Towards a fully coupled Integrated Climate Assessment Model: FRIDA Version 0.1 (Feedback-based knowledge Repository for IntegrateD Assessments)

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Abstract

We document FRIDA V0.1, a simple, box-model-type joint climate - IAM (Integrated Assessment Model), or World-Earth model, using the computational framework of System Dynamics. It places nature and humans on similar footing: both sides are extensively calibrated (back to 1980), and of similar complexity. The objective is to deliver to the international climate community a model that overcomes several key weaknesses of state-of-the-art Earth System Models (ESMs) and IAMs: limited level of connections from climate to human societies, lack of transparency into the models, limited understanding of uncertainty associated with model results, and limited scope for stakeholder engagement. These weaknesses can be mitigated by using the System Dynamics framework to its full extent, involving domain expertise from the climate research community.

We will develop FRIDA in several steps. V0.1 focuses on the effects of climate-to-human feedbacks. The strongest impact of including those feedbacks is not that the rate of warming, nor the level of anthropogenic emissions, changes greatly. The greatest change is found in the global economy. Models run without feedbacks from the climate to human societies are, according to our study, likely to greatly underestimate the detrimental effect of climate change on the economy.

1. Introduction: The challenges of modeling the changing climate

Climate change, in all its forms, poses numerous impacts and risks to humans and ecosystems alike. When the UNFCCC Climate Convention (UNFCCC) was signed in 1992, the threat of climate change was recognized - it already had been recognized for decades (see eg. Supran et al., 2023) - but the impacts were considered to lie far ahead in the future. However, the occurrence of human suffering and economic damages from climate change impacts have grown rapidly during the past 40 years (Rosvold and Buhuang, 2021). Now the impacts are felt across societies all around the globe.

The sheer complexity of the climate change challenge has put practical constraints on the modeling communities and has caused an implicit division of labor between Earth System analysis of biogeophysical climate processes, and integrated assessment and the interpretation of future climate pathways with climate impacts. The cooperation framework for this division of labor has been one of knowledge exchange, an extremely successful approach, both in breadth and depth of scientific explorations (see O'Neill et al., 2020, for a thorough assessment). But it has caused a quantitative and methodical disconnect between the various research communities involved in climate research. Broadly speaking, the disconnect exists between researchers involved in the physical science climate change (whose publications are assessed in IPCC's Working Group I - the physical science), those involved in climate change impact research (the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it; assessed in IPCC's Working Group II) and those involved in climate change mitigation research, i.e. how to reduce anthropogenic climate change (assessed in IPCC's Working Group III). This is not to say the three IPCC Working Groups do not collaborate - with each assessment report the collaborations have increased - but rather that a more integrated approach needs to be taken for scenario and model development.

Central to the analysis of climate mitigation pathways assessed in Working Group III are Integrated Assessment Models (IAMs). IAMs were used to develop the Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) used for Earth System Model (ESM; natural climate) projections in the Fifth and Sixth IPCC Assessment Reports (Moss et al., 2010; Riahi et al., 2017). They project how greenhouse gas and air pollutant emissions from various sectors such as energy, transport, industry, forestry, petroleum and agriculture industries might change in the future under different assumptions of future population and economic growth. Contributions from several other scenarios and

IAM groups worldwide were solicited by WGIII, resulting in over 1200 emissions pathways detailing potential societal transitions over the 21st Century (Byers et al. 2022).

When developing the scenarios, reduced-complexity climate models such as MAGICC and FaIR are used to quantify the climate change response (in particular the global mean temperature change) of the various IAM-derived emissions scenarios (Forster et al., 2021; Nicholls et al., 2021; Rogelj et al., 2018). These reduced-complexity models are calibrated to the responses of comprehensive ESMs (Leach et al., 2021) and then constrained to reproduce observed climate change and geophysical uncertainty ranges assessed by the IPCC (Smith et al. 2021, Forster et al., 2021).

But what will be the consequences of climate change for ecosystems and biodiversity? And what will be the impacts of climate change on human societies, cultures and settlements, given the various emission scenarios? The division of labor between the ESM and IAM communities - the fact that the models of the subsystems are not properly coupled (Figure 1) - makes it hard to elucidate the interactions between the subsystems of climate.

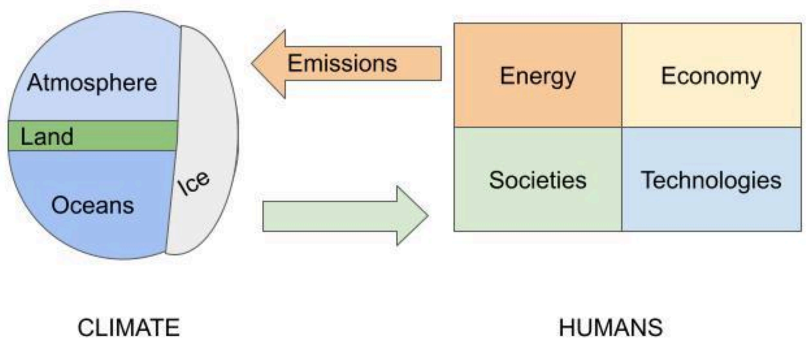

Figure 1: Schematic of the subsystems that constitute climate change. On the left hand side are found the components of nature that together react to changes in greenhouse gas and aerosol emissions. On the right hand side are found the components of human activities that together create the emissions. The lower, green arrow - from climate to humans - is often missing in current assessments of climate change.

This is a serious weakness: informed climate policy discussions should be based on understanding the complicated inter-linkages between the natural system, the energy system, the economic system, political processes and issues of fairness and justice. In a recent assessment of IAMs, Calvin and Bond-Lamberty (2018) found that in the cases where feedbacks between the human and natural system have been explored, there is not even agreement on the sign - let alone the magnitude - of the feedbacks. In most IAMs at present, the arrow of causality only runs in one direction: from population and GDP storylines provided exogenously (e.g. in the SSPs; (Riahi et al., 2017)) through to the technology-energy-economy and land-biosphere systems, to emissions, and finally to projections of global mean surface temperature. The post-hoc treatment of climate in the current generation of process-based IAMs is a significant weakness, in that the climate does not feed back into land-use, economy, demography, or the energy system (Thornton et al., 2017; Calvin and Bond-Lamberty, 2018; Woodard et al., 2019), but not one that has been systematically addressed by modeling groups. In the real world, climate affects almost every aspect of the human and natural system. Clearly, the feedbacks from climate to humans needs to be taken into account.

One tempting solution is to couple complex, process-based IAMs to similarly complex ESMs. However, this solution is extremely costly, computationally. While progress has developed in this area, climate impacts can be very localized, and the current crop of ESMs used to derive climate impacts may not have sufficient resolution to capture impacts at the local scale. Furthermore, the sheer computational requirements of fully coupled ESM-IAM systems are such that they are not yet useable for the kind of “what-if” scenario analysis required by Working Group III.

Our approach is to address the the structural weakness in current IAMs – namely the limited representation of important biophysical and social feedbacks – in order to deliver significant, rather than incremental, improvements in IAMs for climate and sustainability. We sacrifice details of particular sectors or processes, instead aiming to capture the essence of their functions to investigate the dominant phenomena acting within and across domains.

2. Our approach: sacrificing process details for system understanding

In order to address the interlinkages of the system we have chosen to build a box model of the full system, as depicted in Figure 1, for the globe itself. We are not looking at differences between regions and countries, but instead looking for variables of universal importance, such as average well being and health, atmospheric and oceanic temperatures, aggregate emissions and so forth. Box modeling has been used successfully in the natural sciences for a century, addressing for instance the atmospheric radiation budget, the energy and carbon cycles of the Earth, and ocean circulation. The System Dynamics method (Ford, 2010; Forrester, 1971) facilitates box modeling for time dependent problems in an intuitive manner, such that one can co-create a model and bring together the diverse discipline perspectives and include information based in a variety of formats, such as equations (e.g. Newton's laws of nature), data (e.g. time series observations of harvest volume or GDP), and non-quantitative measures (e.g. cultural experiences). We have therefore chosen to use the System Dynamics method when developing our model FRIDA.

3. Our starting point: The System Dynamics landscape of integrated global models

Modeling global change issues is a road well-traveled, and it generally follows the roadmap of Figure 1. We will briefly describe the four most well-known System Dynamics global system models that come before FRIDA: WORLD3, Earth4All, En-ROADS and FeliX.

WORLD3: The model underlying the Limits to Growth book (book: Meadows et. al 1972, 1974). The work was commissioned by the Club of Rome, and was built on Forrester's 1971 World Dynamics. The simulation model studied the interactions between four global scope subsystems: population, industry, pollution, and nonrenewable resources tying them all together with an endogenous model of global development. Over time the model underwent continued development appearing in such books as Beyond the Limits (Meadows et al. 1993) and Limits to Growth: the 30 year update (Meadows et al. 2004).

Earth4All: In preparation for the fiftieth anniversary of the publication of Limits to Growth in 1972 and the Earth Summit in Stockholm that same year, the Club of Rome instigated a new project Earth4All in 2021. The aim was to identify major turnarounds to "put our societies on a pathway towards wellbeing for all within planetary boundaries'' to quote the website (https://www.earth4all.life). The model Earth4All was developed by a team including Jørgen Randers (a key member of the World3 modeling team and co-author of the Limits to Growth book) to accompany the book. Earth4All is available as an open source System Dynamics model. The documentation and model can be found at the website https://earth4all.life and in Randers & Collste 2023.

En-ROADS: (Energy Rapid Overview and Decision Support) is a simulation model developed by Climate Interactive that allows policy makers and the general public alike to test different policies for addressing climate change. The model simulates interactions between energy production, consumption, land use, transportation, industry and climate change. The model provides a simple to use intuitive web based interface which gives end-users a plethora of policy options and assumptions to explore in their quest to reduce global temperature increase in the year 2100. En-ROADS (Siegel et al., 2018) was built off of C-ROADS, another famous system dynamics model of the carbon cycle used to assess greenhouse gas emission reduction policies. Documentation for EN-ROADS can be found online here: https://docs.climateinteractive.org/projects/en-roads/en/latest/

FeliX: FeliX (Full of Economic-Environment Linkages and Integration dX/dt; Eker et al., 2019; Rydzak et al., 2013; Walsh et al., 2017)) was built to assess the economic, social and environmental benefits of earth observations. It aims to represent a strongly interlinked Earth system and socio-economic system components forming a complex dynamic system. It consists of nine sectors, namely Economy, Energy, Emissions, Carbon Cycle, Climate & Environment, Population, Technology, Land Use, Energy and the Global Earth Observation System of Systems (GEOSS). All model sectors are highly interrelated and bring the global perspective to the GEO benefits assessment. In order to bring some of the GEO benefits assessment public there was developed a simulator based on the FeliX model equipped with a user friendly interface. The first version of the model was developed by Felicjan Rydzak and Michael Obersteiner. Between 2014 and 2017, FeliX model maintenance and development has been led by Brian Walsh. Currently, the model maintenance and development is undertaken by Sibel Eker. Documentation can be found here: https://druptest.iiasa.ac.at/staff/sibel-eker

4. On the relationship between Earth4All and FRIDA

The starting point for FRIDA was the May 2022 open source version of Earth4All (Dixson-Declève et al. 2022, Earth4All 2022, Randers & Collste, 2023), downloaded from the Earth4All website link[1]. The development of Earth4All is funded by private foundations with the aim of catalyzing collective movement towards rethinking the global economy. The Earth4All project has been successful in its purpose, delivering its messages at a wide range of high-profile outreach platforms. For the readers interested in pursuing Earth4All developments we refer to the book Earth For All: A survival guide for humanity (Dixson-Declève et al., 2022) and documentation of that model at the website https://earth4all.life.

The May 2022 version of Earth4All had a very attractive structure for our purposes. As is well known, models should be judged by their usefulness with respect to their purpose (Barlas, 1996). The purpose of our work, in the EU Horizon project WorldTrans, is to develop a model in support of a new kind of integrative scientific study, aimed at underpinning the IPCC assessments. We embarked upon a new model, from the starting point of Earth4All, for two reasons: First of all because it is a different team that develops FRIDA, with and by scientists that are highly involved in the IPCC processes; and secondly we deem it very likely that FRIDA and Earth4All will continue to diverge greatly as the two project teams move forward.

For our purposes, the model structure needed significant refinement/reworking, more attention to the feedbacks between the domains of nature and humans, and a rigorous calibration to observed historical data. Because the models share a common lineage, the period chosen for analysis in FRIDA matches that of Earth4All and is 1980 to 2100. 1980 was chosen as a starting point to allow for ample history for calibration purposes, and 2100 as the end point because of the ever expanding uncertainty bounds of such a large-scope simulation surpassing what is useful in a policymaking context. This time horizon also matches the ambition set out in Earth system sciences already at its foundation (NASA, 1988; Steffen et al. 2020). In the following sections we will document this first version (V0.1) of FRIDA in comparison to the May 2022 Earth4all model.

