Supplement of "FASTMIP-CMIP7: A Coordinated Multi-Emulator Ensemble for Rapid, Spatially Resolved Climate Projections under CMIP7 Scenarios"

1 EXTENDED RESULTS

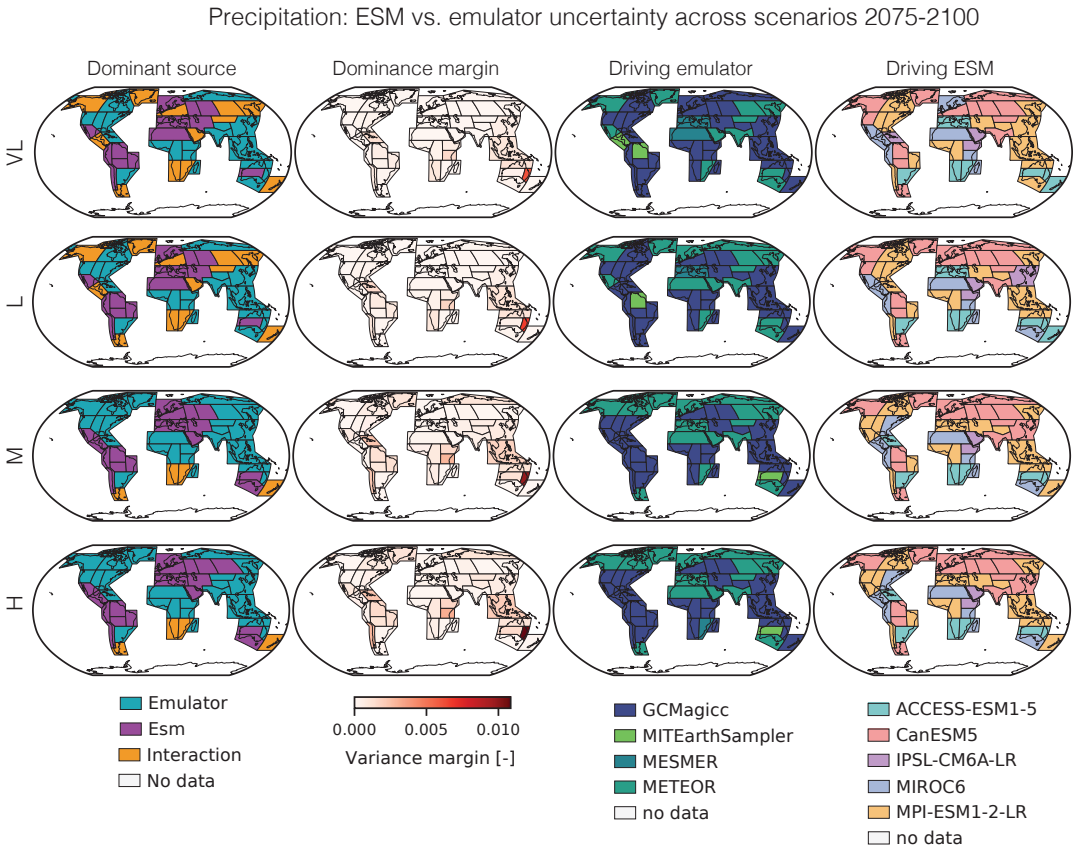


Figure S1. Relative importance of ESM vs. emulator choice in variance decomposition. Color scale indicates the deviation between the standard deviation from ESMs and emulators. Blue areas: the spread in ESMs exceeds the spread from emulators and red vice vers.

