CMIPnext: facilitating international climate science

Paul J. Durack – WIP Co-Chair, CMIP Panel member

Tuesday 1st August 2023

2023 US CLIVAR Summit (Seattle, WA, USA)
Overview

- **Model Intercomparison Projects (MIPs) Overview**
- **CMIP6 status** (current phase)
- **CMIPnext planning**
  - CMIP surveys; CMIP6Plus
- **CMIP7**
  - Forcing protocol (idealized/historical-proxy forcings); Data quantities, identities and formats
- **CMEC**
  - PCMDI Metrics Package (PMP); Collaborative activities in (climate) model evaluation
MIPs Overview
What are *MIPs

- **Model Intercomparison Projects**
- Started with Atmospheric-only MIP (AMIP) in 1989
- Coupled (atmosphere & ocean) MIP (CMIP) initiated 1995, evolved to Earth System Models (ESMs) in CMIP5
- Standardized protocols
  - Experimental (simulation length, model components)
  - Forcing (idealized, or historical-proxy forcings)
  - Data formats, identities and quantities
- Expanded for non-model activities servicing core modelling activities
  - **input4MIPs** – input (forcing) datasets for MIPs
  - **obs4MIPs** – observations for MIPs/model evaluation

# Timeline of *MIPs*

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>AMIP1</td>
<td>AMIP2</td>
<td>CMIP1</td>
<td>CMIP2/CMIP2+</td>
<td>CMIP3</td>
<td>CMIP5</td>
<td>CMIP6</td>
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<tr>
<td>Data Volumes</td>
<td>~1GB</td>
<td>~500GB</td>
<td>~1GB</td>
<td>~500GB</td>
<td>50TB</td>
<td>2PB</td>
<td>&gt;20PB</td>
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<tr>
<td>Host Infrastructure</td>
<td>LLNL FTP</td>
<td>LLNL FTP</td>
<td>LLNL FTP</td>
<td>LLNL FTP</td>
<td>LLNL FTP</td>
<td>ESGF 41# nodes</td>
<td>ESGF 30 nodes</td>
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<td>Data formats</td>
<td>Fortran formatted binary</td>
<td>Fortran formatted binary, GRIB → DRS</td>
<td>GRIB → DRS</td>
<td>GRIB → DRS</td>
<td>CF netCDF-3</td>
<td>CF netCDF-4</td>
<td>CF netCDF-4</td>
</tr>
</tbody>
</table>

*For some groups in addition to data distribution, LLNL computing facilities were used to run contributing simulations.

▽ Data Retrieval and Storage (DRS) software library developed at PCMDI – pre-netCDF file format.

# The start of data federation - just 17 CMIP5 nodes remain, a ~50% loss from the CMIP5 peak - highlights tier 1 node importance for MIP data preservation.
↑ complexity →
More models, forcings; more differences across the archive to keep track of
CMIP6 status
CMIP: driving science, informing policy

CMIP6: biggest yet!
- 24 endorsed MIPs
- 26 countries
- 48 institutions
- 130 models
- 322 experiments
- 8450 citations of CMIP6 and MIP design papers
- Nearly 26 PB of CMIP6 data
- 30+ ESGF data nodes
CMIP6 – current phase

- DECK (core)
  - Diagnostic, Evaluation and Characterization of Klima
  - 4 experiments (1pctCO2, abrupt-4xCO2, piControl, AMIP) + historical + ESM variants

- 24 community MIPs focused on
  - ESM systematic biases
  - Forcing and feedback responses
  - Variability, predictability and future projections
  - Negative emissions pathways

CMIP structure

The DECK (Diagnostic, Evaluation and Characterization of Klima) and CMIP historical simulations (1850 – near-present) that maintain continuity and help document basic characteristics of models across different phases of CMIP.

The MIPs

Model Intercomparison Projects (MIPs) address specific science questions across the climate and earth science communities. They are driven bottom up by the community.

Participation in MIPs by individual modelling groups is at their own discretion and depends on their scientific interests and priorities.

