Pacific Northwest
NATIONAL LABORATORY

PNNL-36804

Hector-FACTS Technical Report & User Guide

Integrating Hector into the Framework for Assessing Changes To Sea-level

September 2024

1 Kalyn R. Dorheim
2 Ciara E. Donegan
3 Claudia Tebaldi

U.S. DEPARTMENT OF ENERGY
Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

Available to DOE and DOE contractors from
the Office of Scientific and Technical Information,
P.O. Box 62, Oak Ridge, TN 37831-0062
www.osti.gov
ph: (865) 576-8401
fox: (865) 576-5728
email: reports@osti.gov

Available to the public from the National Technical Information Service
5301 Shawnee Rd., Alexandria, VA 22312
ph: (800) 553-NTIS (6847)
or (703) 605-6000
email: info@ntis.gov
Online ordering: http://www.ntis.gov

Project Summary

Project Name	EPA Climate Modeling
Project No.	O2309-068-089-013161
Product Management Office No. / Organization	N/A

Revision History

Revision	Date	Comments
0.1	09/26/2024	Original
0.2	10/04/2024	Cleared Information Release

Table of Contents

1.0 Introduction

Sea level rise (SLR) is a major concern arising from anthropogenic climate change as it threatens coastal communities and ecosystems, with impacts easily reverberating much beyond them. Future projections of SLR are of critical interest to both the scientific and decision-making communities. There are multiple factors, such as the thermal expansion of water, melting glaciers and ice sheets, and changes in land water storage, which contribute to SLR. The uncertainty surrounding these processes, along with potential feedback mechanisms, complicates the challenge of producing accurate quantitative SLR projections. These projections are essential for key climate reports and for informing effective adaptation strategies (Enevoldsen et al., 2024; Fox-Kemper et al., 2021a). Understanding and addressing this complexity is vital for safeguarding vulnerable coastal regions in the face of ongoing climate change.

The **F**ramework for **A**ssessing **C**hanges **T**o **S**ea-level (FACTS) platform was developed by (Kopp et al., 2023) as an open-source modular tool capable of generating probabilistic projections for global mean sea-level change and future relative and extreme sea-level change at New York City (Kopp et al., 2023). FACTS is the first open-source modular tool designed to explore deep uncertainty in SLR while also synthesizing across different modeling groups and integrating the various components of SLR (Figure 1) used in key climate reports (Fox-Kemper et al., 2021a; Slangen et al., 2023; Sweet, W. V., Hamlington, B. D., Kopp, R. E., Weaver, C. P., Barnard, P. L., Bekaert, D., W. Brooks, M. C., Dusek, G., Frederikse, T., Garner, G., Genz, A., Krasting, J. P., Larour, E., D. Marcy, J. J. M., Obeysekera, J., Osler, M., Pendleton, M., Roman, D., Schmied, L., Veatch, W., White, K. D., and Zuzak, C., 2022).

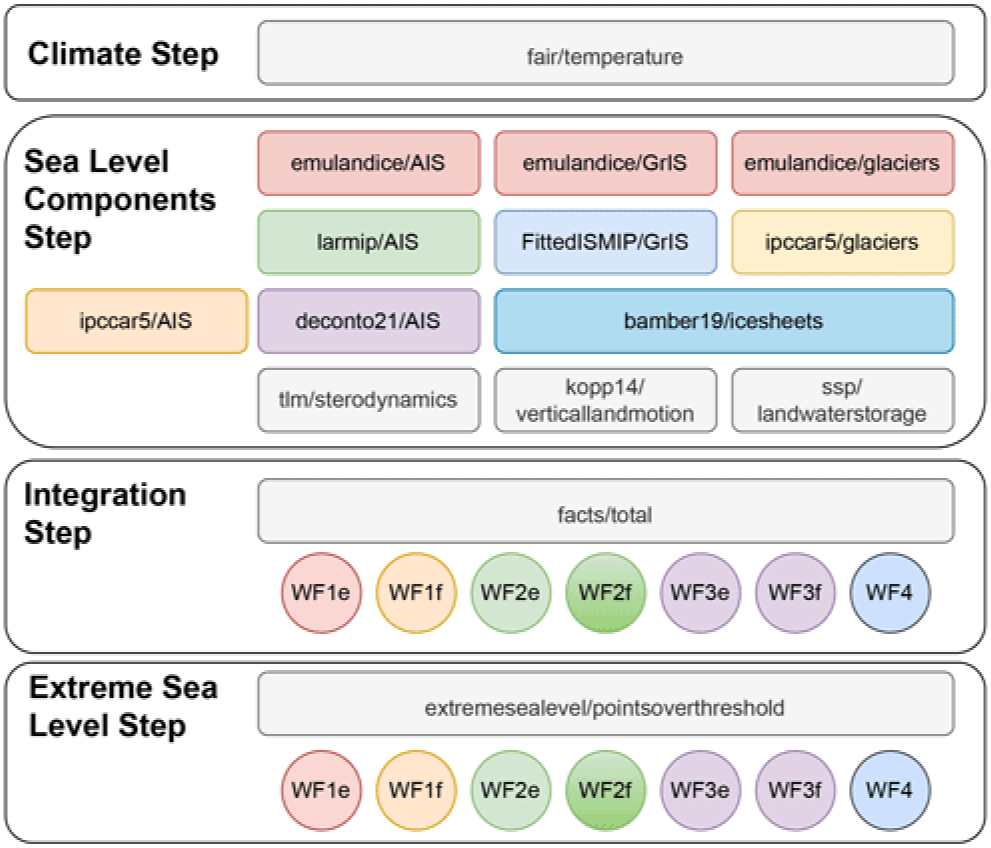


Figure 1: Schematic of the FACTS experiment and modules from (Kopp et al., 2023).