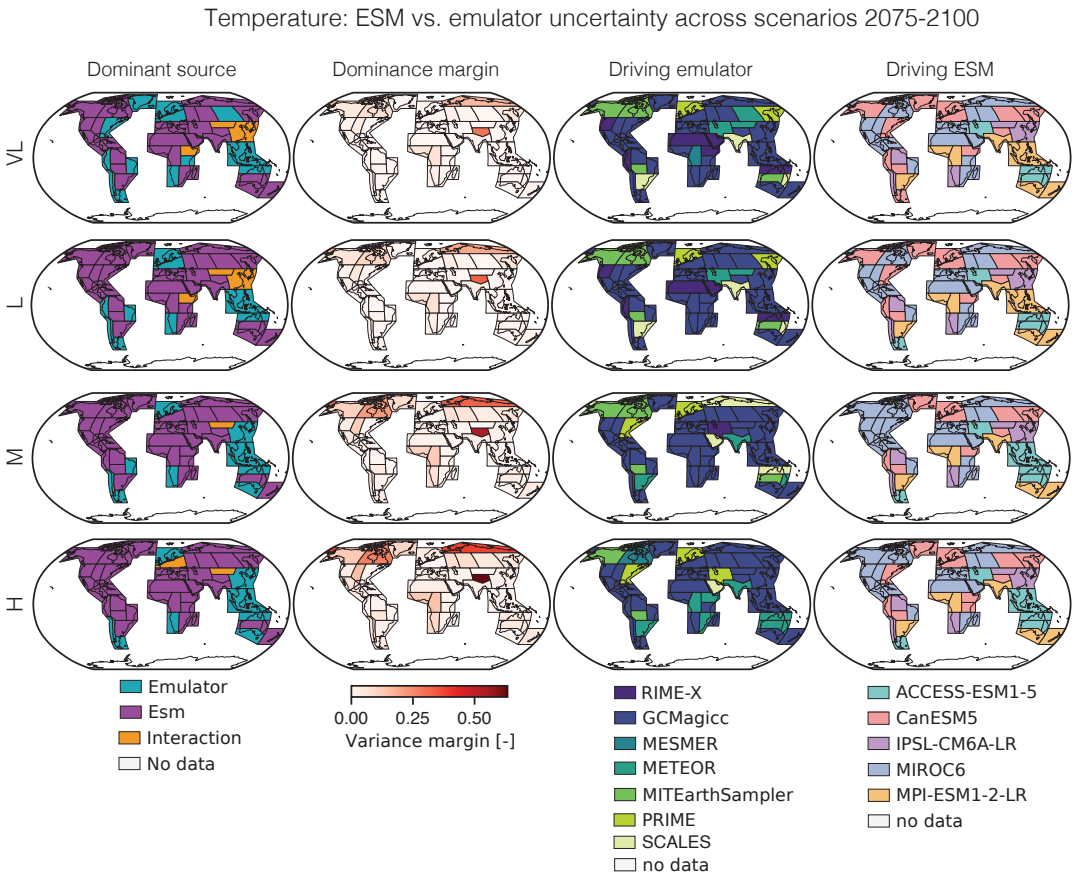


Figure S2. Relative importance of ESM vs. emulator choice in variance decomposition. Color scale indicates the deviation between the standard deviation from ESMs and emulators. Blue areas: the spread in ESMs exceeds the spread from emulators and red vice vers.

2 CMIP6 EARTH SYSTEM MODELS

Table S1. Number of ensemble members available for each model and scenario as per the Brunner archive.

scenario model	ssp119	ssp126	ssp245	ssp370	ssp534-over	ssp585
ACCESS-CM2	0	10	5	5	0	10
ACCESS-ESM1-5	0	40	40	40	0	40
AWI-CM-1-1-MR	0	1	1	5	0	1
BCC-CSM2-MR	0	1	1	1	0	1
CESM2	0	5	6	8	0	5
CESM2-WACCM	0	1	5	1	3	5
CNRM-CM6-1	0	6	6	6	0	6
CNRM-ESM2-1	5	5	10	5	0	5
CanESM5	50	50	50	50	5	50
CanESM5-1	2	2	20	20	0	20
EC-Earth3	52	59	73	58	50	58
FGOALS-g3	1	4	4	5	0	4
FIO-ESM-2-0	0	3	3	0	0	3
GFDL-ESM4	1	1	3	1	0	1
GISS-E2-1-G	2	10	15	22	6	10
HadGEM3-GC31-LL	0	1	5	0	0	4
HadGEM3-GC31-MM	0	1	0	0	0	4
IPSL-CM6A-LR	6	6	11	11	1	7
MIROC-ES2L	10	10	30	10	0	10
MIROC6	50	50	50	50	1	50
MPI-ESM1-2-HR	0	2	2	10	0	2
MPI-ESM1-2-LR	50	50	50	50	0	50
MRI-ESM2-0	5	5	5	5	1	6
NorESM2-LM	0	1	4	1	1	1
UKESM1-0-LL	5	16	17	16	5	5