Common standards and open access

Common standards: experimental, forcing, data; allowing coordination on infrastructure and documentation that facilitates distribution of model outputs and the characterization of the model ensemble.
ESGF Published CMIP6 data

- Over 6.4 million CMIP6 ESGF datasets across activities/MIPs
- Seamless delivery – thanks to ESGF data challenges/stability testing
- Datasets - unique variable collections per experiment RIPF (unique simulations)
- Footprint – units of Petabytes
CMIP6 in AR6/IPCC

- CMIP6 “hot models” - climate sensitivity > Sherwood et al. (2020) and > AR6 assessed very likely range
- AR first “constrained projections” - models weighted by observational agreement - downward “correction”
- Getting forcing (and response!) right underpins observed climate change attribution, future projections utility
- Projection user community growing markedly
- Raises model evaluation importance - model projections use requires specialist guidance
- Operational “climate services” need next-level climate science guardrails
CMIPnext planning
CMIP – a team sport!

- PCMDI
  - U.S. DOE provided 34-years of MIP support

- ESGF
  - Originated by U.S. DOE ~2007
  - Major recent contributions from numerous others
  - IS-ENES and ENES-RI follow-on
  - European contribution to ESGF & CMIP infrastructure
  - Numerous other projects and institutions, including DKRZ, IPSL, CEDA, ES-DOC, NASA, NOAA, ...
  - CMIP6: 30+ ESGF nodes, 17 countries, 131 models, 48 institutions representing 26 countries, and many, many more...

Every modelling group, every forcing dataset provider, ...
CMIP expanded to point where coordination of elements requires dedicated administration and facilitation support.

IPO established March 2022 at host institution, ESA’s ECSAT site in Harwell, UK.

IPO team consists of:
- Director (Eleanor O’Rourke)
- Programme Manager (Briony Turner)
- Science & Communications Officer (Beth Dingley)
- Technical Officer (Daniel Ellis)
- Part-time administrative support (Alice Kolesnikov)
CMIP6 Survey: Suggestions for CMIP7

- No big structural CMIP6 change but evolution.
- Retain IPCC alignment in some form.
- Reduce huge burden on modelling centres.
- Need for greater focus on climate impacts and adaptation relevant experiments (including updated scenarios).
- Need for operationalisation of critical elements (e.g., forcing) – delays in forcing had major CMIP6 delivery impacts.
- Build on substantial CMIP6 data infrastructure progress to facilitate science and support improved, and more user friendly, data access.
- Continue and enhance active community input to the experimental design process.
- Nurture the CMIP future community and promote young and global South scientists.
<table>
<thead>
<tr>
<th>You said.....</th>
<th>We are.....</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMIP6 = burden on modelling centres</td>
<td>Reducing numbers of experiments.</td>
</tr>
<tr>
<td>IPCC timelines causes pressure</td>
<td>Proposing streamlined experiments on IPCC timeline. Freeing up community driven MIPs</td>
</tr>
<tr>
<td>Need for greater focus on climate impacts and adaptation relevant experiments</td>
<td>Seamless delivery across WGI, WGII and WGIII via updated scenarios tailored for mitigation and impacts policy applications with timely delivery to facilitate downscaling</td>
</tr>
<tr>
<td>Need for operationalisation of critical elements</td>
<td>Established Task Teams to deliver recommendations for sustainable delivery of near real time forcings.</td>
</tr>
<tr>
<td>Need sustainable funding of infrastructure to support improved, and more user friendly, data access.</td>
<td>Established Task Teams to deliver recommendations on requirements for future infrastructure and engaging with funders.</td>
</tr>
<tr>
<td>Continue and enhance active community input to the experimental design process.</td>
<td>Expanded CMIP Panel and established Task Teams through open calls plus rolling out extensive community engagement.</td>
</tr>
<tr>
<td>Nurture the future CMIP community and promote young and global South scientists.</td>
<td>Launched ECR group (Fresh Eyes on CMIP) and planning for CMIP Panel members from the global South.</td>
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The Task Teams

CMIP Task Teams have been established to drive forward definition of CMIP7 in an open and collaborative manner.