5. The philosophy of the FRIDA model

A classical climate, or Earth System, model has spatial resolution in the range of 5 to 100 km, with around fifty layers in the atmosphere and ocean. It simulates the laws of nature, and is only forced by external factors such as solar insolation, volcanic eruptions and anthropogenic actions. Climate models have to be spun up, often for several thousands of model years, to reach an equilibrium state in the atmosphere and ocean. The equilibrium state is usually chosen to be the period before large-scale anthropogenic influence, representative of year 1850 conditions. Before being used for production runs, models will often undergo a calibration and tuning processes to ensure the top-of-atmosphere energy budget is approximately in balance and consistent with observations, which may require tuning of sub-grid-scale parameters (often involving convection and clouds) that cannot be explicitly resolved. A set of standard diagnostic experiments are requested from climate models that contribute to the World Climate Research Program's Coupled Model Intercomparison Project (CMIP; Eyring et al. 2016), which provides a large evidence basis to IPCC Working Group I. One diagnostic experiment is the reproduction of climate over the period of anthropogenic influence (1850 to

[1] https://stockholmuniversity.app.box.com/s/uh7fjh52pvh7yx1mqfwqcyxdcvegrodf

near-present), where model performance can be compared to actual observations. . When creating simpler, box-model-type climate models, calibration towards the more complex climate models is typically performed, with observational constraints used to benchmark model performance (Leach et al. 2021). In this way, the simple climate models undergo a similar calibration as the system dynamics models do. In contrast, there is limited practice in evaluating historical performance of IAMs over the anthropogenic era or of calibration to observations, though these issues have been identified (Wilson et al. 2021). The IAMs are normally based on empirical relationships built together to cover the entire economy - technology- energy nexus.

FRIDA is developed as a simple, box-model-type joint ESM and IAM, using the computational framework of System Dynamics. The climate and humans sides are on similar footing: both sides are of reasonably similar complexity, and both are extensively calibrated (using data dating back to 1980).

For the version presented herein (V0.1) we focus on the effects of climate-to-humans feedbacks. The feedbacks from climate to humans are represented as simple responses to changes in temperature on three economic measures: the growth rate of Total Factor Productivity, the life of capital, and the cost of capital; and on three other wellbeing measures human mortality, electricity demand and crop yields. We are interested in how model generated scenarios develop through the rest of the 21st century when these feedbacks are strong or weak.

As we move on to FRIDA V1 and beyond we aim to further develop the feedback mechanisms of the model, to investigate and quantify the importance of these, and to investigate the potential for extreme responses (including the potential for tipping points) if for instance two or more feedbacks covary nonlinearly. At each step of model development we will ask progressively mode difficult questions. We will use the model to build intuition with stakeholders (be it students of climate or policymakers) by jointly creating and asking “what if?”-questions. And finally, we will use the model to create and run different policy scenarios in support of for instance the IPCC, EU and UNEP processes.

6. FRIDA’s structure

FRIDA is organized as a series of interconnected modules – the root level of which are depicted below in Figure 2. When compared to the overall framework of Figure 1 it is clear that the FRIDA model aims to fully couple all the subdomains. Each of the four main subsystems is represented by its own module, and the multitude of connections between those subsystems are represented in the heavy pink connectors. Astute readers will notice that there is not a specific technology module. In FRIDA technology is modeled in the places it is used and appears throughout each of the modules.

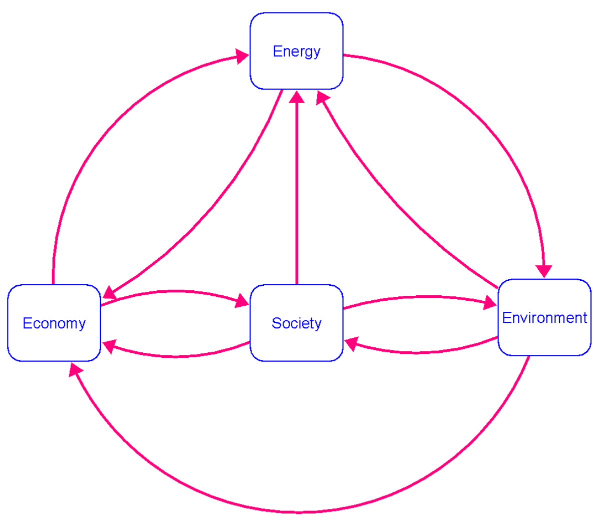

Figure 2: High level modules of the FRIDA model version 0.1

In terms of high-level concepts, FRIDA, like Earth4All, tracks the following global average variables : CO_2, CH_4, and N_2O concentrations in the atmosphere; radiative forcing; land use by type (old growth forest, forest, agricultural land, unused land, urban land), population, capital, income distribution, inequality, household debt, government debt, fossil energy production capital and renewable energy production capital. In FRIDA, all these variables are modeled endogenously (i.e. internally in the model), using data only for initialization purposes, with no exogenous, unconstrained (by observed data) forcing functions. The primary sources of interconnection between the root level modules are the following variables: Emissions, Inequality, Population, Surface Temperature Anomaly (STA) and GDP. FRIDA contains 579 variables, and 33 stocks. A full listing of all equations, and the source model are available in the supplementary materials[2].

6.1. Environment module

Carbon dioxide emissions into the atmosphere during the past 50-60 years have primarily been driven by emissions of fossil fuels, with land use change representing the remaining 10 percent (Figure 3). We therefore include both a climate module and a land use module in the Environmental module (Figure 4).

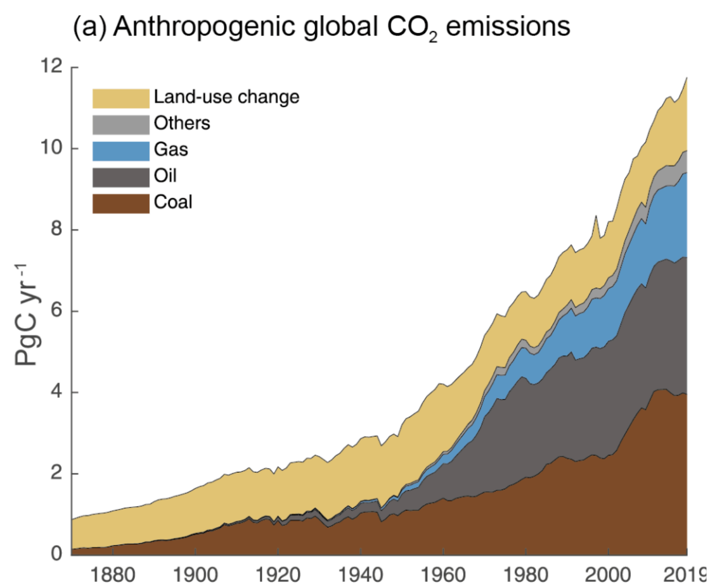

Figure 3: Global anthropogenic CO_2 emissions to the atmosphere. Figure 5.5 in IPCC AR6 WGI (Masson-Delmotte et al., 2021).

In FRIDA; as in Earth4All, these two modules depend upon each other, as well as the other root level modules.

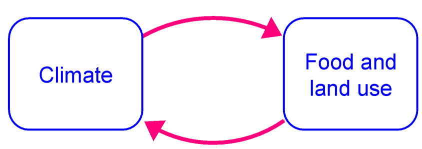

Figure 4: Modules making up the Environment subsystem in FRIDA V0.1.

6.1.1. Climate module

The climate module, depicted by Figure 5, is very similar in FRIDA and Earth4All. It is a simple (or [highly] simplified) climate simulator which calculates Surface Temperature Anomaly by accumulating “Extra heat in surface” produced since 1980. In both models, Extra Heat in Surface is driven by four heat fluxes. The first three are heat dissipation to space, the deep ocean, and heat used to melt ice and snow. The final flux is heat generated from radiative forcing from human sources. In both models, heat dissipation is driven by internal feedback processes involving changes in albedo from melting ice and snow, and the impact that the gradual warming of the oceans has on the ocean’s future heat absorption capabilities but the equations representing those relationships differ between the two models. In addition, in both models the climate module incorporates the water vapor feedback whereby a warmer atmosphere can hold more water

[2] https://github.com/metno/WorldTransFRIDA; https://docs.google.com/document/d/1Bnz2hNQmOQBaiRXnMa_dRD1GbEDyh3CQIKkI08X4xEs/edit?usp=sharing

vapor (itself a greenhouse gas). Differently in FRIDA, this reinforcing feedback is taken into account using a calibrated logistic function with STA as the input.

As in Earth4All, anthropogenic forcing (human driven forcing) is calculated from the sum of radiative forcing from CO_2, CH_4, N_2O and an exogenous residual forcing for all other anthropogenic forcers including minor GHGs, aerosols, ozone and albedo changes as a result of land use change. Different from Earth4All, the residual anthropogenic forcing is taken from the IPCC's best estimate time series for 1750-2014 (Smith et al. 2021), and for 2015-2100 is the median from 1202 IAM scenarios contributing results to the IPCC AR6 Scenario Database for Working Group III (Byers et al. 2022; Riahi et al. 2022) evaluated using v1.6.2 of the FaIR climate emulator (Smith et al. 2018), using each scenario's median residual forcing projection. In both models, forcing for each of the explicitly modeled gasses is based on their atmospheric concentrations which are based on accumulated stocks of each gas in the atmosphere, driven by the emissions and absorption of each of the gasses. In FRIDA, the forcing based on the atmospheric concentration of CO_2, CH_4 and N_2O uses Meinshausen et. al.'s (2020) formulation which captures the impacts of all three gasses and their interactions on radiative forcing due to each gas. For CO_2, as in the Earth4All model, emissions are calculated as the sum of CO_2 emissions from energy and industry (coming from the Energy module, Section 6.4) and CO_2 emissions from land use cover changes (coming from the Food and Land Use module, Section 6.1.2). In addition, both models also capture the oxidation of CH_4 into CO_2 in the atmosphere. For CH_4, as in Earth4All, emissions are calculated primarily as a function of Crop Production from the Food and Land Use module (section 6.1.2), and N_2O emissions are primarily a function of Fertilizer Use also calculated in the Food and Land Use module. Both models vary absorption times of CO_2 in the atmosphere; in FRIDA this is done using a calibrated linear function based on the amount of extra CO_2 sequestered since 1850 which allows for the absorption process to slow by a factor of 2x over the simulation period accounting for the known changes in rates of CO_2 sequestration by the oceans and biosphere (Friedlingstein et al. 2006). Unlike Earth4All, the breakdown of CH_4 is based on a calibrated ~12 year lifespan (Mar et al. 2022) which changes over time as a result of a calibrated linear function using the amount of CH_4 currently in the atmosphere as its input. The breakdown of N_2O is based on a calibrated constant ~116 year lifespan (Prather et al. 2015) which is similar to Earth4All in that it is constant, but different, as Earth4All uses 95 years.

A significant departure from Earth4All is the calibration of the parameters related to the calculation of STA from a given time series of anthropogenic forcing. Specifically, the way that the Climate module dissipates of Extra heat in surface, and the parameterization and equations for the relationships which control the the water vapor and albedo feedbacks were driven both by reproducing historical observations of the STA and to reproduce the future projections of Version 1.6.2 of the FaIR climate emulator (Smith et al. 2018) that was used to generate the IPCC AR6 climate estimate, when FaIR is fed the identical anthropogenic forcing time series that FRIDA generates (see Figure 14 for comparison to FaIR using identical time series of anthropogenic forcing). It was necessary to calibrate FRIDA to FaIR's future projections (as well as observed historical warming) because in its current state the Climate module does not represent enough of the climate system process detail to shed new insight on potential warming trends given a set of anthropogenic forcing.

In future versions of FRIDA the climate module will be replaced with FaIR and expanded to include active ocean, atmosphere and cryosphere components (see Figure 1).

