on Schumpeterian dynamics of innovation and creative destruction

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(Schumpeter, 1942; Aghion & Howitt, 1992, 2009)) to simulate the dynamic circular flow of income (Grimeland et al. 2026, Schoenberg et al., 2025).

○ The Behavioral Change module is conceptualised using the Motivation–Agency–Past Behaviour (MAP) meta-theoretical framework (van Valkengoed, Perlaviciute and Steg, 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, Thompson and Matchar, 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 CO2 concentration and quadratic in absolute temperature, capturing the antagonistic relationship between CO2 fertilization and heat stress (Wells et al., 2026a, Schoenberg et al., 2025).

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 ~2020–2150. Details are laid out in Schoenberg et al., 2025.

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4. FRIDA's Endogenous Behaviour/Model Behavior

A useful feature of a (nearly)-all-inclusive model like FRIDA is that the model does not need external forcing to run into the future. The processes that are deemed important for the problem, ie. 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 once you hit "start", nothing happens except what the model itself generates. It is "endogenous" because every variable that changes does so because of the model's own dynamics. And the results are stocks, flows and feedback loops. And it is 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, during the historical period.

The ~~We consider~~ the significance of the EMB run is to be twofold: 1) it gives us insights into how the system would evolve into the future without further policy changes or other external forcing, i.e. assuming that all of the processes modelled in FRIDA operate according to the structure we've built, and all of the processes not modelled in FRIDA continue to operate as they have historically, 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

8. Running experiments with FRIDA

Given a transparent, fast-running model like 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 dozens of experiments on one's desktop in minutes order to build intuition. 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).

The EMB run is a starting place for comparing all other experiments — whether we want to see the effect of implementing regulations in the future or ask "what would have happened if" this or that regulation were

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372 implemented in the past. To set up experiments with FRIDA we have developed a few guiding principles and a
373 wide range of external levers that can be pulled to run experiments.

374 8.1 ~~Best practices for running experiments: Type of research question vs type of experiment~~

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

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

384 ~~**Research question type 2:** *What would have happened to the system if this or that change (to*
385 ~~*structure or policy) was introduced in past times?* For instance: what would the system have looked~~
386 ~~like if the carbon tax had been implemented in 1990. In this case the experiment is made the same way~~
387 ~~as in the previous case, except that the change is introduced to the calibration validation period, so we~~
388 ~~compare a factual and a counterfactual system (the EMB run vs the experimental run).~~ This can be applied
389 ~~both to policy changes (i.e. carbon taxes) as well as system structure, i.e. including or not including a~~
390 ~~feedback or a physical process. These are hypothetical “what if” type questions.~~~~

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

396 ~~**Research question type 4:** *What is the difference between models at various levels of maturity?*~~
397 ~~Specifically, what was the impact of including this or that process/feedback in an upgrade of FRIDA?~~
398 ~~For instance: what is the impact of using complex vs simple feedbacks from climate to the human~~
399 ~~side? Or: what are the impacts of the improvements made to FRIDA 2.1, compared to FRIDA 1.0? In~~
400 ~~this case we compare two different models, for instance FRIDA 1 and FRIDA 2, or FRIDA 2 and~~
401 ~~FRIDA2simpleClimateFeedbacks. It must be recognized that the impacts of the differences between~~

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402 ~~the two models will spill over to the entire system, i.e. the impacts will be system wide, so the~~
403 ~~interpretation of these impacts will be complex. This approach is to be used for analysis of model~~
404 ~~differences, not for hypothetical what if questions like the ones in number 1 and 2. This approach is~~
405 ~~extremely labor intensive, because it requires full model recalibration, so it should be used sparingly.~~

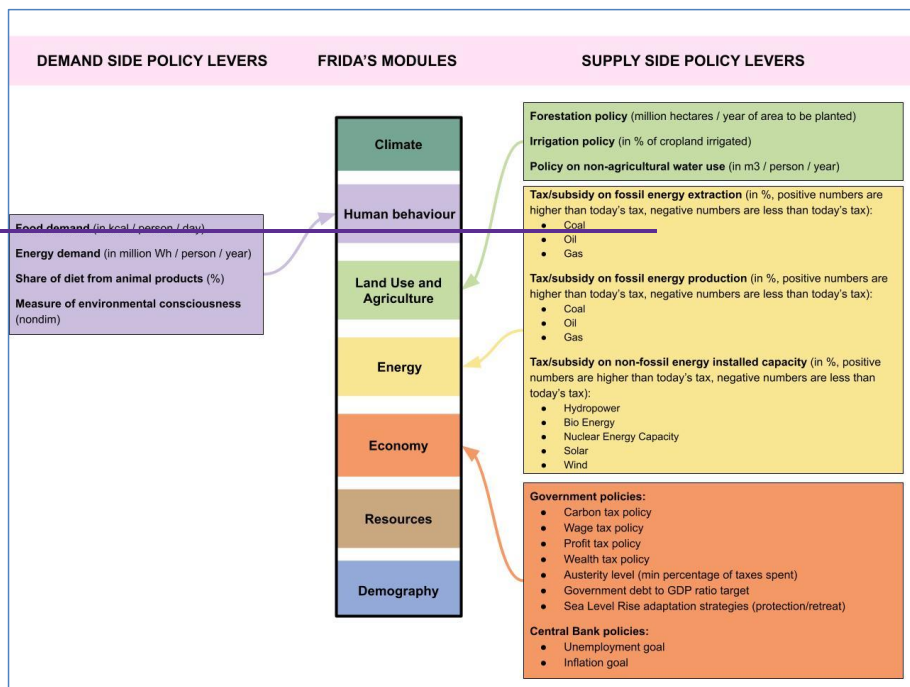
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406 8.2 External intervention available in FRIDA V2.1