- Data access (Robert Pincus and Atef Ben-Nasser)
- Data citation (Martina Stockhause and Sasha Ames)
- Data request (Martin Juckes and Chloe Mackallah)
- Forcings (Paul Durack and Vaishali Naik)
- Model benchmarking (Birgit Hassler and Forrest Hoffman)
- Model documentation (David Hassell and Guillaume Levavasseur)
- Strategic ensemble design (Ben Sanderson and Isla Simpson)
- Fresh Eyes on CMIP (currently under evaluation)
The role of CMIP within the Modelling Multiverse
Need for multi-model ensembles beyond CMIP6

- CMIP - provides proven method for testing/validating climate models.
- Enhanced process understanding enabled by improved model fidelity, increased complexity and resolution (e.g., emergent properties).
- Hypothesis testing using climate change projections based on new, updated, and extended scenarios. CMIP infrastructure enables this.
- New observational comparison opportunities emerged that motivate new diagnostics and MIPs (e.g., SWOT, EMIT, BGC Argo – also obs4MIPs).
- CMIP - key international climate service (serves IPCC, policymakers).
- An extended ‘gap’ in CMIP delivery could result in poorer quality climate information being used by the policy and downstream user community.
CMIP Infrastructure

- Leveraging the CMIP6 infrastructure to benefit wider WCRP activities (CMIP6Plus).
- New and ongoing MIP activities can request guidance and limited support.
- Enable responsive activities (e.g., CovidMIP, ZECMIP, LESFMIP, CERESMIP, RAMIP, ...).
- Support CMIP and wider activities’ evolution and potential operationalisation of components (e.g., testing next generation forcings).
- Determining a sustainable funding model for CMIP infrastructure.
CMIP6Plus: facilitating and enabling science

Can we leverage existing infrastructure investments, while not waiting?

- Agile, responsive evolution
  - Continuous DECK is a start
  - Facilitate, respond and enable science opportunities
    - CovidMIP, ZECMIP/C4MIP

- Allow CMIP to evolve and “operationalise”
  - Incremental change (e.g., maintain ESGF dependence)
  - Next generation forcings and observations
  - Change little, increment and allow modelling groups to focus on science

- Best prepare CMIP for exascale and the AI/ML onslaught.
CMIP6Plus: facilitating and enabling science

Can we leverage existing infrastructure investments, while not waiting?

- Continue beyond CMIP6 with few changes as CMIP7 is planned
  - Reduce time pressures – loosen CMIPx to IPCC ARx linkage
  - Continuous CMIP science – move away from monolithic ~7 year phases

- Facilitate and recognise contributors
  - Ensure all contributions are recognised
  - How can we support forcing data providers?
  - Funding? (“CMIP endorsed” data provider)
  - Infrastructure support?
Looking forward: CMIPnext ideas

Can we optimise to meet science goals without bloating the archive?

- Not just data request – rather, MIPs provide diagnostics/code to implement
  - Rather than requesting data, request the targeted diagnostic
  - Plus = less data, minus = locks out spontaneous science opportunities

- MIPs define diagnostics to implement within models
  - Advance the inclusion of key simulators (e.g., COSP)
  - Encourage MIP diagnostic team development – move workload to MIP chairs, not modellers

- How to best leverage community diagnostics
  - ESMValTool, CMEC (Coordinated Model Evaluations Capabilities), NOAA-MDTF

- Amalgamate efforts to reduce overheads (e.g., input4MIPs, obs4MIPs)
Climate forcing

- *MIP history proved external climate forcing matters
- Historical forcings are keys to climate change attribution
- Future forcing will determine future state (accurate projection/predictions)
- input4MIPs began the process
  - CMIP forcing dataset coordination
  - Version control and documentation
- Beyond CMIP6
  - Evaluate, quantify and better understand uncertainties
  - Dataset harmonization across products
  - Quantify, version control and document forcings
  - Feedback on MIP experimental design through forcing evaluation
Climate forcing

