

1 **This is FRIDA**

2 V2: Submitted April 22, 2026

3 Cecilie Mauritzen

4 Climate Division, Norwegian Meteorological Institute, 0131 Oslo, Norway

5 **Correspondence to:** Cecilie Mauritzen (ceciliem@met.no)

6 **Abstract**

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

12 FRIDA was developed through the European Horizon project *WorldTrans – Transparent Assessments*
13 *for Real People* (2022-2026). The journal *Geoscientific Model Development* has given us space to
14 document FRIDA, including its submodules and spin-offs, in a special *GMD Collection*¹. This brief
15 paper is the introduction to the GMD FRIDA collection of papers. The purpose of the introductory
16 paper, written by the project lead on behalf of the consortium, is to provide the conceptual and
17 institutional context for the original model and to make explicit the initial design requirements that
18 guide FRIDA’s ongoing development as a living knowledge repository.

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

25 What sets FRIDA apart from traditional IAMs is its shift from exogenous, narrative-based scenarios to
26 a fully feedback-driven framework, in which human activities and climate change co-evolve within a

¹ <https://gmd.copernicus.org/articles/collection12.html>

27 single system of equations. By explicitly representing these two-way feedbacks, FRIDA accounts for
28 the impacts that climate change has already begun to exert on human systems; without them,
29 projections of the human activities that drive climate change will become increasingly unreliable.
30 Preliminary results suggest that including these feedbacks lead to systematically less optimistic
31 projections than conventional IAM baselines.

32 **1 Introduction**

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

42 For long, climate change was hard to notice. But by now, the world has entered the realm of
43 *dangerous climate change*. In 2024, global average temperature exceeded 1.5 °C above pre-industrial
44 levels for the first time (Bevacqua et al., 2025). While an isolated year above this threshold does not
45 yet mean the high ambition goal of the Paris Agreement — to hold global temperature increase well
46 below 2 °C and to pursue efforts to limit it to 1.5 °C on a sustained basis — human-caused climate
47 change is already causing widespread adverse impacts and losses and damages (**O'Neill et al., 2022**
48 (IPCC AR6 WGII Chapter 16)), including observed increases in extreme heat, heavy precipitation and
49 drought (Seneviratne et al., 2021 (IPCC AR6 WGI Chapter 11)), indicating that dangerous climate
50 change is already being experienced.

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

55 For as long as the UN has engaged in climate change negotiations, these questions have been on the
56 table, and answers have been sought using a myriad of models and expert negotiation processes. But
57 climate has continued to change. These recognitions — that negotiations still fail and that climate now

58 affects our lives — were strong motivations for introducing a new IAM that explicitly includes diverse
59 climate change impacts on humans. We call this new model FRIDA, with the subtitle *Feedback-based*
60 *knowledge Repository for IntegrateD Assessments*.

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

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

72 **2 Requirement for FRIDA**

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

- 78 ● **Take advantage of conservation laws to constrain the model.** This involves including the
79 carbon, heat and water cycles.
- 80 ● **Begin with a non-regional model.** By building a global, rather than a regionally segregated
81 model, the model output remains simpler to analyze, due to the reduced number degrees of
82 freedom (which is large already on the global scale). The result is increased transparency and
83 a better chance at building intuition and insights.
- 84 ● **Balanced representation of climate and humans.** This means focusing on the minimum
85 detail necessary to capture the important interconnections between subsystems.
- 86 ● **Complete treatment of climate change forcing.** This means to include the main greenhouse
87 gases (CO₂, CH₄, N₂O and HFCs) and the main cooling aerosol agent (SO₂), and to account
88 for the effect of other climate forcers, such as those associated with land use change. It also
89 means to model the sectors that create the greenhouse gas emissions (transport sector, energy