The version of FACTS that contributed to the Intergovernmental Panel on Climate Change Sixth Assessment Report (Fox-Kemper et al., 2021a; Slangen et al., 2023; Sweet, W. V., Hamlington, B. D., Kopp, R. E., Weaver, C. P., Barnard, P. L., Bekaert, D., W. Brooks, M. C., Dusek, G., Frederikse, T., Garner, G., Genz, A., Krasting, J. P., Larour, E., D. Marcy, J. J. M., Obeysekera, J., Osler, M., Pendleton, M., Roman, D., Schmied, L., Veatch, W., White, K. D., and Zuzak, C., 2022) used FaIR (Smith et al., 2018),, a simple climate model, to calculate temperature and ocean heat content for a given emissions scenario. FaIR's climate results then drive the various seal level components components supported by FACTS (Figure 1). This user guide introduces Hector-FACTS, a modified version of FACTS V1.1.2 that enables users to conduct experiments using Hector V3.2.0 as the driving simple climate model.

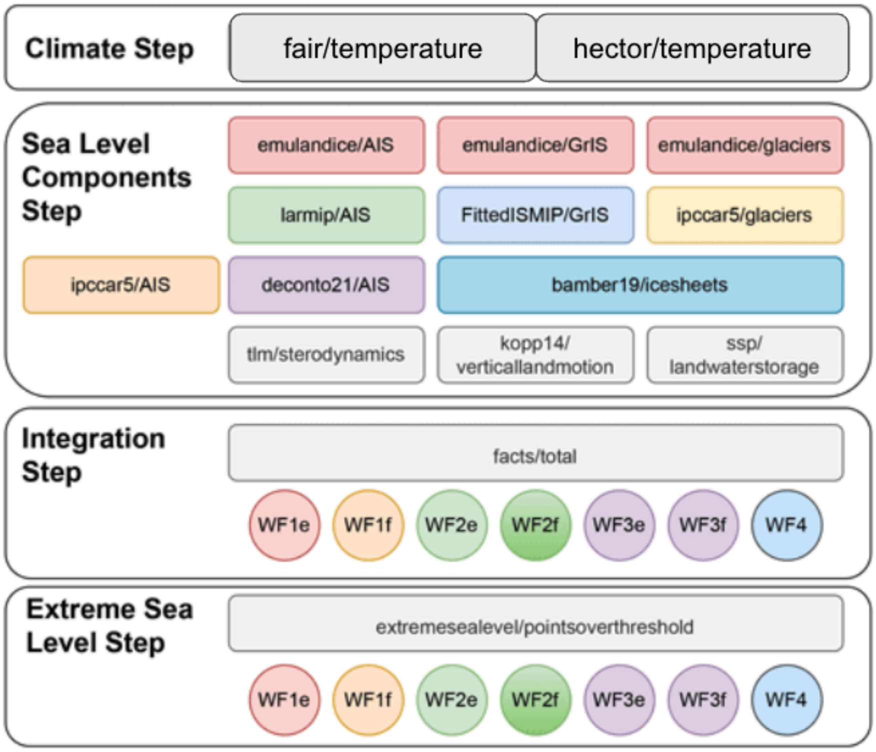


Figure 2: Modified from (Kopp et al., 2023) this schematic illustrates the Hector-FACTS workflow. Now, users will have the ability to choose from driving the Sea Level Components Step with temperature and ocean heat content results from Hector.

Hector is the reduced-complexity carbon cycle and climate model developed by the Pacific Northwest National Laboratory (PNNL). Originally created by (Hartin et al., 2015)., Hector is a flexible and modular tool that efficiently represents critical Earth system processes on a global and annual scale. In our recent work, (Dorheim, Gering, et al., 2024)., we document significant updates to the model, particularly in its terrestrial carbon cycle, radiative forcing, and temperature components. The ocean component has remained largely unchanged since its initial release. By integrating Hector into the FACTS platform, PNNL leverages its modeling capabilities to produce probabilistic sea level rise projections consistent with the methodology used in the IPCC Sixth Assessment Report (Fox-Kemper et al., 2021a).