(e) Radiative Forcing Components

(f) Energy Budget 1971-2018

IPCC AR6 WG1, 2021, Box 7.2 Fig 1 doi:10.1017/9781009157896.009
Forcings provision (including scenarios)

- Delays in forcing dataset provision were highly problematic during CMIP6.
- There is a need to update, and develop new forcing datasets with adequate time for robust evaluation before CMIP7 commences.
- Scenario development is increasingly important to ensuring policy makers have the information they will need to address post 2030 mitigation and adaptation planning.
- Forcings session at AGU23 in December 2023.
Evolving CMIP7 structure
CMIP7 will address WCRP science objectives

1. **Fundamental understanding of the climate system**
   - Help reconcile the observational refutation of high ECS models and their continued prevalence in the ensemble.

2. **Prediction of the near-term evolution of the climate system**
   - Assess forcing uncertainty e.g., the potential to explore sensitivity to high aerosol forcing.

Meehl et al. (2020)
CMIP7 will address WCRP science objectives

3 Long-term response of the climate system

Sea level rise will continue for millennia, but how fast and how much depends on future emissions.

- Sea level rise: observations and projections 2100, 2150, 2300 (relative to 1900)
  - Uncertainties in sea level rise and greenhouse gas emissions contribute to risk

Focus beyond 2100 including overshoots and e.g., how to better constrain sea level rise “deep uncertainty” under >3°C warming.

4 Bridging climate science and society

IPCC AR6 SYR
For the subset of CMIP7 experiments aimed at IPCC alignment, engagement with the new IPCC leadership is underway. Planning will coalesce in late 2023. Community MIPs do not need to align with that timeline, although they may choose to do so. Current estimates suggest:

- **Historical forcings**: Update expected, with data extending until December 2021 available by mid-2024 and revised in 2026 ([CMIP Forcings timeline – current status](#)).
- **Scenario forcings**: late 2026 ([link to ScenarioMIP pages](#)).
- **Data request**: Initial production versions expected early to mid-2025, with regular updates thereafter.
- **Modelling centres**: Consulting on expectations for when new models and associated infrastructure will be ready.
- **ESGF nodes**: ESGF needed to collate and serve the data. Ongoing discussions led by the WIP and ESGF community.
- **CMIP7 description paper**: Intention for submission in 2024.
Coordinated Model Evaluation Capabilities (CMEC)

- Effort to bring together a diverse set of analysis packages developed to facilitate Earth System Model systematic evaluation
  - PCMDI Metrics Package (PMP)
  - International Land Model Benchmarking Package (ILAMB)
  - Toolkit for Extremes Climate Analysis (TECA)
- Technical alignment, providing a simple and consistent driver interface across all contributing modules
- Coordinates and organizes output data produced by CMEC packages

https://cmec.llnl.gov
The PCMDI Metrics Package (PMP)

The PCMDI Metrics Package (PMP) provides a diverse suite of relatively robust high-level summary statistics that gauge differences between models and observations. The emphasis is on the physical system in Earth System Models (ESMs) and their component sub-models. The PMP provides holistic summaries spanning space and time scales for the simulated atmosphere, ocean, ice and land with the CMTEC examples available on this site highlighting atmospheric characteristics.

The goals of the PMP are to:

- Provide objective performance summaries of all CMIP6/DEC and Historical simulations.
- Incorporate results spanning six generations of CMIP/AMIP, and to track performance changes through eras of climate model evolution.
- Enable modeling groups to use the PMP in their own analysis/development workflow, so to generate near-instant feedback at the time of the model simulation completion, rather than wait for feedback through the multi-year process that occurs through peer publication.
- Collaborate with US and international expert teams to further diversify the suite of objective tests and expand these in new and novel ways.
- Further leverage and advance the conventions and protocols that were developed by PCMDI for CMIP, and use these to facilitate open-source software collaboration across research groups and institutions.