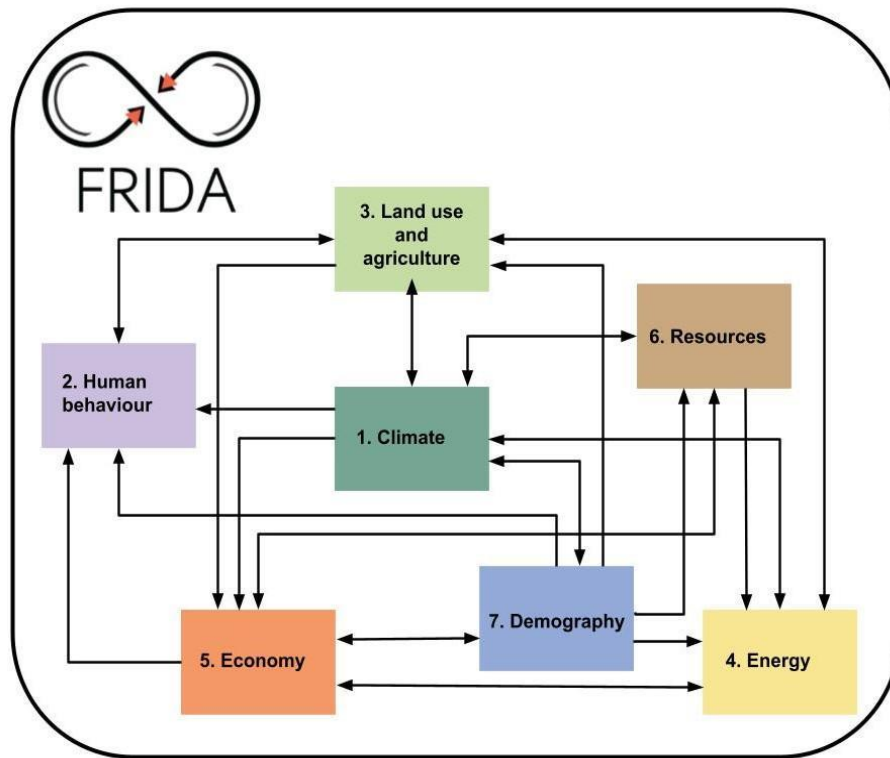
90 production, land use and agriculture, chemical industries, cement production and waste). And
91 it means to consider the underlying economic system and demography that creates changes in
92 those sectors.

- 93 ● **Complete treatment of climate-driven feedback.** This implies taking into account,
94 quantitatively, how climate affects (mostly damages) these sectors and the underlying
95 economy and demography.
- 96 ● **Complete treatment of uncertainty.** This implies keeping the computing speed low, to allow
97 for large ensemble runs.
- 98 ● **Include human needs, desires and behavior.** This means that (modelled) people can have an
99 impact on the system, by changing behavior with respect to, for instance, dietary and mobility
100 choices. This implies a departure from describing humans as purely theoretical economic
101 beings maximizing profit or utility.
- 102 ● **A dynamic representation of the economy.** This means to model the economy as a system
103 that moves forward in time and acts and reacts to its surroundings, just like we model the rest
104 of the system.
- 105 ● **Modular organization of the model.** This is a requirement that improves the transparency of
106 the model.
- 107 ● **Familiar external levers.** To generate change in the system we include the possibility of
108 acting as a decision maker within the various modules of the model (for instance within
109 government, or within the financial or energy sector)
- 110 ● **An accompanying toolbox for users of the model.** Since every model, even the simplest, is
111 hard to interpret, we have developed a set of tools to aid the use of the model, aimed at our
112 three user groups: 1) the *decision-maker* who would normally use IAM-based analysis to
113 inform decisions about climate action. An important use context for the decision maker is the
114 European Green Deal; 2) a *scientist*, say, a typical IPCC author who needs improved
115 information flows and shared understanding of the system links and feedbacks between
116 physical climate, the social and environmental impacts of climate change, adaptation
117 responses, and mitigation efforts; and 3) the *engaged citizen* who is concerned about the
118 climate challenge, but lacks the knowledge needed to engage in and catalyze a deeper societal
119 discussion on the topic.

120 3. Design of FRIDA

121 FRIDA is built using the tools of System Dynamics (see e.g., Forrester 1961, Sterman 2000). This
122 approach facilitates, at relative ease, the inclusion of very different disciplines and their methods,
123 ranging from the laws of nature to empirical relationships, direct observations and co-created