1.1 Background

Additional material and supporting information for Hector and FACTS can be found in the following:

1.1.1 Hector

Brown, J. K., Pressburger, L., Snyder, A., Dorheim, K., Smith, S. J., Tebaldi, C., & Bond-Lamberty, B. (2024). Matilda v1.0: An R package for probabilistic climate projections using a reduced complexity climate model. PLOS Climate, 3(5), e0000295. (Brown et al., 2024)

Dorheim, K., Bond-Lamberty, B., Hartin, C., Link, R., Nicholson, M., Pralit, P., Pressburger, L., Shiklomanov, A., Vega-Westhoff, B., & Woodard, D. (2024). Hector a simple carbon-climate model (v3.2.0). Zenodo. https://doi.org/10.5281/zenodo.10698028 (Dorheim, Bond-Lamberty, et al., 2024)

Dorheim, K., Gering, S., Gieseke, R., Hartin, C., Pressburger, L., Shiklomanov, A. N., Smith, S. J., Tebaldi, C., Woodard, D. L., & Bond-Lamberty, B. (2024). Hector V3.2.0: functionality and performance of a reduced-complexity climate model. Geoscientific Model Development, 17(12), 4855–4869.(Dorheim, Gering, et al., 2024)

Hartin, C. A., Patel, P., Schwarber, A., Link, R. P., & Bond-Lamberty, B. P. (2015). A simple object-oriented and open-source model for scientific and policy analyses of the global climate system--Hector v1. 0. Geoscientific Model Development, 8(4), 939–955.(Hartin et al., 2015)

Vega-Westhoff, B., Sriver, R. L., Hartin, C. A., Wong, T. E., & Keller, K. (2019). Impacts of observational constraints related to sea level on estimates of climate sensitivity. Earth's Future, 7(6), 677–690. (Vega-Westhoff et al., 2019)

1.1.2 FACTS

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., & Yu, Y. (2021a). Ocean, Cryosphere and Sea Level Change. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1211–1362). Cambridge University Press. (Fox-Kemper et al., 2021a)

Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., & Yu, Y. (2021b). Ocean, Cryosphere and Sea Level Change Supplementary Material. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth

Assessment Report of the Intergovernmental Panel on Climate Change. (Fox-Kemper et al., 2021b)

Kopp, R. E., Garner, G. G., Hermans, T. H. J., Jha, S., Kumar, P., Slangen, A. B. A., Turilli, M., Edwards, T. L., Gregory, J. M., Koubbe, G., Levermann, A., Merzky, A., Nowicki, S., Palmer, M. D., & Smith, C. (2023). The Framework for Assessing Changes To Sea-level (FACTS) v1.0-rc: A platform for characterizing parametric and structural uncertainty in future global, relative, and extreme sea-level change. In EGUsphere. https://doi.org/10.5194/egusphere-2023-14

Kopp, R. E., Garner, G. G., Jha, S., Hermans, T. H. J., Reedy, A., Slangen, A. B. A., Turilli, M., Merzky, A., & Koubbe, G. (2023). Framework for Assessing Changes To Sea-Level (FACTS) (v1.1.2). Zenodo. https://doi.org/10.5281/zenodo.10403331. (Kopp et al., 2023)

Smith, C. J., Forster, P. M., Allen, M., Leach, N., Millar, R. J., Passerello, G. A., and Regayre, L. A.: FAIR v1.3: a simple emissions-based impulse response and carbon cycle model, Geosci. Model Dev., 11, 2273–2297, https://doi.org/10.5194/gmd-11-2273-2018, 2018.

1.2 Acknowledgments

This work was supported by the U.S. Environmental Protection Agency, Climate Change Division, under Interagency Agreements O2309-068-089-013161. The views and opinions expressed in this paper are those of the authors alone.

2.0 Hardware/Software Requirements & Software Installation

The software requirements defined below express what has been tested and known to work. It is possible and likely that newer versions of operating systems and software will work fine with Hector-FACTS, but they are untested at the time of this release.

Table 1: Hardware Overview

MacOSX	Windows
Model Name: MacBook Pro Model Identifier: Mac14,9 Model Number: MPHE3LL/A Chip: Apple M2 Pro Total Number of Cores: 10 (6 performance and 4 efficiency) Memory: 16 GB	Model Name: HP Elite x360 1040 G9 Model Number: 712Q3UP#ABA Chip: Intel Core i7-1265U Total Number of Cores: 10 Memory: 16 GB

Other software that must be installed to run Hector-FACTS include Git and Docker. Installing wget, R, and RStudio is recommended but not required.

2.1 Hardware and Software Requirements

2.1.1 Git

Git is an open-source version control system that tracks changes, allowing multiple scientists to collaborate on projects. Hector-FACTS is hosted on GitHub. Users must follow the appropriate Git installation for their machine to download and install Hector-FACTS.

Install git (if not already installed)

To install git, open your terminal and use the appropriate command for your operating system:

On Ubuntu or Debian-based systems:

```
sudo apt-get update
sudo apt-get install git
```

On macOS:

```
brew install git
```

On Windows:
Install git via the [Git for Windows installer.]
To verify git is installed, run:

```
git --version
```

2.1.2 Docker

Docker is an open-source platform that simplifies software deployment by enabling the sharing of lightweight, portable containers, ensuring that applications can run consistently across different environments. FACTS relies on the Radical-PILOT computing stack, which is designed to operate exclusively on Linux platforms. The Docker image created for Hector-FACTS allows any user to run Hector-FACTS locally, provided that Docker is properly installed.