The PMP summaries include metrics from PCMDI’s research, which rely on several summary diagrams designed by PCMDI (Taylor, 2001; Gleckler et al., 2008) that are now widely adopted by the research community. Well-established metrics generated by various expert teams (e.g., CCVAR Pacific Region Panel for ENSO) are being implemented into the PMP. The software leverages advanced Python-based model analysis tools that have been developed with over two decades of support from the U.S. Department of Energy, along with the Earth System Grid Federation (ESGF), CMIP6, CMIP5, CMIP3 and earlier data holdings based on site at LLNL.

As PMP development continues, we welcome collaborations from modeling groups and expert teams to further expand and improve the comprehensiveness of the calculated metrics.

Quick links: Repository, Installation, CMIP5/6 AMIP and Historical Results, CMIP5/6 interannual variability.

Contact: Peter J. Gleckler (gleckler1@llnl.gov)

https://pcmdi.llnl.gov/research/metrics/
While the datasets and software found on this site can be used to contrast models, we also maintain a collection of results for the community use. Below is a short description of each along with a preview and links to the full results pages.

**Land Comparison of CMIP5 and CMIP6 Models**
We examine the performance of historical simulations from a selection of coupled Earth system models with a contribution in the CMIP6 and CMIP6 era.

**Land Comparison of CMIP5 Models**
This land-focused study includes coupled model results for the historical experiment from the CMIP5 era. We also use this as a testing ground to include new datasets and additional models. If you have a suggestion of a reference dataset or would like to request we include a model, please raise an issue.

**Land Comparison of Offline CMIP5 Models**
We examine performance differences among a selection of land models (CLM, ISBA-CTMRI, and JSBACH) run using different forcings (CMIP5, CRU, and Fnotation).

**Ocean Comparison of CMIP5 and CMIP6 Models**
While the focus of ILAMB has been on land, we also have used the software to compare ocean model output which we refer to as International Ocean Model Benchmarking (IOMB). This study is analogous to the land comparison of CMIP5 and CMIP6 era models over the historical period.

https://www.ilamb.org
Earth System Metrics and Diagnostics Standards (EMDS)

The Earth System Metrics and Diagnostics Standards serve as a guidance document for the design of Earth system metrics and diagnostics based software utilities. The standards document provides requirements for software interfaces, metadata, and metrics output format that are designed to promote the interoperability of software packages and reproducibility of results.

Standards document

The Earth System Metrics and Diagnostics Standards can be accessed in this repository at standards.md. This is a living document that can be updated at any time. The procedures for updating the standards is provided in the Governance section.

Background and aims

The Earth System Metrics and Diagnostics Standards arose from a collaboration on common standards between the National Oceanic and Atmospheric Administration Model Diagnostics Task Force (MDTF), https://www.mdtf.noaa.gov, and the Department of Energy Coordinated Model Evaluation Capabilities (CMEC) effort https://cmecc.ornl.gov. The MDTF-CMEC coordination has been a bottom-up scientific collaboration, initiated in 2018 by P. Ullrich (CMEC) and D. Neelin (MDTF), recognizing the usefulness of a common standard and design commonalities that facilitate this.

The EMDS aims to foster interoperability of climate and weather model evaluation tools across agencies and among research groups, facilitating the flow of diagnostics from process research to improvement of climate models and helping to create a natural continuum between performance metrics and process oriented diagnostics. Outreach to additional agencies with related model evaluation requirements is underway.

Projects

Projects that make use of these standards include Coordinated Model Evaluation Capabilities (CMEC) and NOAA Model Diagnostics Task Force (MDTF).

CMEC
LLNL, ORNL, LBNL
Dept of Energy

NOAA-MDTF
NOAA-GFDL, UCLA, U/NCAR, PNNL, Colorado State, Florida State, UCD, UW
Dept of Commerce/NOAA

https://github.com/
Earth-System-Diagnostics-Standards
Thank You!