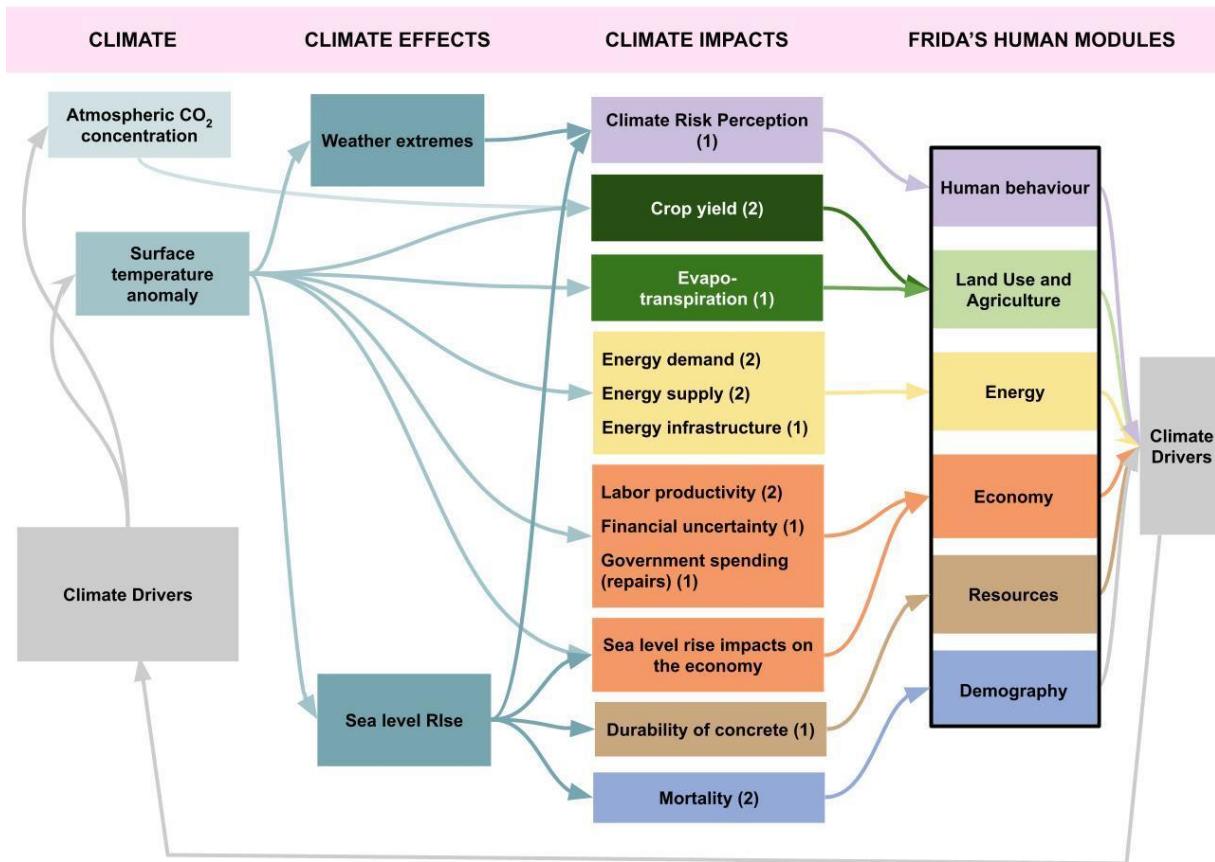
124 knowledge. Central to the approach are feedback and delay perspectives, which highlight the complex
 125 and oftentimes circular interactions between system components that endogenously generate behavior,
 126 making it a suitable approach to coupling the natural climate system with the many aspects of human
 127 life that can affect — and are affected by — climate. FRIDA is divided into seven modules: Climate,
 128 Human behavior, Land use and Agriculture, Energy, Economy, Resources and Demography (Fig. 1).
 129 All these interlinkages within and between the modules collectively create the complex dynamics of
 130 the system. This is what make it is easy to state that “everything is connected to everything”, but
 131 comparably difficult to explain how.



132
 133 **Figure 1:** The modules and interlinkages in FRIDA V2.1. All modules except the climate module are
 134 collectively referred to as the “anthropogenic” modules of FRIDA. Note, however, that the “Land Use and
 135 Agriculture” module contains information about both nature and agriculture.

136 In FRIDA, climate impacts are modelled as recognizable processes, such as the assessment of climate
 137 risk made by financial institutions, changes in demand for animal food products because of personal
 138 norms driven by climate risk perception, changes in demand for energy as a consequence of changing

139 temperature; changes in labor productivity, changes in water use for irrigation, and so forth. To
 140 determine which impacts to include, the starting point was IPCC WGII AR6's assessment of literature
 141 on climate impacts and risks (Pörtner et al., 2022). Decisions were based on three criteria: 1)
 142 applicability to the [global] scope of FRIDA; 2) the expected global magnitude of the effect as agreed
 143 upon in the extant literature; 3) when the scope and magnitude of the impact was not agreed upon in
 144 the literature, was there enough data present in the literature to reproduce at least one pre-existing
 145 global study with wide uncertainty parameters? In addition, we added some climate impacts that are
 146 of relevance to the scope of FRIDA yet not included in the IPCC assessment. Details on the
 147 implementation of climate drivers and impacts in FRIDA are documented in Wells et al. 2026a and
 148 Ramme et al., 2025. A graphical representation of the implementation of climate effects and impacts
 149 in FRIDAv2.1 is given in Fig. 2.