To install docker, follow the instructions for your operating system:

On Ubuntu or Debian-based systems:

```
sudo apt-get update
sudo apt-get install docker.io
sudo systemctl start docker
sudo systemctl enable docker
```

On macOS or Windows:
Download and install Docker from the official Docker website. To verify docker is installed, run:

```
docker --version
```

2.2 Install Hector-FACTS

After installing the prerequisites, it is time to install Hector-FACTS by cloning the repository. Run the following command.

```
git clone https://github.com/JGCRI/hector-facts.git
```

Navigate to the Hector-FACTS directory. This will be the root project working directory (PROJ_DIR) for the rest of the instructions.

Navigate to the hector-facts/module-data folder and run the following to install the input files for Hector-FACTS. These files are too large to be stored on GitHub and are hosted on Zenodo. The modules-data.urls.txt file contains links to where the input data is stored and available for download. Alternatively, users can run the following command to install all the required files.

```
cd modules-data
wget -i modules-data.urls.txt
```

2.3 Set-Up & Getting Started

Please see the official docker documentation for examples and reference materials. Here, we provide minimal instructions for getting Hector-FACTS running.

This process will install Hector and all the dependencies and set up the necessary environmental conditions. This can be time-consuming but only needs to be done once (or after updating the Dockerfile or shutting down the image). From the root project directory, run:

```
cd docker
sh develop.sh
```

Now, build the Docker container, which will be the active version where Hector-FACTS will run. Use the following command:

```
docker run --rm -it -v PROJ_DIR:/opt facts
cd opt
```

Note: Replace PROJ_DIR with the full path to the location where the Hector-FACTS repository is installed on your machine. This command will create and start a container in detached mode, mounting your project directory to the `/opt` directory within the container.

Confirm that everything is set up properly by running the `dummy` experiment with the following command.

```
python3 runFACTS.py experiments/dummy
```

You should see messages similar to this:

```
EnTK session: re.session.db906fca-1de6-11ef-9cca-0242ac110002
```

```
Creating AppManager
Setting up ZMQ queues
ok
AppManager initialized
ok
Validating and assigning resource manager
ok
****** STEP: sealevel_step ******
Setting up ZMQ queues
n/a
All components created
Update: dummy.dummy.facts.dummy state: SCHEDULING
Update: dummy.dummy.facts.dummy.preprocess state: SCHEDULING
Update: dummy.dummy.facts.dummy.preprocess.task1 state: SCHEDULING
Update: dummy.dummy.facts.dummy.preprocess.task1 state: SCHEDULED
Update: dummy.dummy.facts.dummy.preprocess state: SCHEDULED
Update: dummy.dummy.facts.dummy.preprocess.task1 state: SUBMITTING
Update: dummy.dummy.facts.dummy.preprocess.task1 state: EXECUTED
Update:  dummy.dummy.facts.dummy.preprocess.task1 state: DONE
Update: dummy.dummy.facts.dummy.preprocess state: DONE
Update: dummy.dummy.facts.dummy state: DONE
All components terminated
```

If you see “All components terminated” your setup is confirmed to be working correctly! And you are ready to start launching other experiments. To launch a different experiment, run the following command, replacing NAME with the name of your experiment:

```
python3 runFACTS.py experiments/NAME
```

The subdirectories within the `experiments` directory correspond to different workflows or experiments that can be executed. The prefix `hector` or `fair` indicates whether the Hector or FaIR simple climate model is driving the sea level modules in a particular workflow. If a simple climate model is not specified in the experiment name, the modules are driven by non-climate factors (e.g., population). Table 2 provides a brief overview of the experiment names. For more detailed information on specific FACTS experiments and module names, please refer to the FACTS documentation manuscript (Kopp et al., 2023).

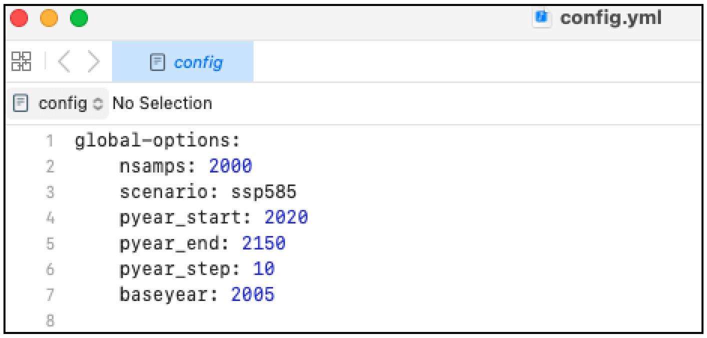
Table 2: Description of the experiment name elements