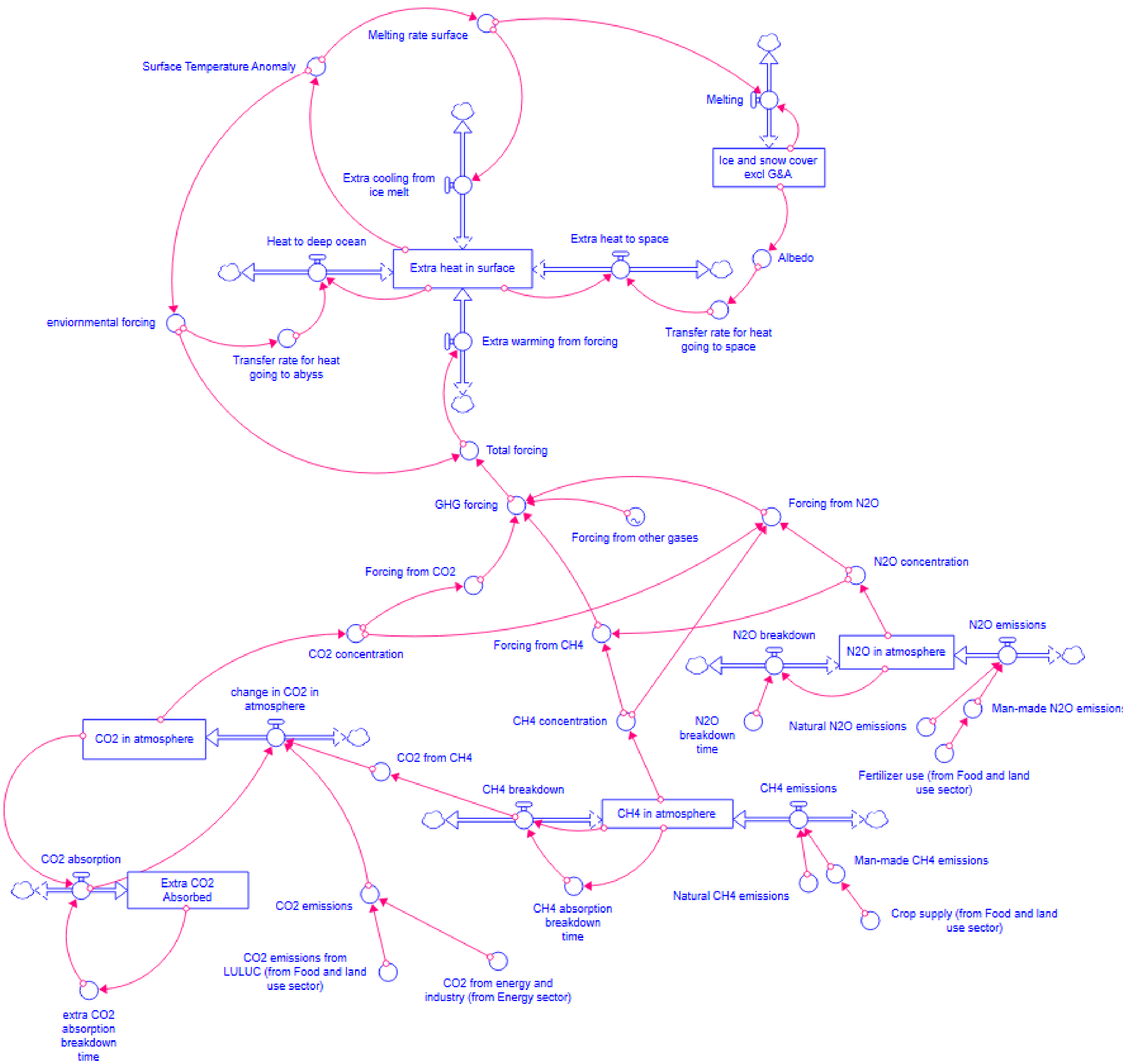

Figure 5: The main feedback structure internal to the climate system

6.1.2. Food and land use module

The Food and Land Use module pictured in Figure 6 has largely the same structure as the equivalent Earth4All module. In both models, this module simulates the demand for crops, an aggregate index of global soil quality, crop production, and an allocation of land between old growth forests, forestry land, agricultural land, unused/barren land, and urban land. The primary outputs are Fertilizer Use, Crop Production, and CO_2 emissions from land use cover change.

As in the Earth4All Food and Land Use module, FRIDA calculates Fertilizer Use and Crop Production using Crop Demand. Both models use GDP per person to determine Crop Demand (Tilman et al. 2011). FRIDA uses a calibrated regression based reinforcing power function of GDP per person for this purpose. The nature of this regression, and the removal of the distinction between crops for food directly vs. for livestock are two of the important differences between the food aspects of the models. Both models use Crop Demand, along with the stock of Agricultural Land to determine the Average Crop Yield, based on a reinforcing feedback loop of continued Fertilizer Use negatively affecting soil quality which places a strong downward pressure on Average Crop Yield, and drives the decay of Agricultural Land into Unused Land. In addition, in both models, the Average Crop Yield is also negatively impacted by the STA (from IPCC AR6 WGI, Chapter 12 (Ranasinghe et al., 2021)), and is bolstered slightly in comparison by the increasing concentration of CO_2 in the atmosphere due to plantlife respiring CO_2 (Kimball et al. 1983). Both models have Crop Production as a function of the Average Crop Yield (supported by Fertilizer Use) and Agricultural Land which is used to calculate the crop (supply/demand) balance. The source of Agricultural Land is different between the models; both allow Forestry Land to be converted, while only FRIDA allows conversion of Unused Land into Agricultural Land (Edgerton 2009; Lambin and Meyfroidt 2011).

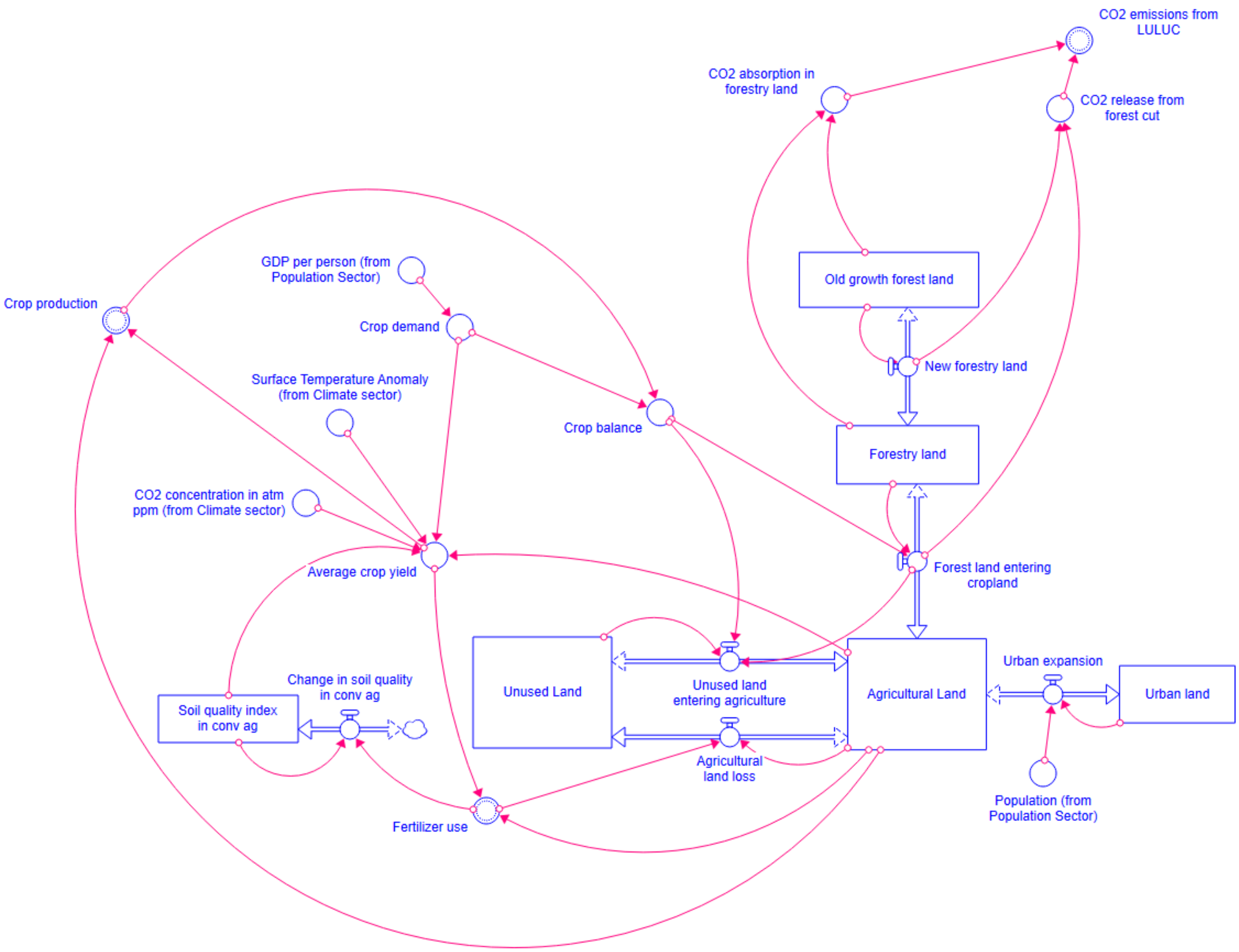

Figure 6: The Food and Land Use module

In both models the remaining portion of the Food and Land use module is concerned with CO_2 emissions from land use and land cover changes. Those emissions are based on the two forest land stocks. CO_2 is released via the destruction of both old growth and forestry land, but CO_2 is sequestered by both stocks of forest land. The emissions and absorption properties of each on a per hectare basis were both calibration derived. Old growth forests are converted into Forestry land via a calibrated linear removal rate. Forestry land is then converted into Agricultural Land based on the needs of the agricultural system using the crop balance discussed above. Agricultural Land is converted into Unused land by the soil decay process discussed above, or into Urban Land via a reinforcing linear function of Population, representing the increasing land needs of the human population as it expands.

6.2. Society module

A well-used approach to simulating humans in IAMs is to estimate their economic behavior, often in terms of optimal, rational economic behavior. The human population and its wellbeing are key drivers of the economic system. Human society is the core of any economic system. An important aspect of the development of FRIDA is to represent humans in the system more realistically. What is the human impact on crop yield? On the food system? On material consumption? How does climate affect well-being, human health and so forth. At this level of model development (V0.1), the Society module only contains a representation of population. It is missing a representation of human wellbeing and health. In future versions of FRIDA the Society module will be greatly expanded.

6.2.1. Population module

The population modules of FRIDA and Earth4All differ significantly in implementation, but not intent or aggregations of cohorts. FRIDA's population module (Figure 7) is a continuous cohorting system (Eberlein and Thompson, 2013) using Stella's (isee systems, 2023) conveyors, to represent the dynamics of aging along with age group specific mortality which is not present in Earth4All. The population module is used to project global population, and GDP per person using GDP from the Economy's Supply module (section 6.3.1). The continuous cohorts are grouped into 6 age categories: Infants, Aged 1-20, Aged 20-40, Aged 40-60, Aged 60-80, Aged Over 80 for the purposes of simulating different mortality rates. These age groups were chosen based on their distinct age specific mortality rates, and the needs of the Labor module (section 6.3.2) to determine the size of the global labor force and are similar to those from Earth4All. The age specific cohorts are initialized using United Nations (2022) data of global population by age in 1980.

The age group specific mortality rates introduced in FRIDA are calculated based on calibrated balancing power function regressions using GDP per person as the input - increasing GDP per person, places downward pressure on death rates (Miladinov, 2020). The other factor used to determine the age group specific death rates is a calibrated reinforcing linear impact of the STA (from the Climate module, section 6.1.1) on each death rate, capturing the demographic impacts of sea level rise, mass migration, etc. (IPCC, 2022). Like in Earth4All, births are based on a calculated fertility rate, the result of a calibrated balancing power function regression using GDP per person as an input. With rising standards of living and education, birth rates drop exponentially (Callegari & Stoknes, 2023; Kirk, 1996; Lesthaeghe, 2010; Marquez-Ramos and Mourelle, 2019, Proto and Rustichini, 2013).