150

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

153

154 To build each module of FRIDA, the team entered an iterative cycle of mapping essential feedback
155 loops, selecting equations and theoretical frameworks from scientific literature and developing novel
156 "expert-supplied functional forms" when literature is insufficient, as documented in Schoenberg et al.,
157 2025. Examples include:

158 ● **Laws of Nature:** The model embodies the laws of nature within its Climate module,
159 representing the Earth's radiation balance, carbon cycle, and water cycle. Specific examples
160 include the three-layer energy balance model (simulating heat exchange between ocean layers)
161 and the carbonate chemistry system in the ocean (Wells et al., 2026b, Schoenberg et al., 2025)

162 ● **Leading Theoretical Frameworks:**

163 ○ The Economy module uses a monetary model of production, consumption, and
164 finance based on Schumpeterian dynamics of innovation and creative destruction
165 (Schumpeter, 1942; Aghion & Howitt, 1992, 2009)) to simulate the dynamic circular
166 flow of income (Grimeland et al, 2026, Schoenberg et al., 2025).

167 ○ The Behavioral Change module is conceptualised using the Motivation–Agency–Past
168 Behaviour (MAP) meta-theoretical framework (van Valkengoed, Perlaviciute and
169 Steg, 2025), which integrates motivational drivers, enabling conditions, and
170 behavioural path dependence (Rajah et al., 2025, Schoenberg et al., 2025).

171 ○ Population changes in the demography module are modeled as a continuous cohorting
172 system (Eberlein, Thompson and Matchar, 2012), using "conveyors" to represent the
173 physical dynamics of aging and age-specific mortality rates (Schoenberg et al., 2025)

174 ● **Expert-Supplied functional Forms:** When established literature is insufficient for certain
175 feedback loops, the team uses "expert-supplied functional forms" that are dimensionally
176 consistent and behaviorally logical under extreme conditions. For example, energy
177 infrastructure damage by climate is modeled as a power law function of the global temperature
178 anomaly, representing how extreme warming increases the decay rate of capital. Climate
179 impact on crop yields is modelled as a complex functional form that is linear in CO2
180 concentration and quadratic in absolute temperature, capturing the antagonistic relationship
181 between CO2 fertilization and heat stress (Wells et al., 2026a, Schoenberg et al., 2025).

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

196 **4. FRIDA’s Endogenous Behaviour**

197 A useful feature of a (nearly)-all-inclusive model like FRIDA is that the model does not need external
198 forcing to run into the future. The processes that are deemed important for the problem, ie. within the
199 scope of the model, exist inside the model. This is contrary to a typical Earth System Model and many
200 process-based Integrated Assessment Models, which require external forcing to run (the former: for
201 example, greenhouse gas emissions; the latter: for example, population growth). We call FRIDA’s
202 “free”, or “unforced”, or “endogenous” run the “*Endogenous Model Behavior*” (EMB) run. In the
203 EMB run, all the change comes entirely from its internal feedback structure. The run is “free” because
204 once you hit “start”, nothing happens except what the model itself generates. It is “endogenous”
205 because every variable that changes does so because of the model’s own dynamics. And the results are
206 tied to reality in the sense that where possible, the governing equations are based on science, and the
207 parameterizations are arrived at through calibration with observations.

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

212 **5. Using FRIDA**

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

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

231 **6. Comparisons with other projections**

232 FRIDA projections have been compared to the five Shared Socioeconomic Pathways: SSP1
233 (Sustainability), SSP2 (Middle of the Road), SSP3 (Regional Rivalry), SSP4 (Inequality), and SSP5
234 (Fossil-fueled Development) (O’Neill et al., 2017). In this comparison, Schoenberg et al., (2025) find
235 that SSP1-, SSP2-, and SSP5-Baseline are overly optimistic regarding future economic growth, while
236 SSP3- and SSP4-Baseline align more closely with FRIDA’s ensemble behaviour. The reason is the
237 structural difference: FRIDA represents the climate–human system as a fully coupled, feedback-rich
238 system, rather than treating many climate-to-human effects as exogenous, omitted, or highly
239 aggregated. In conventional IAMs, much of the climate-damage literature has focused on aggregate
240 GDP losses in top-down assessments (Howard and Sterner, 2017), often through highly aggregated
241 damage functions that have been criticized as empirically weak and “black box” in nature (Pindyck,
242 2017). FRIDA replaces this with a more disaggregated, process-based representation of impacts
243 (Grimeland et al., 2026; Wells et al., 2026a).