Name	**Description**
ar5k14	Refers to the Intergovernmental Panel on Climate Change Fifth Assessment Report
dummy	Launches experiments that do nothing but confirm that the Docker container is set up properly and ready for runs.
esl	Extreme sea level rise

fair	Indicates that fair is being used (Smith et al., 2018)
hector	Indicates hector is being used (Dorheim, Gering, et al., 2024)
bamber19	Icesheet projections based on the expert judgment reported in (Bamber et al., 2019)
coupling	This indicates that this experiment will run all FACTS modules and complete the integrate steps (totaling across the different SLR components) as indicated in the integration step included in Figures 1 and 2.
larmip	An implementation of the Linear Antarctic Response Model Intercomparison Project ice sheet loss linear impulse response function (Levermann et al., 2020)
emulandice	Stands for Greenland and Antarctic Ice sheets
global	Indicates that global SLR will be calculated
local	Indicates that local SLR will be calculated
fittedismip	Greenland Ice Sheets based on processed ISMIP results
onemodule	Launches a single user-defined SLR module, no integration step
ipccar6	Refers to the Intergovernmental Panel on Climate Change Sixth Assessment Report
rcp2.6, rcp4.5, rcp8.5	Refers to the Representative Concentration Pathway being used in the experiment
ssp119, ssp126, ssp245, ssp370, ssp585	Refers to the Shared Socioeconomic Pathway Representative Concentration Pathway scenario being used in the experiment
tlm	Refers to the sterodynamics two-layer model documented in (Fox-Kemper et al., 2021a).

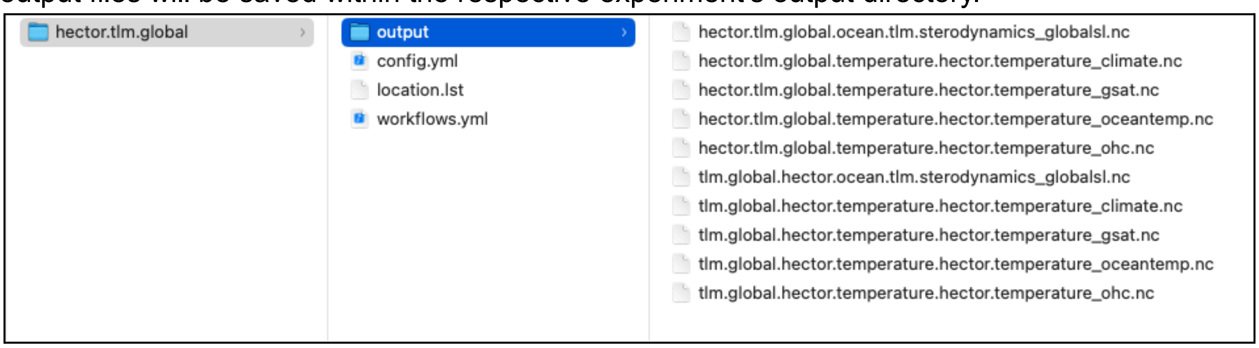
Within a specific experiment directory will be a config.yml, which is where different FACTS steps (**Figures 1** & **2**) and global options, such as the number of runs to complete and scenario to use (**Figure 3**). The number of samples controls the ensemble size produced by the experiment and accounts for climate uncertainty. The experiment uniformly samples uncertainty in key climate model parameters, which are then used to drive the simple climate model to generate a probability distribution for global mean air temperature and ocean heat content. The Hector parameters were generated using Hector's probabilistic framework, Matilda (Brown et al., 2024) and are included in the Hector-FACTS supplemental materials see the Software and Data Management Plan section.

Figure 3: Screenshot of the global options section in an experiment configuration file. When debugging an experiment, we encourage users to decrease the sample size (nsamps)



Once you see the message "All components terminated", the experiment is successfully completed. The results are stored in NetCDF format within the output folder for your experiment (**Figure 4**). These NetCDF files, generated by Hector-FACTS, are self-describing and include detailed information about the experiment and the workflow used to produce them. Users are encouraged to analyze these files with their preferred software, such as Python or R.

Figure 4: Screenshot of output files from the Hector-FACTS hector.tlm.global experiment. All output files will be saved within the respective experiment's output directory.



2.3.1 Challenges

When integrating Hector into the FACTS platform, there were substantial challenges. When debugging, we recommend reducing the number of runs in the `experiments/specific_experiment/config.yml` file. We also recommend running the following to create a shell script and debugging from there.

```
python3 runFACTS.py --shellscript experiments/hector.tlm.global > test.sh
```

To troubleshoot issues within the experiment using `test`. You can run the script line by line in a terminal. This approach allows you to isolate and identify the specific line where the problem is occurring.

2.4 Example Run - hector.tlm.global

In this section, we will walk through one of the Hector-FACTS experiments. We assume that you have already completed the installation process and are working with an active Hector-FACTS Docker container. Additionally, you should have navigated to the opts directory or the root directory where Hector-FACTS is mounted within the Docker container.

We will be running the experiment titled “hector.tlm.global”, this experiment uses Hector in the climate step (**Figure 2**) to calculate ocean heat content for the SPP5-8.5 scenario. Hector’s climate results are then used as inputs to the Fox-Kemper et al. two-layer model (TLM) which uses ocean heat content to calculate global sea-level rise. Ultimately, this experiment uses calculations of global mean thermosteric sea-level rise, ocean dynamic sea-level change, and the inverse barometer effect to produce global mean sea-level rise projections.