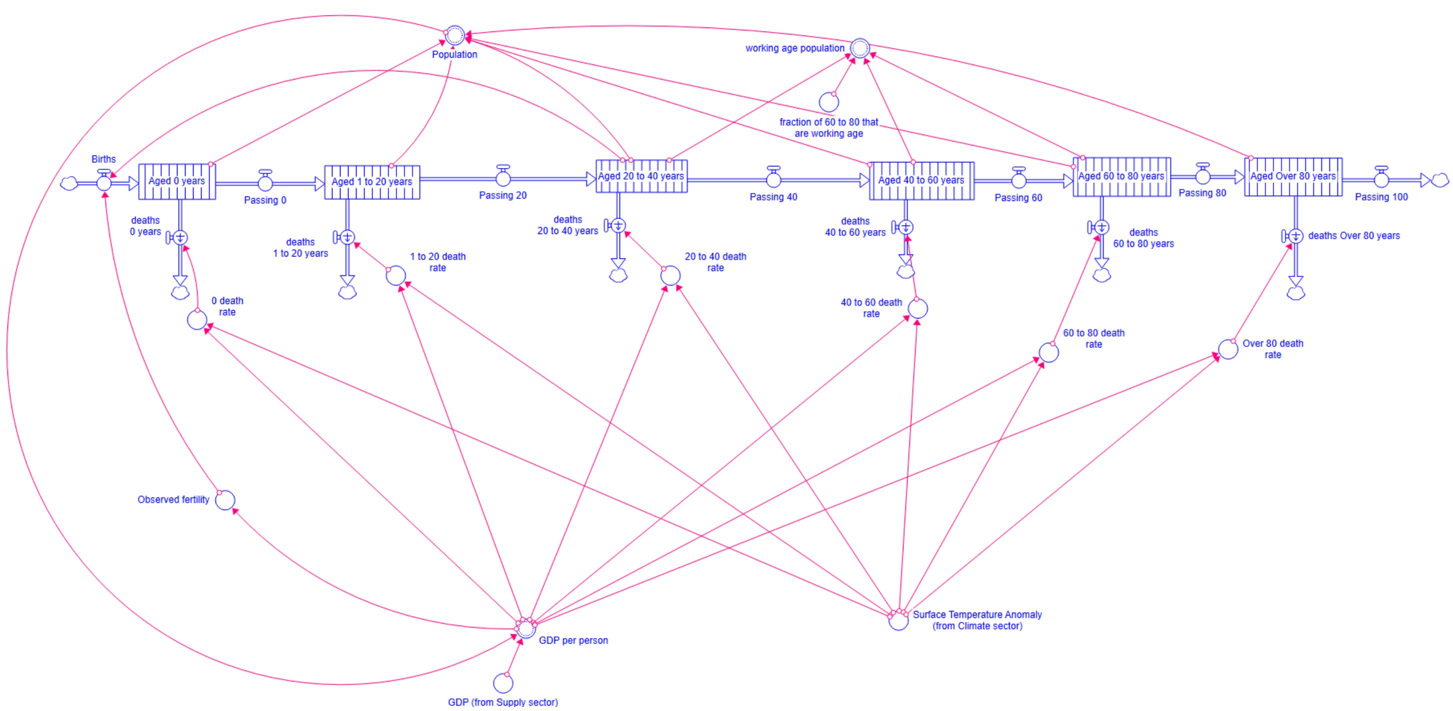

Figure 7: The Population module

6.3. Economy module

Macroeconomics is structured around understanding the economy i.e. the behavior of markets, firms, consumers, and government. Macroeconomic theory gives us tools to understand how well an economy is performing and what are the forces that drive it. At a global scale, GDP is the standard (albeit often criticized) measure used to quantify economic output. Changes in GDP are generally understood to be caused by a combination of labor inputs and human and physical capital. When there is a residual growth in total output of a firm, industry or national economy that cannot be explained by the accumulation of traditional inputs such as labor and capital it is usually caused by technological advances or efficiency efforts. This residual growth, i.e. the combined per unit capital and per unit labor productivity termed “Total factor productivity” (TFP), is an important contributor to GDP change.

We have organized our economy module (Figure 8) around those same macroeconomic concepts and the module organization we use is a subset of the Earth4All economic system. The Supply module is concerned with Capital, and TFP. The Labor module is concerned with Worker Share of Output and Labor Use. Finally, the Demand module, tracks debt, consumption, savings and investment. In future versions of FRIDA, the Economy module will be expanded to include for instance the financial sector.

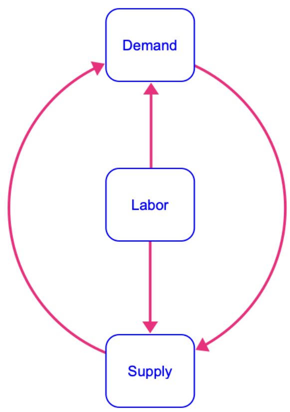

Figure 8: Modules making up the Economy subsystem in FRIDA V0.1.

6.3.1. Supply module

The Supply module pictured in Figure 9 is used primarily to model GDP. The major stock and flow dynamics originate with the Earth4All conceptual framework, and many of the equations are re-used, but FRIDA’s supply module has been altered via a deeper integration with climate and energy via their impacts of TFP, as well as a great many simplifications as compared to Earth4All original. Both models simulate Real GDP Purchasing Power Parity adjusted to 2017 (GDP) using a Cobb Douglas production function (Cobb and Douglas 1928). In both models GDP is a function of Labor Use (from the Labor module, 6.3.2), Capital, and TFP. Both models have the capital component of GDP disaggregated into two types, public and private where each type of capital is modeled using a two stock aging chain of Capital Under Construction, and Capital.

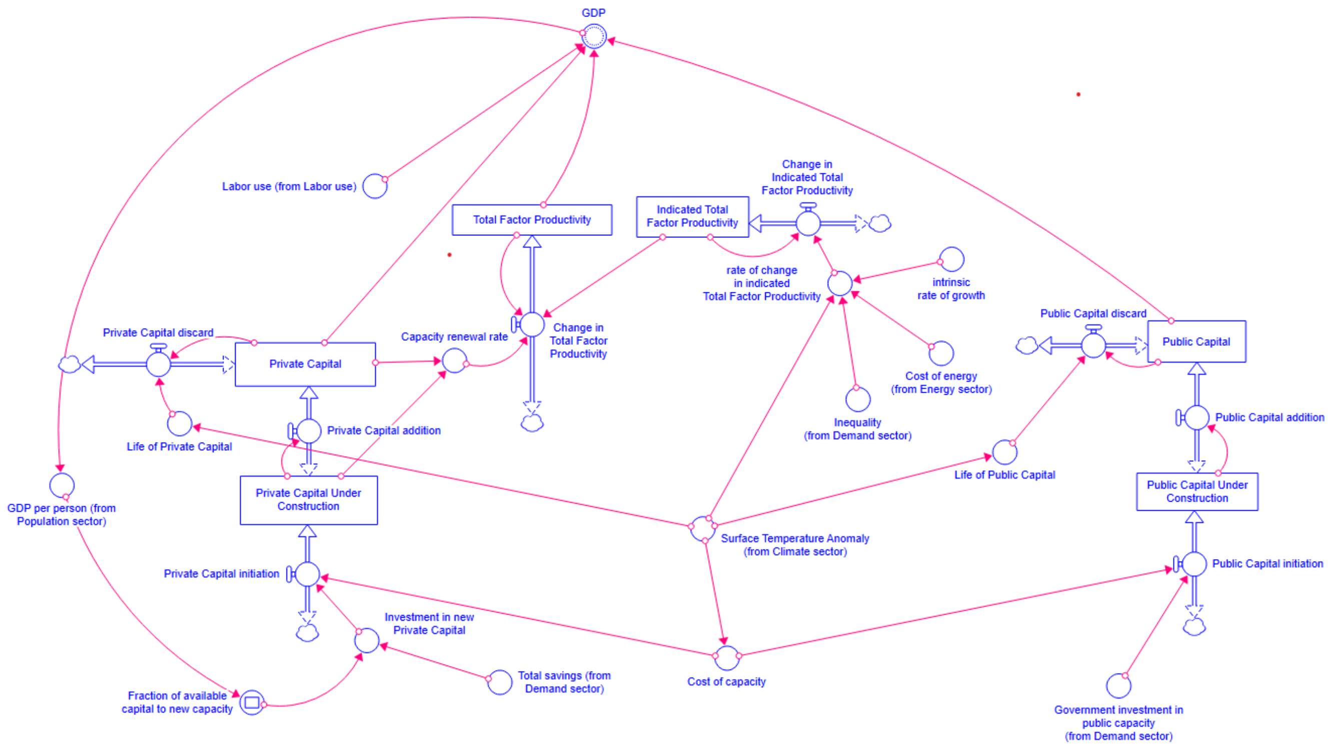

Figure 9: The Supply module

Both models have Private Capital constructed based on Investment, which is a function of Total Savings (from the Demand module in Section 6.3.3) and GDP per person (from the Population module in Section 6.2.1). In both models, Total Savings represents the pool of potentially investable money and the fraction of savings invested in Private Capital is a calibrated increasing linear function of GDP per person based on a 5 year investment planning time. This reflects the correlation between individual income and the percentage of personal savings (Topuz, 2022). Public Capital in both models is constructed based on Government Investment from the Demand module (section 2.3.3). In both models, both the Life of Capital and the Per Unit Cost of Capital, used for both private and public capital are calibrated linear functions of STA representing respectively the rising costs of capital, the declining life of capital as sea level rises, and the incidence of extreme weather events increases (Chinowsky and Arndt, 2012; Espinet et al., 2016, Schaeffer et al., 2012; Solaun and Cerdá, 2019; Wild et al., 2015).

As in the Earth4All model, Indicated TFP is modeled based on a calibrated positive exogenous rate of growth accompanied by an endogenous component affected by Inequality, from the Demand module (section 6.3.3). New to FRIDA is the impact of STA, from the Climate module module (6.2.1), and Cost of Energy, from the Energy module (section 6.4). Inequality is used to capture the inhibitory effects of extreme wealth inequality on ingenuity/technological advancement and therefore productivity growth (Turnovsky, 2015). The STA factor captures the inhibitory effects of extreme weather events, sea level rise, mass migration etc. as demonstrated in IPCC AR6 WGI, Chapter 12 (Ranasinghe et al., 2021). Finally, Cost of Energy captures the impact that cheap energy has had on the rapid accumulation of capital over the last two centuries via massive productivity gains, and the corresponding significant effect that a rapid increase in energy costs would have on further capital productivity (Sohag et al., 2021). In both models, changes in Indicated TFP are not applied immediately to existing capital, but rather delayed according to the ratio of Private Capital Under Construction to Private Capital, accounting for the relative age of built private capital.

6.3.2. Labor module

The Labor module pictured in Figure 10 is a departure from the corresponding Earth4All Labour Market module. While they share the same inputs, and many of the same outputs and concepts, the equations used to compute them differ in noticeable ways. Both models use the Labor module to calculate the Worker Share of Output, the size of the Workforce, and Labor Use. Labor Use is a key component in the Cobb Douglas production function used to calculate GDP in the

Supply module (section 6.3.1). Labor Use in both models is the size of the Workforce multiplied by Average Hours Worked Per Person, which is a calibrated decreasing linear function of GDP per person from the Population module (section 6.2.1), representing the declining labor inputs of industrial and post industrial societies (Feenstra et al., 2015). In both models, the Workforce is based on the Working Age Population which in FRIDA only, is all people from 20 to 60 and half of the people from 60 to 80 (Earth4All models this differently) multiplied by the Labor Participation Rate. In both models the Labor Participation Rate is calculated as a reinforcing calibrated linear function of the Worker Share of Output.

Worker Share of Output is a key stock in this module, and its Earth4All counterpart, but in FRIDA it has different determinants. Worker Share of Output represents the share of GDP which the Workers receive as income vs. the share that Owners receive as income in the Demand module (section 6.3.3). In both models, Worker Share of Output is a function of the Unemployment Rate and a calibrated, fixed long term erosion rate in Worker Share of Output (International Labour Organization, 2022). FRIDA and Earth4All differ in how unemployment is calculated. In FRIDA an index for the Negotiating Power of workers which is used to drive the hiring and firing of workers that drives the Unemployment Rate. This formulation is a departure from the Earth4All original which was necessary to calibrate FRIDA. In both models when the Unemployment Rate is low, the growth rate of Worker Share of Output (and Negotiating Power) is high. The growth rate in the aforementioned variables can be as high as 6% in both models. This happens because when the Unemployment Rate is low, Owners must offer higher wages to attract additional labor. In both models when the Unemployment Rate is high, the growth rate of the Worker Share of Output (and Negotiating Power) drops exponentially to as low as -1%. This happens because during periods of high Unemployment, real wages decline and a higher share of output is captured by profits and rents (i.e. Owners).