3 PROTOCOL

Table S2. FASTMIP Phase 2 modelling protocol. Tiers 2A–2C are independent extensions along separate axes and may be combined in any way, so a group may for example submit monthly output for the five core ESMs while submitting annual output for all 25. All tiers are run for the four CMIP7 scenarios (VL, L, M, H) and forced by a common FaIR ensemble. Groups new to Phase 2 additionally repeat the Phase 1 SSP–RCP experiments. ESMs are listed in Table S3.

Tier	Description	Specification
1	Baseline	Default ESMs; annual; near-surface air temperature and precipitation
2A	Additional ESMs	Output for 25 total ESMs
2B	Increased temporal resolution	Monthly data in place of annual
2C	Additional variables	Additional indicators are defined by individual emulator groups and may not be shared between groups. Examples include crop yields, relative/specific humidity, and climate impact drivers

Table S3. ESMs emulated in FASTMIP Phase 2. The five Tier 1 models were selected on the basis of data availability and TCRE. Models are listed alphabetically within each tier.

Tier	ESM	Reference
1	ACCESS-ESM1-5	[1]
	CanESM5	[2]
	IPSL-CM6A-LR	[3]
	MIROC6	[4]
	MPI-ESM1-2-LR	[5]
2	ACCESS-CM2	[6]
	AWI-CM-1-1-MR	[7]
	BCC-CSM2-MR	[8]
	CanESM5-1	[9]
	CESM2	[10]
	CESM2-WACCM	[11]
	CNRM-CM6-1	[12]
	CNRM-ESM2-1	[13]
	EC-Earth3	[14]
	FGOALS-g3	[15]
	FIO-ESM-2-0	[16]
	GFDL-ESM4	[17]
	GISS-E2-1-G	[18]
	HadGEM3–GC31-LL	[19]
	HadGEM3–GC31-MM	[20]
	MIROC-ES2L	[21]
	MPI-ESM1-2-HR	[5]
	MRI-ESM2-0	[22]
	NorESM2-LM	[23]
	UKESM1-0-LL	[24]

Table S4. Emulator participation. Columns give temporal resolution and ESM coverage; entries give the variable set delivered for that combination: C = core (tas, pr), E = extended (Tier 2C variables in addition to the core). A dash denotes no submission. The annual, five-ESM column corresponds to Tier 1 and is the minimum requirement.

	Annual		Monthly	
Emulator	5 ESMs	25 ESMs	5 ESMs	25 ESMs
GCMagicc	E	–	E	–
MESMER	C	C	C	C
METEOR	C	–	C	–
MIT-EarthSampler	C	–	C	–
PRIME	C	–	–	–
RIME/RIME-X	E	–	E	–

Table S5. Overview of participating emulators and their native specifications. Input: the global quantity used to drive the emulator (GSAT: global surface air temperature; GSAT: global mean surface air temperature; ERF: effective radiative forcing; SCM: simple climate model). Output variables: variables the emulator can provide natively; not all were submitted to FASTMIP-CMIP7 (see Supplementary Table S4). Uni/multi: whether variables are emulated independently (uni), jointly for two variables (bi), or jointly for several variables with cross-variable dependence (multi). Spatial and temporal resolution: native output resolution before regridding to the common $2.5° \times 2.5°$ FASTMIP grid. Available ESMs: CMIP6 models for which the emulator has been trained. Method: core statistical or machine-learning approach, including how internal variability is generated. Comment: further dependencies and caveats.