244 What this means in practice is that FRIDA allows climate damages to feed back onto the drivers of
245 future growth themselves. In the economy module, expected climate impacts reduce economic
246 production primarily through reduced investment growth and financial fragility, while government
247 budgets come under increasing stress from unemployment and demographic change; in some
248 simulations, these combined pressures can even halt growth altogether (Grimeland et al., 2026).
249 Unlike standard IAM baselines, FRIDA therefore does not assume that high GDP growth can continue
250 largely unaffected in a warming world. Rajah et al. (2025) further show that, when behaviour is
251 endogenized, future food and animal-product demand is lower than in the standard GDP-driven
252 approach, producing slightly lower emissions and a somewhat cooler baseline climate. Ramme et al.
253 (2025) likewise show that adding coastal feedbacks can generate non-linear damage patterns,
254 including peak-and-decline storm-surge damages driven by endogenous retreat and reduced coastal
255 investment. Wells et al. (2026b) add that even the climate module differs from standard simple-climate
256 emulators because FRIDA-Clim uses a process-based carbon cycle within the coupled framework.
257 Overall, the FRIDA papers therefore suggest not just a different set of numbers, but a systematically
258 less optimistic future outlook, because once feedbacks from climate damages, finance, behaviour, and
259 adaptation constraints are internalized, future growth paths become lower, more fragile, and less
260 consistent with the high-growth baselines commonly used in conventional IAM exercises (Schoenberg
261 et al., 2025; Grimeland et al., 2026; Rajah et al., 2025; Ramme et al., 2025; Wells et al., 2026a,
262 2026b).

263 **7. Outlook**

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

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

277 positioned to explore risks of systemic destabilization, identify leverage points, and illuminate co-
278 benefits and trade-offs of mitigation and adaptation strategies.

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

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

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

294

295 **Author Contribution**

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

298 **Competing Interests**

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

300 **Code/Data availability**

301 Not Applicable

302

303 **Acknowledgements**

304 The author would like to thank the entire WorldTrans team (<https://worldtrans-horizon.eu/>), and in
305 particular the FRIDA model development team: Benjamin Blanz, Axel Eriksson, Martin Grimeland,
306 Andreas Nicolaidis Lindqvist, Jefferson Rajah, Lennart Ramme, Chris Wells and the coordinator of
307 the model development process: Billy Schoenberg. This research was supported by the Horizon
308 Europe research and innovation programs under grant agreement no. 101081661 (WorldTrans). This
309 work used resources of the Deutsches Klimarechenzentrum (DKRZ) granted by its Scientific Steering
310 Committee (WLA) under project IDs 0033 and 1275.

311

312 **References**

- 313 Aghion, P. and Howitt, P.: A model of growth through creative destruction, *Econometrica*, 60, 323–
314 351, 1992.
- 315 Aghion, P. and Howitt, P.: *The economics of growth*, MIT Press, Cambridge, MA, USA, 2009.
- 316 Bevacqua, E., Schleussner, C.-F., and Zscheischler, J.: A year above 1.5 °C signals that Earth is most
317 probably within the 20-year period that will reach the Paris Agreement limit, *Nat. Clim. Change*,
318 15, 262–265, <https://doi.org/10.1038/s41558-025-02246-9>, 2025.
- 319 Eberlein, R. L., Thompson, J. P., and Matchar, D. B.: Chronological aging in continuous time, in:
320 *Proceedings of the 30th International Conference of the System Dynamics Society*, St. Gallen,
321 Switzerland, 22–26 July 2012, 2012.
- 322 Forrester, J. W.: *Industrial dynamics*, M.I.T. Press, Cambridge, MA, USA, 464 pp., 1961.
- 323 Grimeland, M. B., Blanz, B., Schoenberg, W., and Callegari, B.: Schumpeterian disaggregation and
324 integrated assessment: An endogenous, stock-flow consistent economy in disequilibrium for
325 FRIDA v2.1, *EGUsphere* [preprint], <https://doi.org/10.5194/egusphere-2025-6342>, 2026.
- 326 Howard, P. H. and Sterner, T.: Few and not so far between: A meta-analysis of climate damage
327 estimates, *Environ. Resour. Econ.*, 68, 197–225, <https://doi.org/10.1007/s10640-017-0166-z>, 2017.