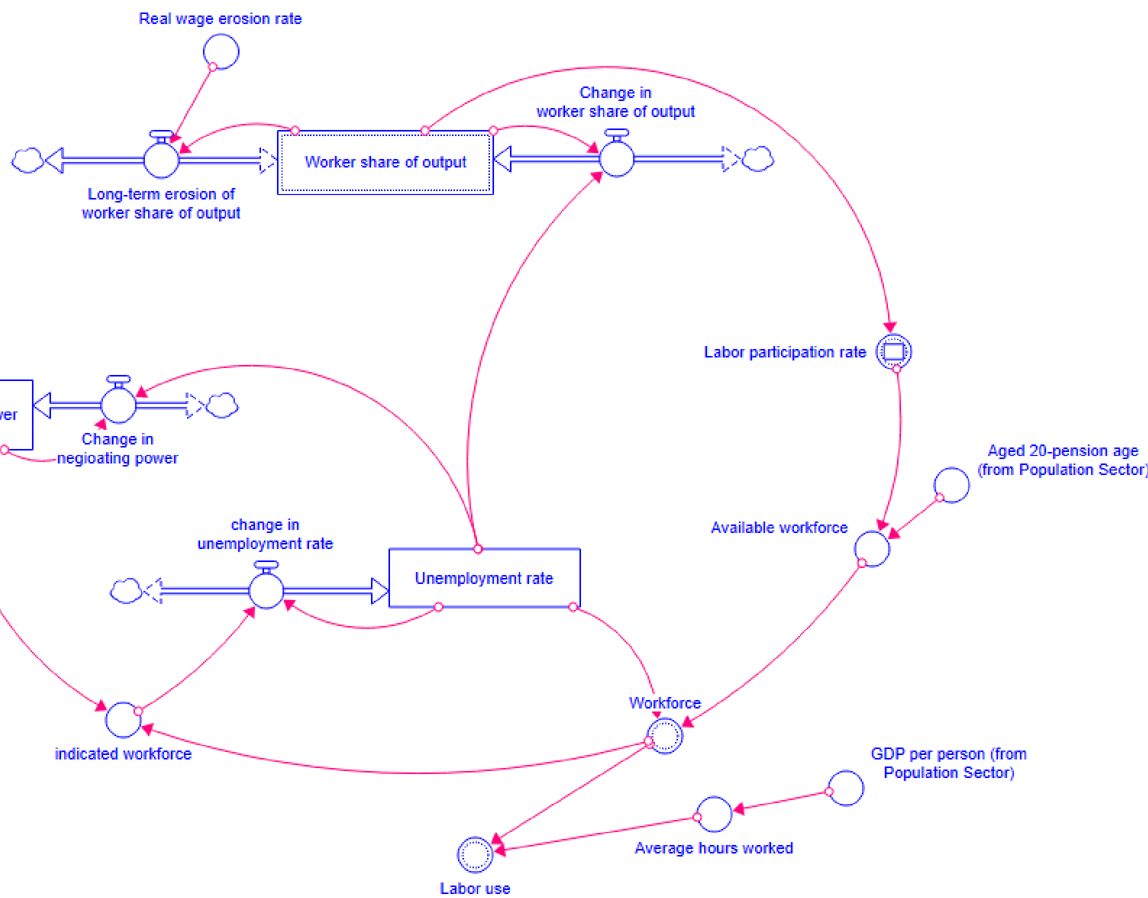

Figure 10: The Labor module

6.3.3. Demand module

FRIDA's Demand module pictured in Figure 11 is nearly the same as its Earth4All counterpart and is used to determine Inequality, Government Investment in Public Capacity, and Total Savings used to determine Investment in Private Capital by allocating GDP and creating Worker (i.e. Household) and Government Debt. The structure of Earth4All has however been changed by simplifying interest rates, and adding in the impacts of the "black market" i.e. illegal investment and consumption which were necessary to properly calibrate this module. Workers, Owners and Government's finances are calculated separately to represent the differential impact of each on other concepts in the model.

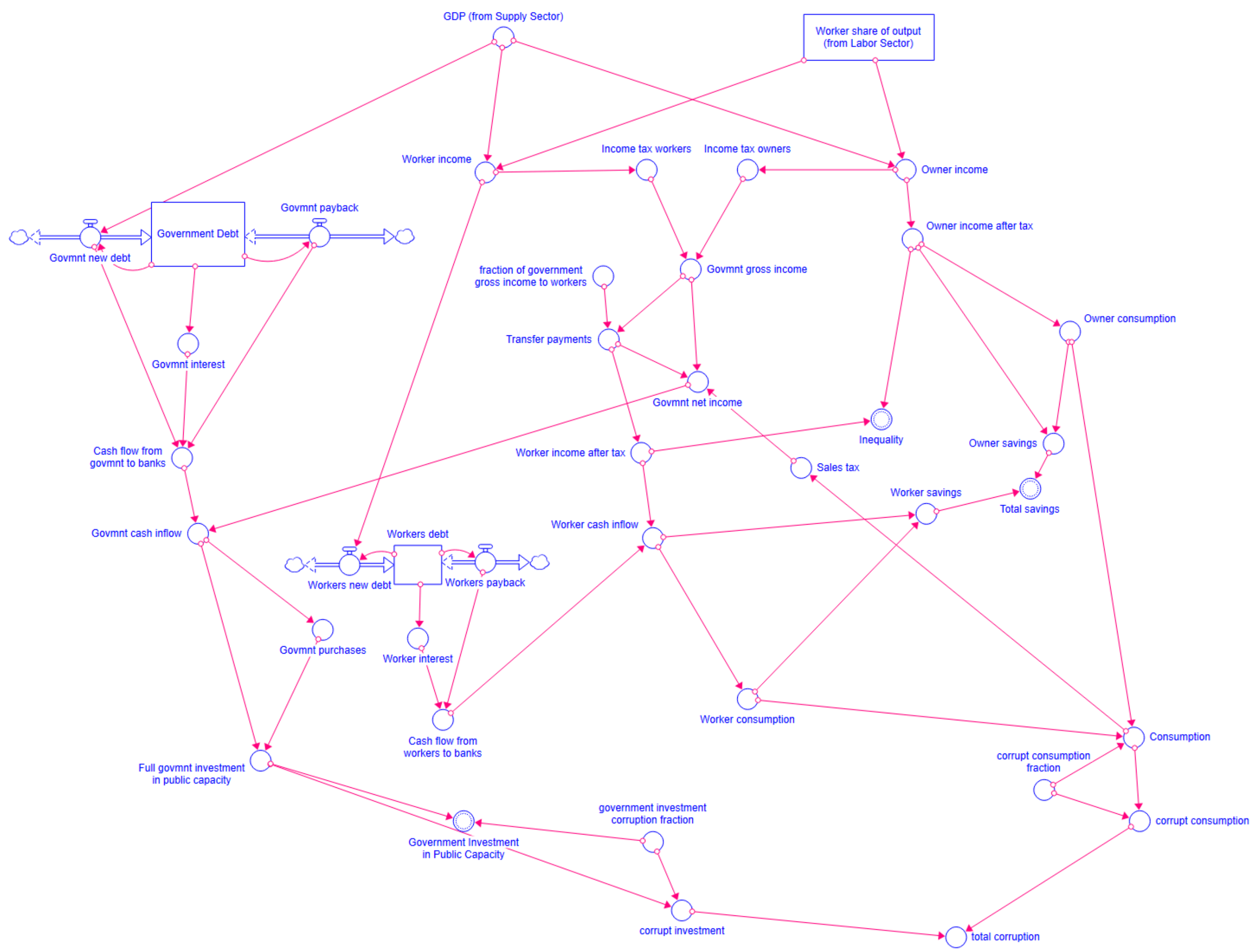

Figure 11: The Demand module

In both models, Owner and Worker Income are calculated based on Worker Share of Output from the Labor Module (section 6.3.2) and in FRIDA, the income tax rates for each are calibrated constants. In both models, Income Tax along with Sales Tax cash flows make up Government Gross Income; a fixed 30% of government gross income is transferred to workers in the form of welfare benefits. In both models, Workers' New Debt is a function of Worker Gross Income, where over a 10 year period workers strive to achieve and maintain a debt to income ratio of 1. Workers pay back their loans over an assumed 20 year period with no forgiveness, and all Worker Debt is subject to interest, which in FRIDA is a calibrated fixed constant. In both models, Worker Cash Inflow is Worker After Tax Income plus the net of any new debt minus payback and interest. The Government Debt structure is set up in much the same way, with the government striving to maintain a Debt to GDP ratio of 1 over 10 years. In FRIDA, Government borrowing costs were calibrated to a lower interest rate than workers, and their payback period was set to be 100 years (in Earth4All its 200). Government cash inflow, like workers, is the sum of Government Net Income and the net of any new debt minus payback and interest.

The income statement for owners is calculated differently than Workers and government in both models. Owners are modeled without an explicit debt component, and their after tax income is their cash flow. Inequality in both models is the ratio of Owner After Tax Income to Worker After Tax Income, and affects the intrinsic growth rate of TFP (in the Supply module 6.3.1).

In both models, once the cash-flow has been determined for each of the 3 groups (Government, Workers, Owners), those incomes are allocated into consumption, investment, and savings. In FRIDA, the model also accounts for "black market'': illegal consumption and investment, which is necessary to account for the off-the-books portions of GDP (Hsiang and Nitin 2016). In both models, the consumption fraction of each group is a fixed calibrated value; for each group, the remaining cash flow is diverted into savings for investment into private capital in the Supply module (section 6.3.1), or, in the case of government, directly into Government Investment in Public Capacity, also in the Supply module. In FRIDA only, illegal consumption is modeled using a calibrated fixed percentage of all consumption, and illegal investment is a calibrated fixed portion of government investment. In both models, all worker and owner consumption is taxed at a fixed calibrated Sales Tax Rate which is passed on to the government as income.

6.4. Energy module

Access to energy is a key component of the World Economy, of human well-being, but unfortunately energy generation is a key source of greenhouse gas emissions. Both the Earth4All and FRIDA energy modules are built to capture the impacts of the generation of energy to power the economy, creating emissions, and new to FRIDA are the impacts of the cost of energy generation on economic growth. The Energy module pictured in Figure 12 is based on its counterpart in Earth4All, and is concerned with the supply, demand, capital, costs and emissions used to produce energy as well as run the economy, both liquid fuel and electricity as well as from all other non-agricultural and land use sources. While FRIDA and Earth4All use the same stocks and high level feedback relationships, the implementation of those relationships have been modified, as well as the units used to measure them. In both models, the energy module represents the global energy production process using two general categories. The first are all Fossil Fuel based energy generation technologies, and the second are all of the Renewables energy generation technologies. At this current early stage, our model assumes that liquid fuels will be fossil in nature for perpetuity (an assumption we will change in the future) and therefore the fossil / renewable transition is modeled completely within the context of electricity production