Model	Input	Output variables	Uni/multi	Spatial res.	Temporal res.	Available ESMs	Method	Comment
MESMER								
MESMER	GSAT	Mean temperature	uni	2.5×2.5	annual	72 CMIP6 ESMs	Pattern scaling + VAR(1) process with empirically estimated & localized covariance matrix	Relies on an SCM to generate GSAT data
MESMER-M	MESMER output	Mean temperature	uni	2.5×2.5	monthly	72 CMIP6 ESMs	Harmonic model + VAR(1) process with empirically estimated & localized covariance matrix	—
MESMER-M-TP	MESMER-M output	Mean temperature, mean precipitation	bi	2.5×2.5	monthly	24 CMIP6 ESMs	Generalized Linear Model + KDE	—
MESMER-X	GSAT	TXx, FWIls, FWIsa, FWIxd, FWIxx, SM, SMmm, (Rx1day)	uni	2.5×2.5	annual	26–58 CMIP6 ESMs	Conditional distributions with probability integral transform + VAR(1) process with empirically estimated & localized covariance matrix	Relies on an SCM to generate GSAT data
PRIME								
PRIME-PS	GSAT	Mean temperature, mean precipitation, diurnal temperature range, shortwave radiation, longwave radiation, near-surface specific humidity, 10m wind speed, surface pressure	uni	3.75×2.5	monthly	34 CMIP6 ESMs	Pattern scaling	Does not sample monthly variability; relies on an SCM to generate GSAT data

Model	Input	Output variables	Uni/multi	Spatial res.	Temporal res.	Available ESMs	Method	Comment
PRIME-Jules	PRIME-PS output and global CO2 concentrations	GPP, runoff (tested), other variables (?)	—	3.75×2.5	?	—	Pattern-scaled fields drive weather generator (IMOGEN) to produce hourly data, which – along with CO2 concentrations – drives JULES	—
RIME	GSAT	Cooling degree days, heatwave events, heatwave days, tropical nights, precipitation intensity index, (very) heavy precipitation days, (very) wet days, consecutive dry days, drought intensity, seasonality, inter-annual variability	uni	0.5×0.5	annual	6 CMIP6 ESMs (ISIMIP3b bias-adjusted & downscaled); 2 hydrological datasets	Time slicing/resampling	—

Model	Input	Output variables	Uni/multi	Spatial res.	Temporal res.	Available ESMs	Method	Comment
METEOR	GHG emissions or concentrations and aerosol emissions, results can be scaled to fit GSAT timeseris	Mean temperature, mean precipitation, heating degree days, cooling degree days, crop yields	uni	native ESM (no regrid-ding)	annual and monthly	Any CMIP6 model which ran DECK + historical and one scenario (METEOR training is fast and sparse, and the code includes automatic data pulls, preparation, caching and training for any models from the google zarray CMIP6 mirror, but can also operate on ESGF outputs, hence we do not store pre-trained versions of the model in repositories)	Pattern scaling with multiple patterns with separate timescales applied to global GHG & aerosol impulse response, seasonal grid-based deterministic function plus VAR-X PCA patterns of noise to create variability and seasonal cycles.	Relies on integrated Cicero-SCM emissions to forcing component to generate forcings from emissions and concentrations, but includes an option to scale to GSAT timeseries, this is how the FaIR forcing is implemented for FastMIP