From the opt directory of an active Docker container, run the following:

```
python3 runFACTS.py experiments/hector.tlm.global
```

The single line of code launches all FACTS steps (**Figure 2**). During the climate step, Hector runs 2,000 simulations, as defined in the `experiments/hector.tlm.global/config.yml` file to be consistent with the fair version of the experiment for the SSP5-8.5 scenario. Each run uses a unique parameter set from the `hector_params.csv` file, which was installed in the `module-data` folder during Hector-FACTS setup. This file contains over 2,800 combinations of six key Hector climate parameters that were found to influence the temperature outcomes from Hector, allowing us to explore uncertainties in the SCM output which we propagate through te SLR computation. These parameters are: aerosol forcing scaling factor, CO2 fertilization factor, equilibrium climate sensitivity, ocean heat diffusivity, pre-industrial net primary productivity, and the temperature sensitivity of heterotrophic respiration. The sets of parameter values were generated using Matilda (Brown et al., 2024), Hector’s probabilistic framework. The Hector results are then passed to the TLM sterodynamics model to calculate global sea level rise. Once the "All components terminated" message appears, the "hector.tlm.global" experiment has been successfully completed, and the results are available in the output directory.

Figures 5 and **6** illustrate the projected sea level rise (SLR) calculated from the combined effects of thermosteric changes—due to the thermal expansion of seawater—and ocean dynamic changes, as calculated by the Hector-FACTS global TLM experiment. In contrast to other FACTS experiments, this analysis does not incorporate changes in ice sheet and glacier dynamics, focusing solely on the ocean's response to climate change. The results of this experiment indicate a large mean SLR increase of 602.3 mm between 2020 and 2150, as depicted in **Figure 5**. **Figure 6** depicts the spread in sea level rise (SLR) projections for the years 2050 and 2100, illustrating the considerable impact of climate uncertainty on future scenarios.

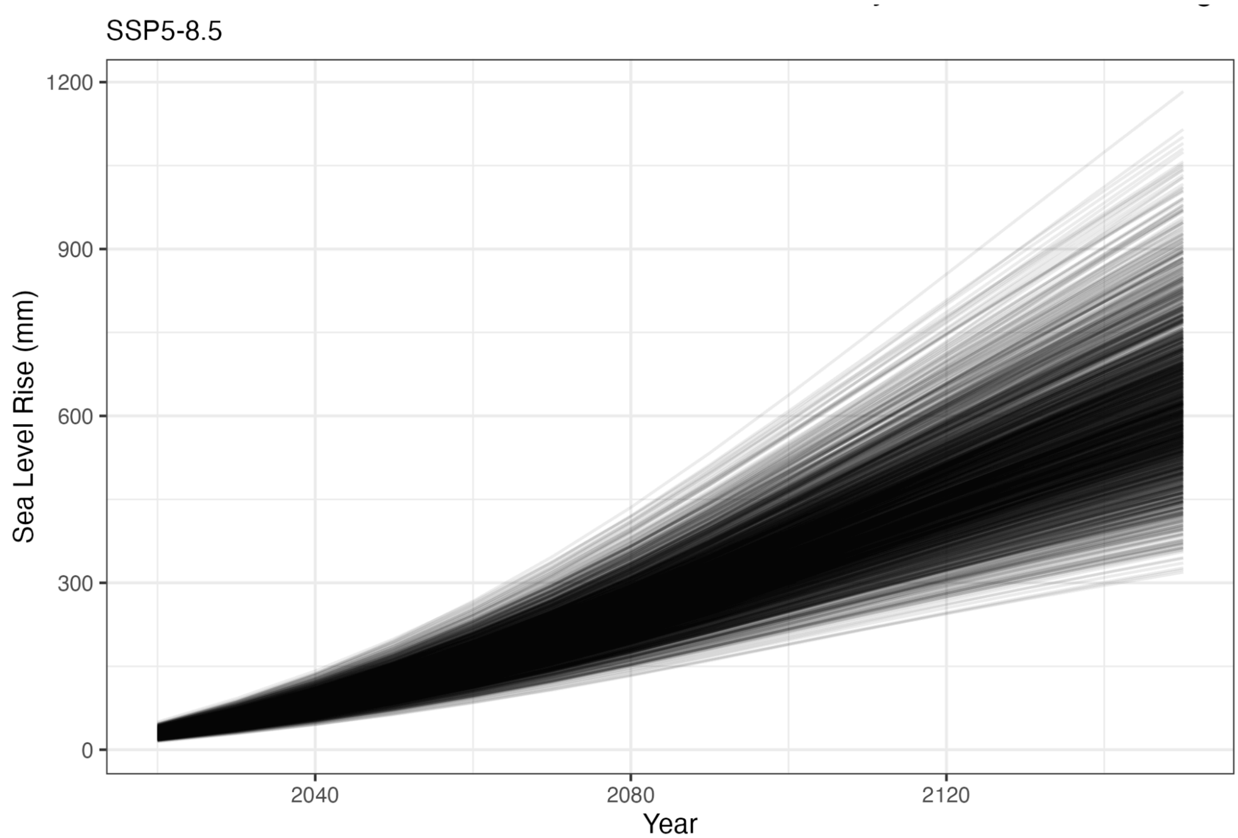


Figure 5: Global sea level rise driven by Hector emission-driven SSP5-8.5 ocean heat content from 2,000 Hector-FACTS runs. Ocean heat from each Hector run was used to drive the TLM sterodynamics module.