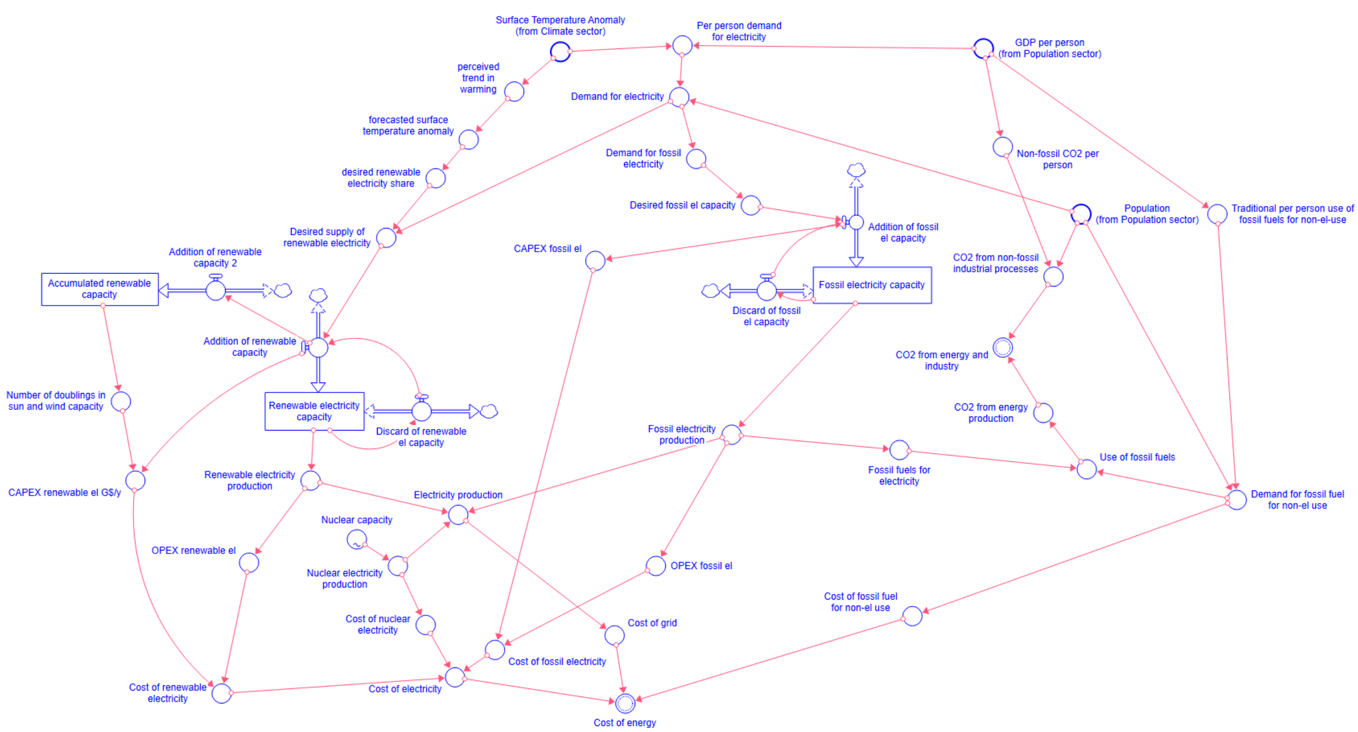

Figure 12: The Energy module

In both models, both demand for electricity and demand for liquid fossil fuels on a per person basis are determined based on a reinforcing calibrated logistic function using GDP per person from the Population module (section 6.2.1), representing the increasing energy demands of a wealthier global society. FRIDA has added a calibrated linear relationship between STA (section 6.1.1) and Per person demand for electricity representing the increased electricity demand as a result of climate change (from IPCC AR6 WGI, Chapter 12 (Ranasinghe et al., 2021)). In both models, Electricity Demand is apportioned between Fossil Fuels and Renewables based on a Desired Share of Renewable Electricity. New in FRIDA is that the desired share of renewables is based on Sterman's (1987) TREND function, used to create a future perception of warming. As people's perception of future warming increases, they demand an increasing amount of their electricity from renewable sources (West et al. 2010). The parameters used to control this structure were calibrated based on known values for renewable capacity, and renewable electricity production. In addition, new to FRIDA is that the model represents the time to meet the desired share of renewable energy as a function of the number of doublings in new renewable capacity to account for people's experience and comfort with technologies like solar and wind as they become more mainstream which allows the system to react to changes in desired renewables more like what has been observed in history. In both models renewable electricity production capital has a calibrated fixed lifespan. In both models, Renewable Electricity Production is the capacity multiplied by a fixed calibrated productivity. In both models, like for renewable electricity, Fossil Electricity Capital is also modeled explicitly and is assumed to have a fixed average lifespan, while being constructed over an assumed 3 year period to meet demand. New to FRIDA, the model captures the decision making context around how much Fossil Electricity Capacity to build using a TREND (Sterman, 1987) of projected [fossil] electricity demand which was necessary to properly calibrate fossil electricity production. In both models, each unit of fossil electricity production capacity has a fixed, calibrated productivity, which yields Fossil Electricity Production. Both models treat Nuclear Electricity as exogenous and fixed after 2020.

In both models, CO_2 emissions from energy and industry are calculated by determining the demand for fossil energy which is the fossil fuels used in demanded liquid fuels, plus the fossil fuels used in electricity production. Both models use a calibrated slow exponential decline in CO_2 per unit of fossil fuel consumed to generate the CO_2 emission from energy. In both models the industry portion of CO_2 emissions is based on per capita CO2 emissions which is generated from a calibrated increasing logistic function of GDP per person (from the Population module, section 6.2.1) which captures the CO_2 intensity of industrial development (Tucker, 1995).

Finally the Cost of Energy is calculated identically in both models. In FRIDA only this cost is used to influence TFP (from Supply Module, 6.3.1). The Cost of Energy is calculated as the sum of fossil fuel costs for non-electricity purposes, electricity costs and electricity grid costs. Grid costs scale linearly based on electricity production regardless of source. Fossil fuel costs also scale linearly with fossil fuel use for non-electrical purposes. Electricity costs are based on construction costs and operating costs which vary by Fossil vs. Renewables. Capex costs i.e. construction costs for fossil fuel electricity production are assumed to be constant, whereas the capex costs of renewables are modeled to decline relative to the number of doublings in installed renewable capacity (Hayward et al. 2022). Opex costs. i.e. per unit of energy produced running costs for both are assumed to be fixed on a per unit of production basis, with renewables being far less expensive than fossil.

7. Calibrating FRIDA

The calibration of the FRIDA model is totally unrelated to the Earth4All effort. We've performed model calibration, both as a form of model testing, and to estimate model parameters, striving to achieve a match between the observed measurements and the simulation (Barlas, 1996, Olivia, 2003) for the time period 1980-2020 ("the calibration period"). Since changes to the model structure were needed to improve the calibration, the FRIDA model underwent a "validation / verification / calibration" process as described by Walker and Wakeland, (2011). The model was calibrated using Powell's BOBYQA (bound optimization by quadratic approximation) (Powell, 2009), a gradient descent method. We used the version embedded in Stella Architect 3.2.1, which uses the public open source project DLib version 19.7 (Powell 2009, isee systems 2023, Dlib C++ Library 2023).

We used what is called "partial calibration", i.e. separate calibrations for each of five particular areas of the model with a final whole-model calibration at the end. The 5 individual partial calibrations constructed were focused on: Climate, Food and Land Use, Society (population), Economics and Energy. This was done to reduce the computational complexity of the problem, and to allow us to bring the model into range iteratively as we worked on each portion of the model in relative isolation. This had the benefit of reducing the chance of the optimizer getting bogged down in flat areas of the payoff surface, and more importantly, made it far easier to reason about the generated parameter estimates and fits to data. For each payoff we minimized the square error between the observed data (calibration data from section 7.1) and its simulated counterpart. The weights on each component of the payoff were set so that the value of the payoff was approximately equal to the number of data points. This gives a payoff that behaves the same as the negative value of the log likelihood in terms of its response to parameter changes which is optimal for the BOBYQA algorithm.

7.1. Calibration dataset

Data for 49 of the variables in the model spanning the full scope of the model (a listing can be found in Table 1 below) were used to calibrate the model. These variables were selected because they are involved throughout the entirety of the model's structure, and together they cover the full scope of the model. Table 1 shows the origins of the historical data used for the model calibration along with any transformations we applied to it.

The calibration data for the population module and components of demographic change such as fertility and mortality have been collected from the 2022 Revision of World Population Prospects which is the twenty-seventh edition of the official United Nations population estimates and projections that have been prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. This dataset was chosen because it presents population estimates from 1950 to the present for 237 countries or areas, underpinned by analyses of historical demographic trends and is a standard in the population modeling community.

The economic indicators like GDP, Government spending, Consumption share of GDP, Investment share of GDP, Investment in Private Capital and GDP per person have been calibrated against data from Penn World Table version 10.01 (Feenstra et al. 2015). PWT version 10.01 is a database with information on relative levels of income, output, input and productivity, covering 183 countries between 1950 and 2019. This dataset was organized by the Groningen Growth and Development Centre and is well respected within the community as a source for accurate global economic data with purchase power parity-adjusted values of USD$2017 constructed in order to allow for cross-country comparisons over time.

For historical data relating to atmospheric abundances and effective radiative forcing for GHGs such as CO_2, CH_4, N_2O etc, the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) Working Group I (Masson-Delmotte et al. 2021) has been used as it is the gold standard in the climate modeling and integrated assessment community. All climate and emissions data are either directly referenced in the IPCC AR6 or come from the Reduced Complexity Model Intercomparison Project (RCMIP) database (Nicholls et al., 2020) that reflects global annual emissions/concentrations used to run CMIP-class climate models. In all cases these datasets have been written up and published in the scientific literature and the outputs are publicly available and widely trusted.

Historical data for different power generation capacities were retrieved from International Energy Agency (IEA), International Renewable Energy Agency (IRENA) and Power Reactor Information System (PRIS). BP Statistical Review of World Energy; Ember (2022), Maddison Project Database (Bolt and Van Zanden, 2020) and the Global Carbon Project (Friedlingstein et al. 2022) were other databases used to calibrate the Energy module. Historical data used for calibration of the Food and Land Use module has been provided from the Food and Agriculture Organization of the United Nations. The International Labour Organization and World Bank were databases used for calibrating variables like Unemployment rate, Worker share of output and Workforce.

7.2. Performance of the model relative to the calibration dataset

As seen in Table 1, the model captures the characteristic behavior in the calibration dataset spanning the full scope of the model: all but 9 of 49 of the correlation coefficients are above 0.85, and 34 are above 0.95. As an example we show, in Figure 15 (upper panel) the difference between observations and simulation for three of the variables (GDP, Population and STA) for the period 1980-2020. In all three cases the low-pass development of observations and model simulation follow each other closely. For the 9 correlation coefficients that are below 0.85, we have calculated the Theil Inequality statistics, which is a measure of the sources of correlative error, attributing it to differences among the means, variation, and covariation (Table 2). In all the nine cases, the error is heavily concentrated in the covariance, and therefore this error is deemed non-systematic because the variation is the result of the noise i.e. the year to year changes in the data, because the historical observations in these 9 cases show no consistent pattern (Sterman, 2000).

Table 1 - Calibration Dataset and Results

Variable Name (units) in the model	Variable Name in the Database	How data was calculated	Database Name	r (Correlation Coefficient)
Surface Temperature Anomaly (°C)	Individual Global mean surface temperature (GMST) annual values (°C)		Chapter 7 of the IPCC's Sixth Assessment Report, Working Group 1 (Smith et al. 2021)	0.954
CH4 emissions (GtCH4/year)	CH4 emissions (MtCH4/year)	Converting MtCh4 to GtCH4	RCMIP (Nicholls et al. 2020)	0.970
CO2 emissions (GtCO2/year)	Emissions|CO2 (Mt CO2/yr)	Converting MtCO2 to GtCO2	RCMIP (Nicholls et al. 2020)	0.954
N2O emissions (GtCO2/year)	Emissions|N2O kt N2O/yr	Converting ktN2O to GtCO2	RCMIP (Nicholls et al. 2020)	0.857
CO2 concentration in atm (ppm)	CO2 concentration (ppm		Chapter 7 of the IPCC's Sixth Assessment Report, Working Group 1 (Smith et al. 2021)	0.988
CH4 concentration in atm (ppm)	CH4 concentration (ppb)	Unit Conversion ppb to ppm	Chapter 7 of the IPCC's Sixth Assessment Report, Working Group 1 (Smith et al. 2021)	0.988
N2O concentration in atm (ppm)	N2O concentration in (ppb)	Unit Conversion ppb to ppm	Chapter 7 of the IPCC's Sixth Assessment Report, Working Group 1 (Smith et al. 2021)	1.000
Forcing from CO2 (W/m2)	Effective radiative forcing (W/m2)		IPCC, 2021: Annex III (Dentener et al. 2021)	0.996
Forcing from CH4 (W/m2)				0.988
Forcing from N2O (W/m2)				1.000
Agricultural Land (Mha)	Cropland (1000 ha)	Unit conversion from 1000 ha to Mha	Food and Agriculture Organization of the United Nations (2023)	0.964
Forest land (Mha)	Forest land (1000 ha)			0.987
Crop Production (Mtcrop/year)		Sum of production of different crops	Food and Agriculture Organization of the United Nations (2023)	0.997
Fertilizer use (MtN/year)			Breier, J. (2023)	0.970
CO2 emissions from land use land use cover change (GtCO2/year)	Global CO_2 emissions from land use change		Global Carbon Project (Friedlingstein et al. 2022)	0.123
GDP per person (k$/(p*year))			Penn World Table version 10.01 (Friedlingstein et al. 2022)	0.993
Aged 0 Years (Mp)	Total population by single age, both sexes combined (thousands)	Age 0 (thousands)	United Nations (2022)	0.427
Aged 1-20 Years (Mp)		Sum of ages 1 to 19		0.961
Aged 20-40 Years (Mp)		Sum of ages 20 to 39		0.985

