Repository for Tarshish, Jeevanjee, and Fung (2026)

This repository contains the data and code for reproducing the analysis in Tarshish, Jeevanjee, and Fung (2026). The analysis quantifies the warming after emissions cessation and net-zero emissions using the FaIR simple climate model and the ZECMIP multi-model archive.

Contents

- **results.tar.gz**: Contains all of the final data products relevant to the study:
  - FaIR simulation output (`/results/fair/`)
  - Processed ZECMIP data (`/results/ZECMIP_data.json`)
  - Figures (`/results/figures/`)
  - Summary of numerical claims (`/results/summary.txt`)
- **pipeline.tar.gz**: Contains the necessary code (`/pipeline/workflow`) and dependencies (`/pipeline/dependencies`) to reproduce the above results archive.

To cite this repository, use the Zenodo record: 10.5281/zenodo.10120439.

Exploring the results

Untar results.tar.gz:

```
tar -xzvf results.tar.gz
```

Simulation data:

Simulation output from FAIR can be found in `/results/fair/`. The temperature, total forcing, cumulative CO2 emissions, and CO2 airborne fraction are available in netcdf datasets (`.nc`) for all simulations. These simulation are as follows:

File (.nc)	Emissions	Perturbation type	Perturbation year
`historical_all_2024-zec`	All	Zero emissions	2024
`historical_co2_2024-zec`	CO_2-only	Zero emissions	2024
`ssp119_all_2100-zec`	All	Zero emissions	2100
`ssp119_all_net-zero-offset`	All	Offsetting (GWP100)	at net-zero GHG
`ssp119_all_net-zero-offset-GWP20`	All	Offsetting (GWP20)	at net-zero GHG
`ssp119_all_net-zero-offset-GTP50`	All	Offsetting (GTP50)	at net-zero GHG
`ssp119_all_net-zero-offset-GTP100`	All	Offsetting (GTP100)	at net-zero GHG
`ssp119_all_net-zero-zec`	All	Zero emissions	at net-zero GHG
`ssp119_co2_2100-zec`	CO_2-only	Zero emissions	2100
`ssp119_co2_net-zero-zec`	CO_2-only	Zero emissions	at net-zero GHG
`ssp126_all_2100-zec`	All	Zero emissions	2100
`ssp126_all_net-zero-offset`	All	Offsetting (GWP100)	at net-zero GHG
`ssp126_all_net-zero-offset-GWP20`	All	Offsetting (GWP20)	at net-zero GHG
`ssp126_all_net-zero-offset-GTP50`	All	Offsetting (GTP50)	at net-zero GHG
`ssp126_all_net-zero-offset-GTP100`	All	Offsetting (GTP100)	at net-zero GHG
`ssp126_all_net-zero-zec`	All	Zero emissions	at net-zero GHG
`ssp126_co2_2100-zec`	CO_2-only	Zero emissions	2100
`ssp245_all_2100-zec`	All	Zero emissions	2100
`ssp245_co2_2100-zec`	CO_2-only	Zero emissions	2100

File (.nc)	Emissions	Perturbation type	Perturbation year
`ssp370_all_2100-zec`	All	Zero emissions	2100
`ssp370_co2_2100-zec`	CO_2-only	Zero emissions	2100
`ssp434_all_2100-zec`	All	Zero emissions	2100
`ssp434_co2_2100-zec`	CO_2-only	Zero emissions	2100
`ssp460_all_2100-zec`	All	Zero emissions	2100
`ssp460_co2_2100-zec`	CO_2-only	Zero emissions	2100
`ssp534-over_all_2100-zec`	All	Zero emissions	2100
`ssp534-over_all_net-zero-offset`	All	Offsetting (GWP100)	at net-zero GHG
`ssp534-over_all_net-zero-offset-GWP20`	All	Offsetting (GWP20)	at net-zero GHG
`ssp534-over_all_net-zero-offset-GTP50`	All	Offsetting (GTP50)	at net-zero GHG
`ssp534-over_all_net-zero-offset-GTP100`	All	Offsetting (GTP100)	at net-zero GHG
`ssp534-over_all_net-zero-zec`	All	Zero emissions	at net-zero GHG
`ssp534-over_co2_2100-zec`	CO_2-only	Zero emissions	2100
`ssp585_all_2100-zec`	All	Zero emissions	2100
`ssp585_co2_2100-zec`	CO_2-only	Zero emissions	2100

In addition, `/results/fair/A1.nc` holds the FaIR analogue of the ZECMIP A1 experiment (1 %/yr CO_2 ramp to 1000 GtC followed by cessation), produced by the `run_A1` rule.

The raw ZECMIP data global-mean fields can be found in `/pipeline/dependencies/ZECMIP` in the formats provided by the ZECMIP collaboration. Processing and analyzing this output yields `/results/ZECMIP_data.json`.

Figures:

All figures can be found in `/results/figures` and are computed by code located in `/pipeline/workflow/notebooks`.

Reproducing the analysis

The pipeline is implemented in Python and relies on Snakemake, a workflow management system designed for reproducible scientific analysis.