Model	Input	Output variables	Uni/multi	Spatial res.	Temporal res.	Available ESMs	Method	Comment
GCMagicc	Decomposed ERF components (here from FaIR); model index and seasonal descriptors	tas, tasmax, tasmin, pr, hurs, huss, psl, rsds, sfcWind, ts	multi	HEALPix (hierarchical), regridded to 2.5×2.5	monthly	4 CMIP6 ESMs	Generative ML model (GCMagicc-PM configuration): deterministic bias terms plus a stochastic generator trained with an energy-score objective, producing spatio-temporally and cross-variable coherent realisations	Retrained independently for each ESM on its historical simulation; normally coupled to MAGICC, here forced with FaIR; ERA5 splicing and observational alignment not used
MIT-EarthSampler	GSAT	Temperature, precipitation, relative humidity, wind speed	multi	Native ESM	monthly; daily (MPI-only)	5 CMIP6 ESMs	Score-based diffusion model conditioned on pattern scaling kernels; generates monthly/daily realizations	Relies on an SCM to generate GSAT data

REFERENCES

[1] Tilo Ziehn, Matthew Chamberlain, Andrew Lenton, Rachel Law, Roger Bodman, Martin Dix, Yingping Wang, Peter Dobrohotoff, Jhan Srbinovsky, Lauren Stevens, Peter Vohralik, Chloe Mackallah, Arnold Sullivan, Siobhan O'Farrell, and Kelsey Druken. CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.2291.

[2] Neil Cameron Swart, Jason N.S. Cole, Viatcheslav V. Kharin, Mike Lazare, John F. Scinocca, Nathan P. Gillett, James Anstey, Vivek Arora, James R. Christian, Yanjun Jiao, Warren G. Lee, Fouad Majaess, Oleg A. Saenko, Christian Seiler, Clint Seinen, Andrew Shao, Larry Solheim, Knut von Salzen, Duo Yang, Barbara Winter, and Michael Sigmond. CCCma CanESM5 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.1317.

[3] Olivier Boucher, Sébastien Denvil, Guillaume Levavasseur, Anne Cozic, Arnaud Caubel, Marie-Alice Foujols, Yann Meurdesoif, Patricia Cadule, Marion Devilliers, Eliott Dupont, and Thibaut Lurton. IPSL IPSL-CM6A-LR model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.1532.

[4] Hiroaki Tatebe and Masahiro Watanabe. MIROC MIROC6 model output prepared for CMIP6 CMIP, 2018. URL http://cera-www.dkrz.de/WDCC/meta/CMIP6/CMIP6.CMIP.MIROC.MIROC6.

[5] Martin Schupfner, Karl-Hermann Wieners, Fabian Wachsmann, Christian Steger, Matthias Bittner, Johann Jungclaus, Barbara Früh, Klaus Pankatz, Marco Giorgetta, Christian Reick, Stephanie Legutke, Monika Esch, Veronika Gayler, Helmuth Haak, Philipp de Vrese, Thomas Raddatz, Thorsten Mauritsen, Jin-Song von Storch, Jörg Behrens, Victor Brovkin, Martin Claussen, Traute Crueger, Irina Fast, Stephanie Fiedler, Stefan Hagemann, Cathy Hohenegger, Thomas Jahns, Silvia Kloster, Stefan Kinne, Gitta Lasslop, Luis Kornblueh, Jochem Marotzke, Daniela Matei, Katharina Meraner, Uwe Mikolajewicz, Kameswarrao Modali, Wolfgang Müller, Julia Nabel, Dirk Notz, Karsten Peters-von Gehlen, Robert Pincus, Holger Pohlmann, Julia Pongratz, Sebastian Rast, Hauke Schmidt, Reiner Schnur, Uwe Schulzweida, Katharina Six, Bjorn Stevens, Aiko Voigt, and Erich Roeckner. DKRZ MPI-ESM1.2-HR model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.2450.