Aged 40-60 Years (Mp)		Sum of ages 40 to 59		0.987
Aged 60-80 Years (Mp)		Sum of ages 60 to 79		0.970
Aged over 80 Years (Mp)		Sum of ages 80 to 100+		0.898
Population (Mp)		Sum of all ages		0.999
Deaths 0 Years (Mp/year)		Infant Death		0.997
Deaths 1-20 Years (Mp/year)		Sum of death for age 1 to 19		0.984
Deaths 20-40 Years (Mp/year)		Sum of death for age 20 to 39		0.565
Deaths 40-60 years (Mp/year)	Deaths by Single Age - Both Sexes	Sum of death for age 40 to 59		0.930
Deaths 60-80 Years (Mp/year)		Sum of death for age 60 to 79		0.806
Deaths over 80 years (Mp/year)		Sum of death for age 80 to 100+		0.938
Observed fertility (Fraction)	Total Fertility Rate (live births per woman)			0.954
Births (Mp/year)	Birth (thousands)			0.113
Total Deaths (Mp/year)	Total death (thousands)			0.742
Renewable electricity capacity (GW)	Total renewable energy (MW)	MW converted to GW	International Renewable Energy Agency (IRENA) (2022)	0.991
Fossil electricity capacity (GW)	Installed power generation capacity by source	The data was presented on a graph in GW	International Energy Agency (IEA) (2022)	0.996
CO2 from energy and industry (GtCO2/year)	CO_2 emissions by fuel or industry type, World		Global Carbon Project (Friedlingstein et al. 2022)	0.986
Nuclear Electricity production (TWh/year)		Electricity from nuclear (TWh)		0.977
Fossil electricity production (TWh/year)		Sum of electricity from oil, gas and coal (TWh)		0.992
Renewable electricity production (TWh/year)	Electricity production by source, World	Sum of electricity from bioenergy, solar, wind, hydro and other renewables excluding bioenergy (TWh)	BP Statistical Review of World Energy; Ember (2022)	0.997
Electricity production (TWh/year)		Sum of electricity from nuclear, oil, gas, coal, other renewables excluding bioenergy, bioenergy, solar, wind and hydro (TWh)		0.997
Demand for electricity (TWh/year)	Electricity demand (TWh)		BP Statistical Review of World Energy; Ember (2022)	0.995
Energy use per person (toe/(p*year)	Energy use per person (per capita)	Unit conversion: 1 toe = 11630 kWh	Maddison Project Database (Bolt and Van Zanden, 2020)	0.938
Workforce (Mp)	Labor force, total (Billion)	Unit conversion from billion to million	The World Bank (2022)	0.980

GDP (G$/Years)	GDP= rgdpe = Expenditure-side real GDP at chained PPPs (in mil. 2017US$)	For the World, it's sum of all countries	Penn World Table version 10.01 (Feenstra et al. 2015)	0.996
Government spending (G$/year)	Government consumption as fraction of GDP= csh_g= Share of government consumption at current PPPs	Government consumption as fraction of GDP * GDP (G$/year)		0.995
Consumption share of GDP (Fraction)	csh_c= Share of household consumption at current PPPs			0.855
Investment share of GDP (Fraction)	csh_i = Share of gross capital formation at current PPPs			0.731
Investment in new Private Capital (G$/year)		Investments as share of GDP (1) * GDP Investments		0.992
Unemployment rate (Fraction)	Unemployment, total (% of total labor force)	Percentage changed to fraction	International Labour Organization (2023)	0.368
Worker share of output (Fraction)	Labor share of gross domestic product (%)	Percentage changed to fraction	International Labour Organization (2022)	0.702

Table 2 - Results of the Theil Statistics for models variables with correlation coefficients below 0.85.

Variable Name	**U^M (Mean Inequality)**	**U^S (Variation Inequality)**	**U^C (Covariation Inequality)**	**MSE (Mean Square Error)**	**r (Correlation Coefficient)**
CO2 emissions from land use land use cover change (GtCO2/year)	2.94%	35.47%	61.59%	0.29	0.183
Aged 0 Years (Mp)	29.12%	2.05%	68.83%	55.89	0.427
Deaths 20-40 Years (Mp/year)	27.58%	29.78%	42.65%	0.08	0.565
Deaths 60-80 Years (Mp/year)	0.01%	27.76%	72.23%	2.97	0.806
Births (Mp/year)	7.76%	2.48%	89.76%	46.38	0.113
Total Deaths (Mp/year)	0.40%	17.60%	82.00%	7.89	0.742
Investment share of GDP (Fraction)	0.23%	27.21%	72.56%	0.00	0.731
Unemployment rate (Fraction)	0.44%	0.29%	99.26%	0.00	0.368
Worker share of output (Fraction)	0.00%	11.47%	88.53%	0.00	0.702

8. Baseline scenario analysis

FRIDA's baseline scenario is the result of running the calibrated model for the projection period (2020-2100) without any changes or interventions. These results don't represent a "business as usual"-case, meaning human responses and decision making are not fixed at some arbitrary values, but rather human decision making proceeds along the already defined and existing curves identified in the model construction and calibration process, the latter reflecting the last 40 years that the model is calibrated against.

To evaluate the performance of FRIDA in the baseline run we have compared to FaIR v1.6.2's projections of warming (when FaIR is simulated with the same radiative forcing from anthropogenic sources that FRIDA generates in its simulated baseline; see section 8.1 below) (Figure 14). During the first part of the calibration period (1980-2000), FaIR is slightly cooler than both observations and FRIDA, but beyond 2000, FaIR and FRIDA agree well, and both models are consistent with observed warming for the period 2000-2020. This gives us confidence that FRIDA's climate module is capable of producing a realistic projection of future global temperatures from a simulated time series of anthropogenic forcing. Both FaIR and FRIDA simulate in this case a global STA of 2.5 ℃ in 2100.

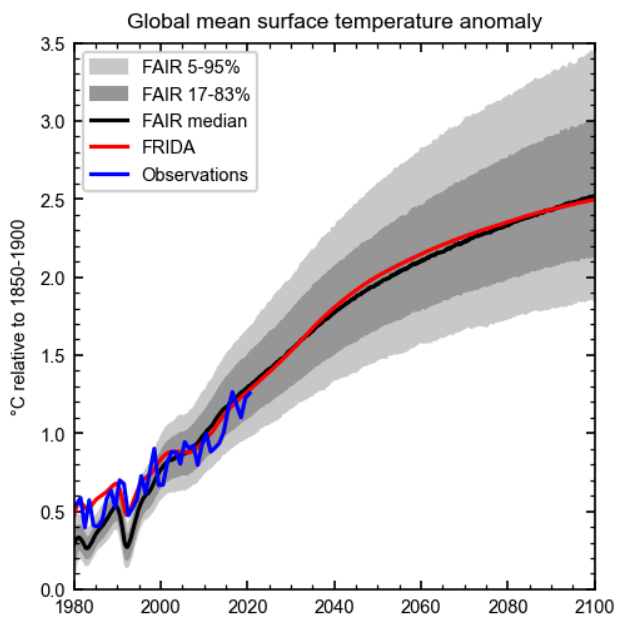

Figure 14: Comparison of FRIDA simulated Surface Temperature Anomaly with FaIR v1.6.2 (Smith et al. 2018) when FaIR uses FRIDA's projections for future anthropogenic forcing (GHG forcing) as input.

Below we discuss this scenario (the FRIDA's V0.1 baseline scenario), showing how climate, demographic and economic outcomes are projected to unfold in that scenario. From there, we discuss how this scenario changes as we reduce the strength of, and ultimately remove the feedback between climate and the rest of the system.

8.1. V0.1 Baseline with strong feedback between the climate and human system

The scenario presented below in Figure 15 is the V0.1 baseline scenario from the FRIDA model with the full strength and set of feedbacks between the climate and the rest of the model as discussed in section 6. As we already saw in Figure 14, the baseline scenario results in 2.5 ℃ warming relative to 1850-1900. Important to note in this baseline scenario is that the GDP reaches a maximum around 2070 and declines thereafter. The same is true for the global population.

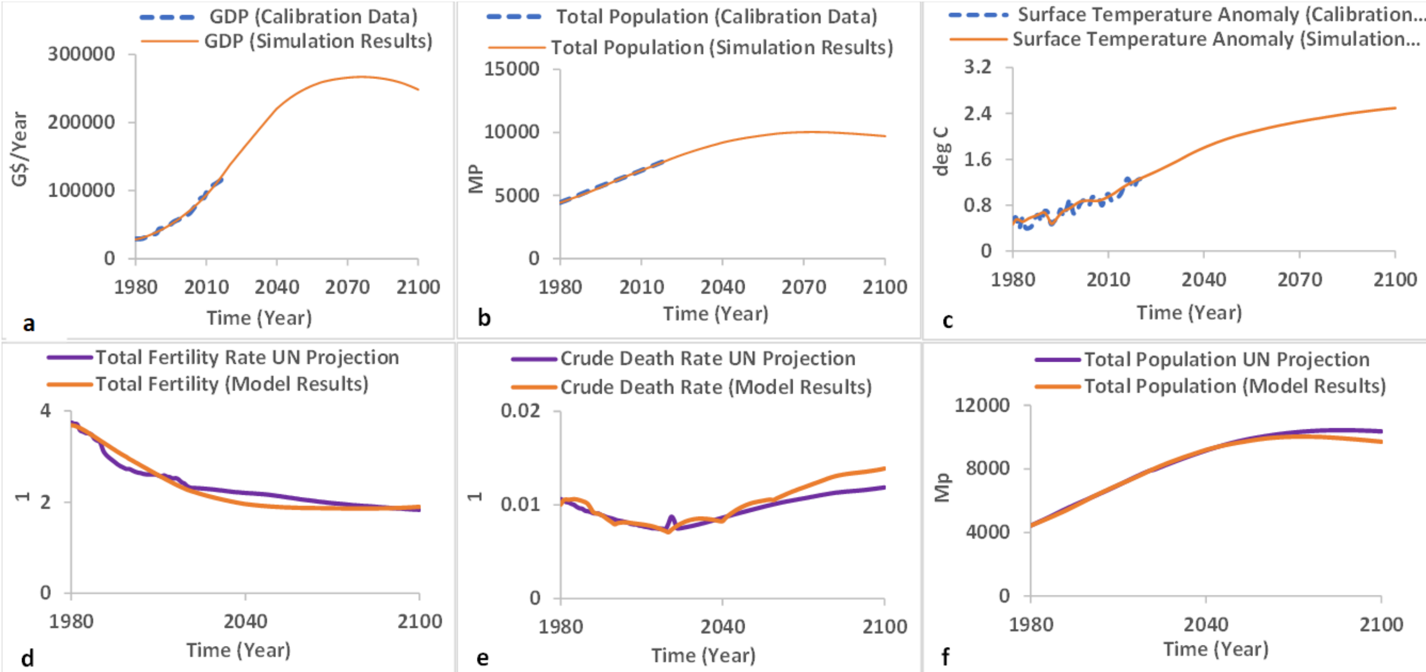

Figure 15: Overview of key results from FRIDA v0.1 Baseline scenario. Lower panel: Population projection comparison with UN projection data (United Nations, 2022)

As seen in the lower panel of Figure 15f, the decline in population after 2070 is at odds with the UN medium projection, which projects continued population growth to the end of the century, whereas the FRIDA baseline run projects a decline in population from 2070 onwards. This population drop at the end of the century is largely a consequence of a deep reduction in fertility (Figure 15d), due to gains in wealth enabling health and education improvements from increases in GDP per person which is largely in line with the UN's projections. In addition, while birth rates are falling, unlike in the UN projection, death rates are slowly rising (Figure 15e) as the deterioration of the environment due to warming counteracts the expected reductions in death rates from the rise in GDP per person, based on model output.

To explain the rise and decline in GDP we need to look at capital, labor and TFP (Figure 16a, b, c). Historically, TFP has grown due to improvements in technology, energy efficiency and availability of cheap energy. This growth continues steadily along the projection period until 2040 (Figure 16c). In the period from 2040 to 2060 the growth in TFP slows and around 2060, the growth rate of TFP goes negative. There are two reasons for the decrease in the growth rate of TFP. First because energy costs have continually grown (Figure 16d) and most importantly because we have explicitly assumed that when the STA (Figure 14) gets above 2 ℃, the growth in capital and labor productivity drops below 0. As discussed in section 6.3.1, this represents the impact of (warming generated) sea-level rise, extreme weather events, and population migration on per unit, capital and labor productivity, i.e. TFP. In section 8.2 below we discuss the implications of this assumption on future projections in more detail.

Energy costs have increased because of the switch to renewables (Figure 16e), along with the increase in energy demand because the global population has continued to increase (Figure 15f), while on average becoming more wealthy (GDP per person) (Figure 16f). All of these effects result in a higher demand for energy on a per capita basis and therefore higher energy costs. Just before this, in the 2040's is the point where renewable electricity production surpasses fossil electricity production (Figure 16e). In figure 16g we see that the projection of CO_2 emissions from energy and industry peaks at the same point in time (around 2040). In that same figure we show total CO_2 emissions as well as the land use emission for completeness. These changes in CO_2 emissions (along with changes in CH_4 and N_2O) are the causes of the changes in the STA (Figure 14). As we can see in Figure 16h the major driver of future changes in STA are CO_2 emissions.