407 One of the attractions of a simple model like FRIDA is that there are few computational limits to the number of
408 research questions one might want to ask. For **research questions of type 1 and 2**, we have developed a wide
409 range of experimental options. Based on the original purpose of FRIDA—to be of use for the European goal of
410 climate neutrality in 2050 with no one left behind—the built-in external levers in FRIDA 2.1 revolve mainly on
411 how to reduce emissions, decrease inequality and maintain growth in the economy without harming the
412 planet. Fig. 6 gives an overview of the present levers, divided into demand-side and supply-side instruments. Do
413 remember, though, that much information about human behavior, whether it is with respect to dietary choices,
414 economic decisions, agricultural practices and so forth, is internal (endogenous) to the model—it entered through
415 the building of the model and the calibration to observations (which is why the EMB run is so interesting by
416 itself).

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417

418 **Figure 6: Overview of the external levers, or interventions, available for experiments with FRIDA 2.1.**

419 **9. Interactive Learning Environment**

420 An important feature of FRIDA is its low computational cost, which enables real-time feedback, interactive
 421 classroom use, and systematic uncertainty exploration through parameter variation. To facilitate the learning
 422 process, the FRIDA model is accompanied by an Interactive Learning Environment (ILE) (Mustafa,
 423 2025). The ILE for investigating interactions between the climate system and human societies, with particular
 424 attention to feedback mechanisms. It combines guided demonstrations with an ,-scenario definition, and
 425 interactive dashboard which can be used to investigate how the model responds to interventions.

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426 ~~Dynamic visualizations~~dashboards with dynamic visualization to illustrate the consequences of decisions
427 across time scales. ~~The~~

428 ~~The introductory module of the FRIDA ILE presents historical and projected developments in variables such as~~
429 ~~global surface temperature, economic output, and income distribution. These examples are accompanied by~~
430 ~~simplified explanations of underlying system interactions, giving users an entry point into the logic of coupled~~
431 ~~human climate dynamics. This stage also introduces the dashboard interface, ensuring that later experimentation~~
432 ~~is grounded in a clear understanding of how model levers translate into system responses.~~

433 ~~Following the demonstration, the user manipulates~~moves on to the dashboard (Fig. 7), where one can
434 ~~investigate how the model responds to interventions. Users manipulate~~ parameters through interactive levers,
435 observe responses across more than 225 variables, and compare results with ~~the EMB run as well as~~
436 ~~with predetermined “goals” for each experiment).~~their initial goals. The visualization framework
437 highlights trade-offs, sensitivities, and unintended consequences, illustrating how even simple
438 interventions can produce complex outcomes.

439 ~~The hypothesis~~idea is that by lowering technical and conceptual barriers, the platform extends beyond
440 research applications to engage students, educators, and lay users. ~~in systems thinking and long-term~~
441 ~~decision-making.~~ This makes the ILE well suited for interdisciplinary teaching, where students can see
442 how their own discipline, whether economics, environmental science, or engineering, is interwoven
443 with other domains in shaping climate futures.

444 6. Comparisons with other projections

445 FRIDA projections have been compared to the five Shared Socioeconomic Pathways: SSP1
446 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5
447 (Fossil-fueled Development) (O'Neill et al., 2017). In this comparison, Schoenberg et al., (2025) find
448 that SSP1-, SSP2-, and SSP5-Baseline are overly optimistic regarding future economic growth, while
449 SSP3- and SSP4-Baseline align more closely with FRIDA's ensemble behaviour. The reason is the
450 structural difference: FRIDA represents the climate-human system as a fully coupled, feedback-rich
451 system, rather than treating many climate-to-human effects as exogenous, omitted, or highly
452 aggregated. In conventional IAMs, much of the climate-damage literature has focused on aggregate
453 GDP losses in top-down assessments (Howard and Sterner, 2017), often through highly aggregated
454 damage functions that have been criticized as empirically weak and “black box” in nature (Pindyck,
455 2017). FRIDA replaces this with a more disaggregated, process-based representation of impacts
456 (Grimeland et al., 2026; Wells et al., 2026a).