Questions, suggestions..?

durack1@llnl.gov

Contact cmip-ipo@esa.int with any questions or feedback.
More information can be found at wcrp-cmip.org
Extra slides
CF Metadata Conventions

The CF metadata conventions are designed to promote the processing and sharing of files created with the NetCDF API. The conventions define metadata that provide a definitive description of what the data in each variable represents, and the spatial and temporal properties of the data. This enables users of data from different sources to decide which quantities are comparable, and facilitates building applications with powerful extraction, regridding, and display capabilities. The CF convention includes a standard name table, which defines strings that identify physical quantities.

Conventions: Latest release [1.19] HTML PDF ➤ Working draft HTML PDF
Vocabularies: Standard names ➤ Area types ➤ Standardized regions

CF is developed through open discussion on GitHub. If you would like to propose a change, make a suggestion, report a problem or ask a question, please see here. Changes are decided according to the CF governance arrangements. The CF community embraces a philosophy of producing excellence by maintaining an open and welcoming culture and an environment that promotes debate and inquiry in a respectful, broad and intellectually rigorous fashion.

Initially CF was developed for gridded data from climate and forecast models (hence “CF”) of the atmosphere and ocean, but its use has subsequently extended to other geosciences, and to observations as well as numerical models. The use of CF is recommended where applicable by Unidata.

Quick links
See also the links in the navigation bar at the top of this page.

- Current issues: general discussion (including standard names), conventions, this website (including governance)
- CF GitHub organisation
- CF FAQ
- List of software for working with CF
- Paper describing the CF data model and reference software
- Overview of CF basics as a presentation and paper

Contact the CF community with questions, comments and suggestions about CF metadata or this website

This site is open source. Improve this page!

http://cfconventions.org
https://github.com/PCMDI/mip-cmor-tables/
**Time-evolving *MIP external forcing**

<table>
<thead>
<tr>
<th>Forcing/MIP era</th>
<th>AMIP1</th>
<th>AMIP2</th>
<th>CMIP1</th>
<th>CMIP2</th>
<th>CMIP3(^a)</th>
<th>CMIP5(^b)</th>
<th>CMIP6(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SST &amp; sea ice</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
<td>Y (AMIP)</td>
<td>Y (AMIP)</td>
<td>✓ (AMIP)</td>
</tr>
<tr>
<td>Greenhouse gases</td>
<td>Y (fixed: CO(_2), CH(_4), N(_2)O)</td>
<td>Y (fixed)</td>
<td>Y (fixed and 1% idealized)</td>
<td>Y (~5 species)</td>
<td>Y (~9 species)</td>
<td>✓ (46 species)</td>
<td></td>
</tr>
<tr>
<td>Ozone</td>
<td>Y?</td>
<td>Y (fixed)</td>
<td>Y (fixed)</td>
<td>½</td>
<td>Y</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Sulphate aerosols (in/direct)</td>
<td></td>
<td></td>
<td>½ / Y</td>
<td>⅘ / Y</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black/Organic carbon</td>
<td></td>
<td></td>
<td>½ / ½</td>
<td>⅘</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land use change</td>
<td></td>
<td></td>
<td>⅓</td>
<td>⅔</td>
<td>✓ (4 states)</td>
<td></td>
<td></td>
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<tr>
<td>Solar irradiance</td>
<td>Y (fixed)</td>
<td>Y (fixed)</td>
<td>Y (fixed)</td>
<td>½</td>
<td>9/10</td>
<td>✓</td>
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<tr>
<td>Volcanic aerosols</td>
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<td>½</td>
<td>9/10 (3 variants)</td>
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<td></td>
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<tr>
<td>Nitrogen deposition</td>
<td></td>
<td></td>
<td></td>
<td>✓ (4 species)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total varying forcings</strong></td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1 (idealized)</td>
<td>~15</td>
<td>~24</td>
<td>~63</td>
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</table>