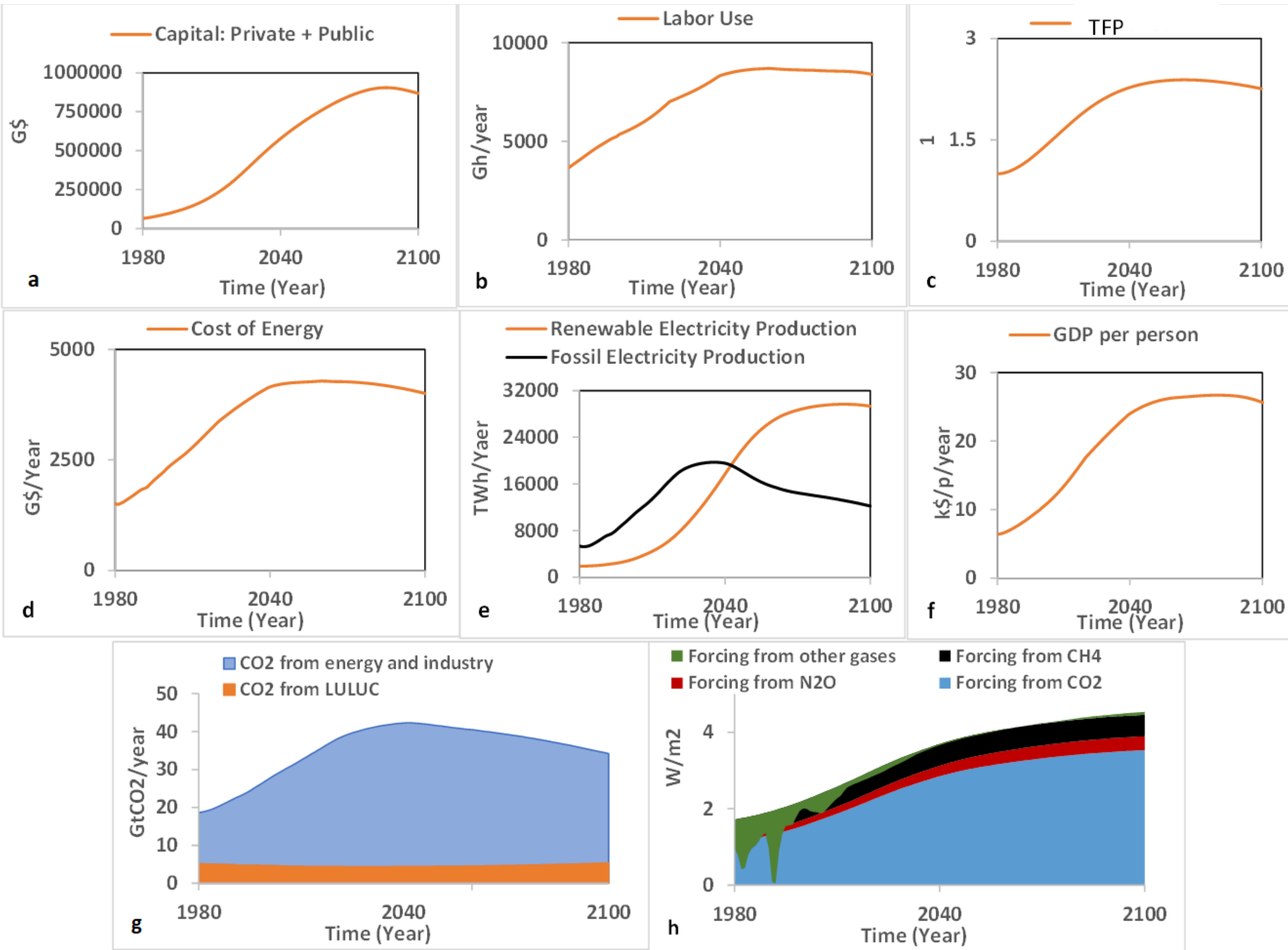

Figure 16: FRIDA v0.1 baseline scenario results, showing the impact of climate change on the economy.

8.2. Examining the importance of the climate feedback

One of the key innovations of the FRIDA model is the way that it endogenizes the climate feedback to the economy, society and energy systems. As mentioned throughout the model description in section 6, the avenues for this feedback include the impact of STA on: the growth rate of TFP, the life of capital, the cost of capital, mortality, electricity demand and crop yields. To demonstrate the impact of these connections on the trajectory of the baseline scenario we've generated two additional runs, the first called "Reduced Feedback" where we've reduced the STA impact on the growth rate of TFP by a factor of seven[3] and the second "No Feedback" scenario where we've cut all of the above-mentioned connections, as well as the connection between the Cost of Energy and TFP. The No Feedback scenario represents the typical process based IAM representation of the relationship between climate and the economy. The Reduced Feedback Scenario demonstrates an absurdly weak link between climate and TFP. To do the comparison properly – for both the Reduced Feedback, and No Feedback scenarios, we had to minimally re-calibrate the model to ensure that in all 3 scenarios history is equivalently reproduced.

The biggest, and most obvious impact of including climate feedbacks is a very significant drop in GDP which begins to occur around 2035 (Figure 17a). This suggests that by ignoring the climate feedbacks one tends to largely overestimate the growth of GDP in the 21st century. The impact of including climate feedbacks is much less pronounced for population

[3] In the Reduced Feedback scenario we've assumed that the growth rate in TFP drops below 0 when STA gets above 12 ℃. In the baseline scenario this is assumed to happen at 2 ℃.

(Figure 17b) and STA (Figure 17c). In the case of population, the inclusion of climate feedbacks keeps the population relatively constant after 2070 (in the No Feedback and Reduced Feedback scenarios we see a sharp decline after 2070). Global warming (STA; Figure 17c) is less if we include climate feedbacks than if we ignore them. To understand these somewhat counter-intuitive results we need to dive into the details of the model.

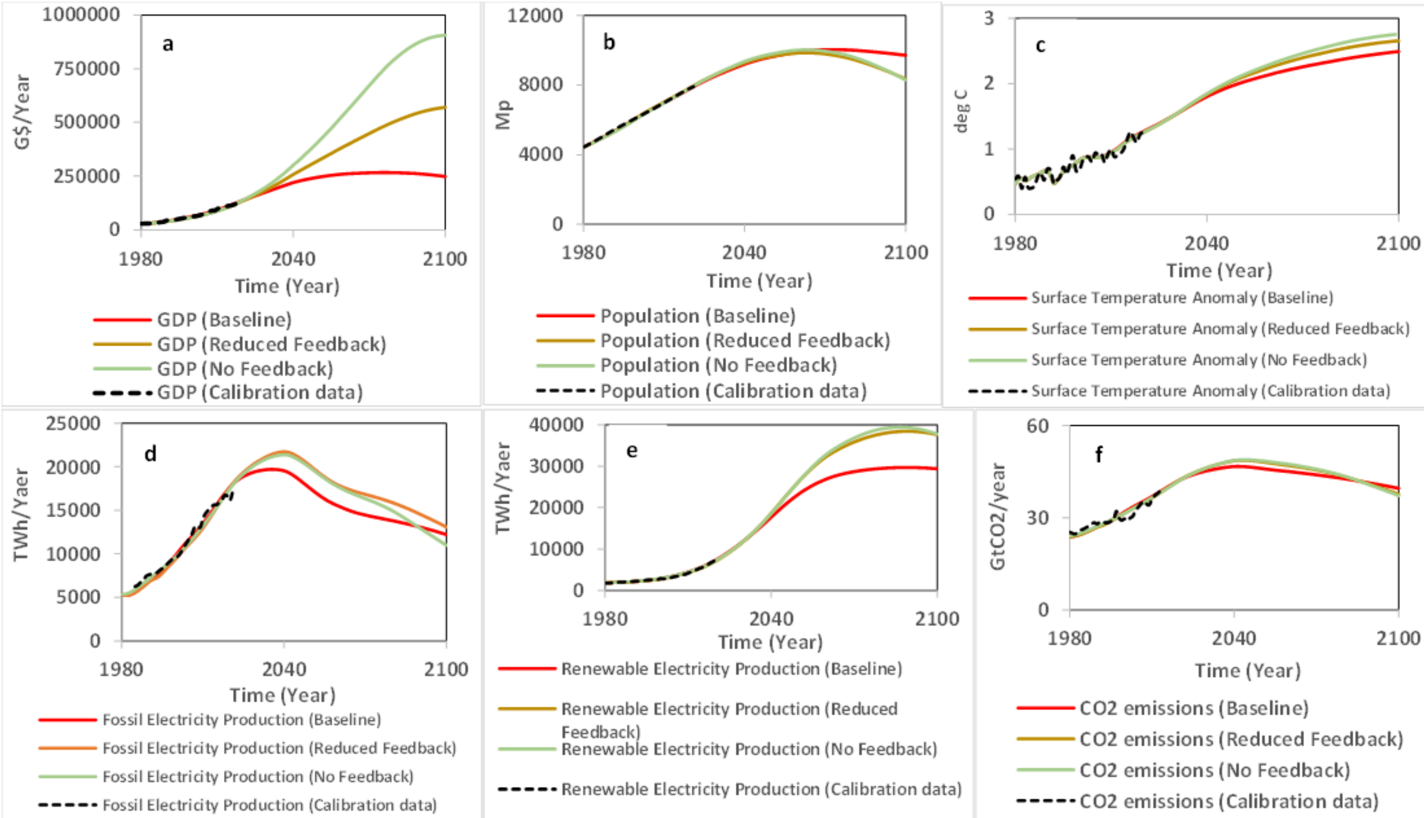

Figure 17: Three scenarios using FRIDA v0.1: The "baseline" scenario, the "Reduced feedback" scenario and the "No feedback" scenario.

The reason that population growth increases as we include the climate feedbacks is that with the climate feedbacks taken into account GDP is lower, which means that fertility is higher. Counteracting - but not overcoming that effect is that mortality is also higher, because of climate feedback which increases in mortality rates in response to increases in STA.

In Figure 17c, the reason that the STA increase is smaller (2.5 ℃ vs. 2.75 ℃ in No Feedback) when we include climate feedbacks is because GDP is lower. Along with a lower GDP, comes lower Energy Demand, and therefore lower Fossil Electricity Production (Figure 17d) and therefore the Emissions from Energy and Industry are smaller. But where is the transition from fossil to renewable fuels in all of this, and with that, the impacts on emissions? We have assumed (see section 6.4) that the demand for renewable energy depends on people's perception of future warming. In the baseline scenario, with full climate feedbacks, the warming is perceived to be less, therefore the demand for renewables is less, therefore the transition to renewables (Figure 16e) is delayed.

Because of that transition, and the reduced range of electricity production (Figure 17d, e) between the three cases, CO_2 emissions (Figure 17f) do not rise as much as would be naively expected just looking at the spread in GDP alone. Because these changes in emissions are happening in the later half of the 21st century, the delays inherent in the system do not allow us to see the maximum spread in STA by the end of the scenarios in 2100 - astute readers will notice that STA in the three scenarios is still diverging even in 2100.

9. Conclusions and next steps

The FRIDA model that we've presented here is just the first step on a long journey towards achieving our goals of developing a new combined climate-IAM that is fully transparent and has a strong social and human component. We've demonstrated that FRIDA is a potentially plausible model of the development of human society and the Earth's climate over the next 80 years. We have explored some of the relationships between the behavior of global warming, population and the economy. And most importantly, we have explored the impact of including feedbacks from climate change to human activities. We see that the strongest impacts of including those feedbacks is not that the rate of warming changes greatly, nor the level of anthropogenic emissions. The greatest change is found in the global economy, in GDP. Models run without feedbacks from the climate to the economy are, according to our study, likely to greatly underestimate the detrimental effect of climate change on the economy.

There are many avenues for future work which we intend to pursue in the next versions of FRIDA (V1 later in 2023, V2 in 2024 and V3 in 2025), under three general headings. First are improvements and additions to the model, in collaboration with a large number of domain experts. This work includes expanding the scope of the model to cover natural resources, freshwater, the financial and monetary system, submitting the climate module to a battery of diagnostic tests, and likely a slew of other concepts. Of key importance is developing a Wellbeing sector within our Society module as a key factor driving economic development, demographics, and future policy options. Key to this process is continuing the validation effort, following in the steps of Barlas (1996) and constantly testing FRIDA looking for invalidities to address. The second heading of future work is based in analysis, both of the mathematical structure of the model and of policy. Work must be done to measure and understand the impacts of uncertainty on the projections that FRIDA makes, plus the work that must be done to understand the loop dominance profile of FRIDA under different uncertainties and policy scenarios. The current version of FRIDA is highly deficient as a policy analysis tool, as it does not feature any policy structure. Work must be done to survey the literature and our stakeholders for policy options, and use the loop dominance analysis to try to identify new areas for intervention and study. The third heading for future work is around stakeholder engagement, co-development of knowledge, and dissemination of findings. There is much work to be done engaging with scientists, policy makers, capital owners and most importantly, the general public to refine both the logic of the model, the scenarios we will generate, the policies we want to simulate/analyze and the methods by which we communicate our findings. All of that to say – keep an eye out for the FRIDA model, we've accomplished plenty, but the majority of the work is still left to be done!

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