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457 What this means in practice is that FRIDA allows climate damages to feed back onto the drivers of
 458 future growth themselves. In the economy module, expected climate impacts reduce economic
 459 production primarily through reduced investment growth and financial fragility, while government
 460 budgets come under increasing stress from unemployment and demographic change; in some
 461 simulations, these combined pressures can even halt growth altogether (Grimeland et al., 2026).
 462 Unlike standard IAM baselines, FRIDA therefore does not assume that high GDP growth can continue
 463 largely unaffected in a warming world. Rajah et al. (2025) further show that, when behaviour is
 464 endogenized, future food and animal-product demand is lower than in the standard GDP-driven
 465 approach, producing slightly lower emissions and a somewhat cooler baseline climate. Ramme et al.
 466 (2025) likewise show that adding coastal feedbacks can generate non-linear damage patterns,
 467 including peak-and-decline storm-surge damages driven by endogenous retreat and reduced coastal
 468 investment. Wells et al. (2026b) add that even the climate module differs from standard simple-climate
 469 emulators because FRIDA-Clim uses a process-based carbon cycle within the coupled framework.
 470 Overall, the FRIDA papers therefore suggest not just a different set of numbers, but a systematically
 471 less optimistic future outlook, because once feedbacks from climate damages, finance, behaviour, and
 472 adaptation constraints are internalized, future growth paths become lower, more fragile, and less
 473 consistent with the high-growth baselines commonly used in conventional IAM exercises (Schoenberg
 474 et al., 2025; Grimeland et al., 2026; Rajah et al., 2025; Ramme et al., 2025; Wells et al., 2026a,
 475 2026b).

476 **7. Outlook**



477
 478 **Figure 7: From FRIDA's Interactive Learning Environment dashboard.**

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479 **10. Concluding remarks**

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

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

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

504 Importantly, not all of our original requirements have yet been met: equity dimensions, certain social
505 and health impacts, and systematic treatment of biodiversity remain outside the current scope of the
506 model. Nevertheless, the framework is designed to facilitate such extensions, ~~and the EMB run ensures~~
507 ~~that FRIDA provides a consistent reference point for evaluating model development and experimental results.~~

508 In sum, FRIDA provides a novel contribution to the family of integrated assessment approaches: it is
509 computationally light, transparent in design, open to interdisciplinary collaboration, and accessible to
510 both expert and non-expert users. We see FRIDA as a living platform that will grow with the scientific

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511 community, and as an instrument to help society confront the complex and cascading challenges of
512 climate change in the decades ahead.

513

514 **Code Availability**

515 [Github link for FRIDA v2.1](https://github.com/metno/WorldTransFRIDA/tree/v2.1) <https://github.com/metno/WorldTransFRIDA/tree/v2.1>

516 [Github link for latest FRIDA](https://github.com/metno/WorldTransFRIDA) <https://github.com/metno/WorldTransFRIDA>

517 [Github link for uncertainty analysis program](https://github.com/BenjaminBlanz/WorldTransFrida-Uncertainty) <https://github.com/BenjaminBlanz/WorldTransFrida-Uncertainty>

518 [Zenodo link for FRIDA v2.1](https://zenodo.org/records/15310860) <https://zenodo.org/records/15310860>

519 [Zenodo link for EMD dataset](https://zenodo.org/records/15396799) <https://zenodo.org/records/15396799>

520 **Author Contribution**

521 The author is the coordinator and scientific lead of the EU project “*WorldTrans - Transparent*
522 *Assessments for Real People*” that developed FRIDA.”

523 **Competing Interests**

524 The author declares that she has no conflict of interest.

525 **Code/Data availability**

526 Not Applicable

527

528 **Acknowledgements**

529 The author would like to thank the entire WorldTrans team ([https://worldtrans-
horizon.eu/https://worldtrans-horizon.eu/](https://worldtrans-
530 horizon.eu/https://worldtrans-horizon.eu/)), and in particular the FRIDA model development team:

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531 Benjamin Blanz, Axel Eriksson, Martin [Grimeland](#)~~Grimelund~~, Andreas Nicolaidis Lindqvist, Jefferson
532 Rajah, Lennart Ramme, Chris Wells, and the coordinator of the model development process: ~~(the~~
533 ~~“father of FRIDA”)~~, Billy Schoenberg. This research was supported by the Horizon Europe research and
534 innovation programs under grant agreement no. 101081661 (WorldTrans). This work used resources
535 of the Deutsches Klimarechenzentrum (DKRZ) granted by its Scientific Steering Committee (WLA)
536 under project IDs 0033 and 1275.
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621 **APPENDIX: Best practices for running experiments: Type of research question vs type of**
622 **experiment**

623 There are many kinds of experiments one may wish to run with FRIDA. How to set up each
624 experiment depends partly on the research questions one attempts to answer. We have identified four
625 types of research questions that require their own type of experiments in FRIDA:
626 **Research question type 1: What happens to the system if we introduce this or that change (structure**
627 **or policy) to the model sometime in the future?** For instance: what happens if we introduce a global
628 carbon tax in 2030, or a new central bank target for inflation in 2040, or a moratorium on the
629 extraction of fossil fuels in 2050? This type of experiment is easy to perform: one changes the relevant
630 lever, or parameter, or flux in the relevant year and compares the EMB run to the experimental run.
631 These are hypothetical “what if”- type questions.

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

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

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

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

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