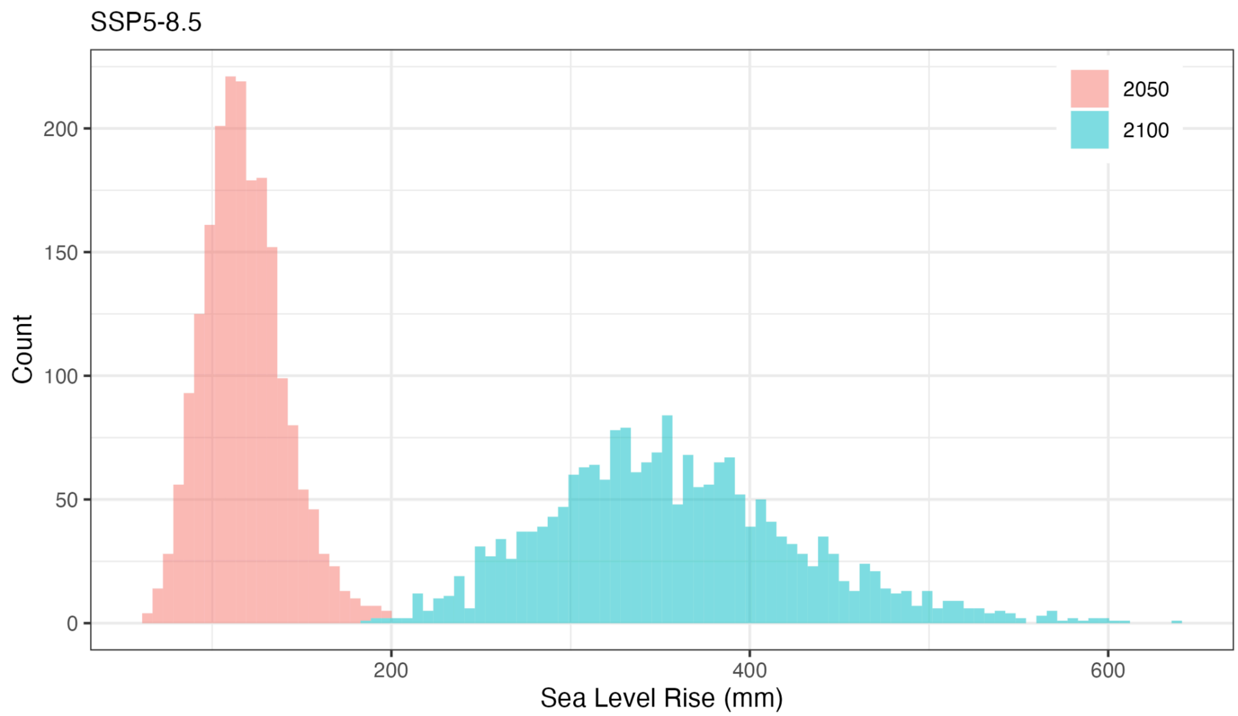


Figure 6: Histogram of 2050 and 2100 global sea level rise for the SSP5-8.5 scenario from the example Hector-FACTS run.

3.0 Software and Data Management Plan

Data sources and processing methods are described in the technical report. Where applicable formal and appropriate metadata standards were applied; otherwise FACTS metadata and terminology as described in Kopp et al. 2023 were used.

Name	Description	Data Source(s) and/or EPA Dissemination Plan
a. Data Used in this Study		
(Kopp 2022a; Kopp 2022b)	Input data sets for the non-Hector modules that were prepared as part of the Kopp et al. 2023 manuscript.	Source data available at: http://dx.doi.org/10.5281/ZENODO.7478448 and https://zenodo.org/records/7478192 Cite as: Kopp, R. E. (2022). Framework for Assessing Changes To Sea-level (FACTS) Module Data (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7478192 and Kopp, R. E. (2022). Framework for Assessing Changes To Sea-level (FACTS) Module Data - Part 2 (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.7478448

Name	Description	Data Source(s) and/or EPA Dissemination Plan
hector-input.tgz	Hector input emission tables and ini files extended out to 2500 as required by FACTS.	Source data available at: https://zenodo.org/records/13774542 Cite as: Dorheim, K., Tebaldi, C., & Donegan, C. (2024). hector-facts-support [Data set]. Zenodo. https://doi.org/10.5281/zenodo.13774542
b. Data Produced by This Study		
hector_params.tgz	CSV file containing 2802 parameter combinations generated using Matilda. Hector parameter values will be drawn from this file depending on the Hector-FACTS experiment configuration.	Hector V3.2.0 is available at: Dorheim, K., Bond-Lamberty, B., Hartin, C., Link, R., Nicholson, M., Pralit, P., Pressburger, L., Shiklomanov, A., Vega-Westhoff, B., & Woodard, D. (2024). Hector a simple carbon-climate model (v3.2.0). Zenodo. https://doi.org/10.5281/zenodo.10698028 Matilda is available at: https://github.com/JGCRI/matilda The code used to generate probabilistic Hector parameters is available at: https://github.com/JGCRI/hector-facts-support
Code	The R script generated the input parameters to drive probabilistic Hector and visualize the Hector-FACTS results.	Available at: https://github.com/JGCRI/hector-facts-support
Potential: Underlying Figure Data	Results from Hector-FACTS experiments	https://zenodo.org/records/13841030

4.0 References

Bamber, J. L., Oppenheimer, M., Kopp, R. E., Aspinall, W. P., & Cooke, R. M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgment. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(23), 11195–11200.