Dependencies

Python dependencies are specified in an `environment.yml` file. These can be managed using Conda or its optimized replacements (miniconda, mamba, micromamba, etc.). Here we use micromamba, but conda can be used as a drop-in replacement. Micromamba can be installed via the following command on Linux, macOS, or Windows:

```
"${SHELL}" <(curl -L micro.mamba.pm/install.sh)
```

Quick start

After installing micromamba, the full reproduction recipe is:

```
tar -xzvf pipeline.tar.gz
cd pipeline
micromamba env create -f environment.yml      # creates environment named 'zec'
micromamba activate zec
snakemake -c 4 all                            # reproduces every figure and summary.txt
```

The `all` rule automatically runs `install_fair` first, which extracts the vendored FaIR tarball and installs FaIR + the shared `utils` module. Replace `all` with any rule name (e.g. `fig_1`, `process_ZECMIP`) to build just that target; `snakemake -c 1 help` lists every rule.

Step-by-step

1. **Untar `pipeline.tar.gz`**:

```
tar -xzvf pipeline.tar.gz
```

2. **Install the environment**:

```
cd pipeline
micromamba env create -f environment.yml      # creates environment named 'zec'
micromamba activate zec
```

3. **Run the full analysis pipeline**:

```
snakemake -c n all       # replace 'n' with the number of cores you wish to use
```

   The first step of `all` is the `install_fair` rule, which extracts the vendored FaIR tarball (`dependencies/FAIR-395ab8a4.tar.gz`, FaIR v2.1.4 at commit `395ab8a4...`), installs it with `pip install -e .`, and installs the shared `utils` module via `pip install -e workflow/utils/`. This step is idempotent — to force a fresh install of FaIR, remove `dependencies/FAIR/` and re-run.

The above commands execute Snakemake rules located in `workflow/Snakefile`. These rules execute scripts and notebooks located in `workflow/scripts` and `workflow/notebooks`, respectively, and draw on resources from the `dependencies` folder. Upon successful completion, the `all` rule will produce the `results` folder, containing the FaIR simulations, ZECMIP analysis, and figures.

External Data

The `dependencies` folder, found inside the `pipeline` archive, includes all the of the data needed to reproduce this analysis:

- ZECMIP global averages (`ZECMIP`)
- FaIR code and configuration files. (`FAIR`, `fair_calibrations`)
- Cui et al. (2025) SWL-2-pc per-ensemble global means used for the permafrost extrapolation (`cui2025_SWL-2-pc.nc`)
- other supporting files (`AR6_metrics.csv`, `forster_2023_CO2_ERF_ensemble.nc`, etc.)

Every file listed here ships inside `dependencies/` — no manual downloads are required. The provenance of each file is documented in the References section below.

References

MacDougall, A. H., Frölicher, T. L., Jones, C. D., et al. **Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2.** Biogeosciences, 17(11), 2987–3016, 2020. doi: 10.5194/bg-17-2987-2020
- **Dataset**: https://terra.seos.uvic.ca/ZECMIP

Forster, P. M., Smith, C., Walsh, T., et al. **Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence**. Earth System Science Data, 16(6), 2625-2658, 2024. doi: 10.5194/essd-16-2625-2024

- **Dataset**: data-v2024.04.25.zip
- **Checksum**: `fa8f73e9b81935a78c293923924b9acf`

Leach, Nicholas J., Jenkins, Stuart, Nicholls, Zebedee, et al. **FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration**. Geoscientific Model Development, 14(5), 3007-3036, 2021. doi: 10.5194/gmd-14-3007-2021 - **Source**: https://github.com/OMS-NetZero/FAIR - **Local copy**: `dependencies/FAIR-395ab8a4.tar.gz` (FaIR v2.1.4, upstream commit `395ab8a4f74d1438fb6075410961942019a9b58f`, vanilla source archive from GitHub) - **Checksum (SHA-256)**: `9a9f2566e7c59e4e1abbf49397df8c608ea528f03bad6abd2e8ddd669476db76`

Smith, C., Cummins, D. P., Fredriksen, H.-B., et al. **fair-calibrate v1.4.1: calibration, constraining and validation of the FaIR simple climate model for reliable future climate projections**. EGUsphere, 2024, 1-36. doi: 10.5194/egusphere-2024-708
- **Dataset**: fair_calibrate.zip
- **Checksum**: `2509a7a03b81f84a19d4e3aa7f9e65fe`

Forster, P., Storelvmo, T., Armour, K., et al. **The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. Chapter 7 Supplementary Material**. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2021. doi: 10.1017/9781009157896.009
- **Dataset**: AR6_metrics.csv
- **Checksum (SHA-256)**: `584fe16c1ffe454a0db4656857f54176cbf290d55a6775ea4e060ae2f461930c`

Cui, M., Ji, D., and Chen, Y. **Permafrost response and feedback under temperature stabilization and overshoot scenarios with different global warming levels**. Earth System Dynamics, 16(5), 1809–1831, 2025. doi: 10.5194/esd-16-1809-2025 - **Dataset**: SWL-2-pc archive — `cui2025_SWL-2-pc.nc` is a trimmed per-ensemble global-mean copy (`A_sat`, `L_permacarb`, year × ensemble) used by the `cui_extrapolation` rule. - **Checksum (SHA-256)**: `1cc16b2955d092cbdd024d64512d85458f6bf2ab101fd7846a9c13af4cec8326`