328 Mustafa, M.: From complexity to clarity: Designing and evaluating an interactive learning
329 environment for human–climate system exploration using FRIDA, Master's thesis, University of
330 Bergen, Bergen, Norway, BORA – University of Bergen Open Research Archive, 2025.

331 O’Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S., van Ruijven, B.
332 J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., and Solecki, W.: The roads ahead:
333 Narratives for shared socioeconomic pathways describing world futures in the 21st century, *Global*
334 *Environ. Change*, 42, 169–180, <https://doi.org/10.1016/j.gloenvcha.2015.01.004>, 2017.

335 O’Neill, B., van Aalst, M., Zaiton Ibrahim, Z., et al.: Key risks across sectors and regions, in: *Climate*
336 *Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the*
337 *Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge
338 University Press, 2411–2538, <https://doi.org/10.1017/9781009325844.025>, 2022.

339 Pindyck, R. S.: The use and misuse of models for climate policy, *Rev. Environ. Econ. Policy*, 11, 100–
340 114, <https://doi.org/10.1093/reep/rew012>, 2017.

341 Pörtner, H.-O., Roberts, D. C., Adams, H., et al.: Technical summary, in: *Climate Change 2022:*
342 *Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment*
343 *Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, 37–118,
344 <https://doi.org/10.1017/9781009325844.002>, 2022.

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

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

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

353 Saltelli, A., Tarantola, S., Campolongo, F., and Ratto, M.: *Global sensitivity analysis: The primer*,
354 Wiley, Chichester, UK, 304 pp., 2008.

355 Schoenberg, W., Blanz, B., Rajah, J. K., Callegari, B., Wells, C., Breier, J., Grimeland, M. B.,
356 Lindqvist, A. N., Ramme, L., Smith, C., Li, C., Mashhadi, S., Muralidhar, A., and Mauritzen, C.:
357 An overview of FRIDA v2.1: a feedback-based, fully coupled, global integrated assessment model
358 of climate and humans, *Geosci. Model Dev.*, 18, 8047–8069, [https://doi.org/10.5194/gmd-18-8047-](https://doi.org/10.5194/gmd-18-8047-2025)
359 2025, 2025.

360 Schumpeter, J. A.: *Capitalism, socialism and democracy*, Harper & Brothers, New York, NY, USA,
361 1942.

362 Seneviratne, S. I., Zhang, X., Adnan, M., et al.: Weather and climate extreme events in a changing
363 climate, in: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to*

364 *the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge
365 University Press, 1513–1766, <https://doi.org/10.1017/9781009157896.013>, 2021.

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

368 Sterman, J. D.: *Business dynamics: Systems thinking and modeling for a complex world*, McGraw-
369 Hill, New York, NY, USA, 982 pp., 2000.

370 van Valkengoed, A. M., Perlaviciute, G., and Steg, L.: Representing the drivers of lifestyle change in
371 integrated assessment models: Introducing the Motivation, Agency, and Past Behaviour (MAP)
372 framework, Environ. Res. Commun., 7, 032001, <https://doi.org/10.1088/2515-7620/acb162>, 2025.

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

378 Wells, C. D., Ramme, L., Smith, C., Breier, J., Muralidhar, A., Li, C., Gjermundsen, A., Schoenberg,
379 W. A., Blanz, B., and Mauritzen, C.: FRIDA-Clim v1.0.1: a simple climate model with process-
380 based carbon cycle used in the integrated assessment model FRIDAv2.1, Geosci. Model Dev., 19,
381 1429–1453, <https://doi.org/10.5194/gmd-19-1429-2026>, 2026b.

382 **APPENDIX: Best practices for running experiments: Type of research question vs type of** 383 **experiment**

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

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

393 **Research question type 2:** *What would have happened to the system if this or that change (to*
394 *structure or policy) was introduced in past times?* For instance: what would the system have looked
395 like if the carbon tax had been implemented in 1990. In this case the experiment is made the same way
396 as in the previous case, except that the change is introduced to the calibration period, so we compare a
397 factual and a counterfactual system (the EMB run vs the experimental run). This can be applied both

398 to policy changes (i.e. carbon taxes) as well as system structure, i.e. including or not including a
399 feedback or a physical process. These are hypothetical “what if”- type questions.

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

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