Brown, J. K., Pressburger, L., Snyder, A., Dorheim, K., Smith, S. J., Tebaldi, C., & Bond-Lamberty, B. (2024). Matilda v1.0: An R package for probabilistic climate projections using a reduced complexity climate model. *PLOS Climate*, *3*(5), e0000295.
Dorheim, K., Bond-Lamberty, B., Hartin, C., Link, R., Nicholson, M., Pralit, P., Pressburger, L., Shiklomanov, A., Vega-Westhoff, B., & Woodard, D. (2024). *Hector a simple carbon-climate model*. Zenodo. https://doi.org/10.5281/ZENODO.10698028
Dorheim, K., Gering, S., Gieseke, R., Hartin, C., Pressburger, L., Shiklomanov, A. N., Smith, S. J., Tebaldi, C., Woodard, D. L., & Bond-Lamberty, B. (2024). Hector V3.2.0: functionality and performance of a reduced-complexity climate model. *Geoscientific Model Development*, *17*(12), 4855–4869.
Enevoldsen, H. O., Isensee, K., & Lee, Y. J. (2024). *State of the ocean report 2024*. UNESCO-IOC. https://doi.org/10.25607/4WBG-D349
Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., & Yu, Y. (2021a). Ocean, Cryosphere and Sea Level Change. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1211–1362). Cambridge University Press.
Fox-Kemper, B., Hewitt, H. T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S. S., Edwards, T. L., Golledge, N. R., Hemer, M., Kopp, R. E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I. S., Ruiz, L., Sallée, J.-B., Slangen, A. B. A., & Yu, Y. (2021b). Ocean, Cryosphere and Sea Level Change Supplementary Material. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.
Hartin, C. A., Patel, P., Schwarber, A., Link, R. P., & Bond-Lamberty, B. P. (2015). A simple object-oriented and open-source model for scientific and policy analyses of the global climate system--Hector v1. 0. *Geoscientific Model Development*, *8*(4), 939–955.
Kopp, R. E., Garner, G. G., Hermans, T. H. J., Jha, S., Kumar, P., Reedy, A., Slangen, A. B. A., Turilli, M., Edwards, T. L., Gregory, J. M., Koubbe, G., Levermann, A., Merzky, A., Nowicki, S., Palmer, M. D., & Smith, C. (2023). The Framework for Assessing Changes To Sea-level (FACTS) v1.0: a platform for characterizing parametric and structural uncertainty in future global, relative, and extreme sea-level change. *Geoscientific Model Development*, *16*(24), 7461–7489.
Levermann, A., Winkelmann, R., Albrecht, T., Goelzer, H., Golledge, N. R., Greve, R., Huybrechts, P., Jordan, J., Leguy, G., Martin, D., Morlighem, M., Pattyn, F., Pollard, D., Quiquet, A., Rodehacke, C., Seroussi, H., Sutter, J., Zhang, T., Van Breedam, J., … van de Wal, R. S. W. (2020). Projecting Antarctica's contribution to future sea level rise from basal ice shelf melt using linear response functions of 16 ice sheet models (LARMIP-2). *Earth System Dynamics*, *11*(1), 35–76.
Slangen, A. B. A., Palmer, M. D., Camargo, C. M. L., Church, J. A., Edwards, T. L., Hermans, T. H. J., Hewitt, H. T., Garner, G. G., Gregory, J. M., Kopp, R. E., Santos, V. M., & van de Wal, R. S. W. (2023). The evolution of 21st century sea-level projections from IPCC AR5 to AR6 and beyond. *Cambridge Prisms: Coastal Futures*, *1*(e7), 1–33.
Smith, C. J., Forster, P. M., Allen, M., Leach, N., Millar, R. J., Passerello, G. A., & Regayre, L. A. (2018). FAIR v1.3: a simple emissions-based impulse response and carbon cycle model.

Geoscientific Model Development, *11*(6), 2273–2297.
Sweet, W. V., Hamlington, B. D., Kopp, R. E., Weaver, C. P., Barnard, P. L., Bekaert, D., W. Brooks, M. C., Dusek, G., Frederikse, T., Garner, G., Genz, A., Krasting, J. P., Larour, E., D. Marcy, J. J. M., Obeysekera, J., Osler, M., Pendleton, M., Roman, D., Schmied, L., Veatch, W., White, K. D., and Zuzak, C. (2022). *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines*. https://oceanservice.noaa.gov/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf
Vega-Westhoff, B., Sriver, R. L., Hartin, C. A., Wong, T. E., & Keller, K. (2019). Impacts of observational constraints related to sea level on estimates of climate sensitivity. *Earth's Future*, *7*(6), 677–690.

5.0 Contact Information

Inquiries regarding Hector-FACTS can be made to:

Kalyn Dorheim
Earth Scientist
Global Change Division / Human-Earth System & Science Group
Phone: (509) 372-6391
Email: kalyn.dorheim@pnnl.gov

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354
1-888-375-PNNL (7665)

www.pnnl.gov