[6] Martin Dix, Daohua Bi, Peter Dobrohotoff, Russell Fiedler, Ian Harman, Rachel Law, Chloe Mackallah, Simon Marsland, Siobhan O'Farrell, Harun Rashid, Jhan Srbinovsky, Arnold Sullivan, Claire Trenham, Peter Vohralik, Ian Watterson, Gareth Williams, Matthew Woodhouse, Roger Bodman, Fabio Boeira Dias, Catia M. Domingues, Nicholas Hannah, Aidan Heerdegen, Abhishek Savita, Scott Wales, Chris Allen, Kelsey Druken, Ben Evans, Clare Richards, Syazwan Mohamed Ridzwan, Dale Roberts, Jon Smillie, Kate Snow, Marshall Ward, and Rui Yang. CSIRO-ARCCSS ACCESS-CM2 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.2285.

[7] Tido Semmler, Sergey Danilov, Thomas Rackow, Dmitry Sidorenko, Dirk Barbi, Jan Hegewald, Himansu Kesari Pradhan, Dmitri Sein, Qiang Wang, and Thomas Jung. AWI AWI-CM1.1MR model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.376.

[8] Xiaoge Xin, Tongwen Wu, Xueli Shi, Fang Zhang, Jianglong Li, Min Chu, Qianxia Liu, Jinghui Yan, Qiang Ma, and Min Wei. BCC BCC-CSM2MR model output prepared for CMIP6 ScenarioMIP, 2019. URL http://cera-www.dkrz.de/WDCC/meta/CMIP6/CMIP6.ScenarioMIP.BCC.BCC-CSM2-MR.

[9] Neil Cameron Swart, Jason N.S. Cole, Viatcheslav V. Kharin, Mike Lazare, John F. Scinocca, Nathan P. Gillett, James Anstey, Vivek Arora, James R. Christian, Yanjun Jiao, Warren G. Lee, Fouad Majaess, Oleg A. Saenko, Christian Seiler, Clint Seinen, Andrew Shao, Larry Solheim, Knut von Salzen, Duo Yang, Barbara Winter, Michael Sigmond, Carsten Abraham, Ayodeji Akingunola, and Catherine Reader. CCCma CanESM5.1 model output prepared for CMIP6 ScenarioMIP, 2019. URL http://cera-www.dkrz.de/WDCC/meta/CMIP6/CMIP6.ScenarioMIP.CCCma.CanESM5-1.

[10] Gokhan Danabasoglu. NCAR CESM2 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.2201.

[11] Gokhan Danabasoglu. NCAR CESM2-WACCM model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.10026.

[12] Aurore Voldoire. CNRM-CERFACS CNRM-CM6-1 model output prepared for CMIP6

ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.1384.

[13] Roland Seferian. CNRM-CERFACS CNRM-ESM2-1 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.1395.

[14] EC-Earth Consortium (EC-Earth). EC-Earth-Consortium EC-Earth3 model output prepared for CMIP6 ScenarioMIP, 2019. URL http://cera-www.dkrz.de/WDCC/meta/CMIP6/CMIP6.ScenarioMIP.EC-Earth-Consortium.EC-Earth3.

[15] Lijuan Li. CAS FGOALS-g3 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.2056.

[16] Zhenya Song, Fangli Qiao, Ying Bao, Qi Shu, Yajuan Song, and Xiaodan Yang. FIO-QLNM FIO-ESM2.0 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.9051.

[17] Jasmin G John, Chris Blanton, Colleen McHugh, Aparna Radhakrishnan, Kristopher Rand, Hans Vahlenkamp, Chandin Wilson, Niki T. Zadeh, John P. Dunne, Raphael Dussin, Larry W. Horowitz, John P. Krasting, Pu Lin, Sergey Malyshev, Vaishali Naik, Jeffrey Ploshay, Elena Shevliakova, Levi Silvers, Charles Stock, Michael Winton, and Yujin Zeng. NOAA-GFDL GFDL-ESM4 model output prepared for CMIP6 ScenarioMIP, 2018. URL http://cera-www.dkrz.de/WDCC/meta/CMIP6/CMIP6.ScenarioMIP.NOAA-GFDL.GFDL-ESM4.

[18] NASA Goddard Institute For Space Studies (NASA/GISS). NASA-GISS GISS-E2.1G model output prepared for CMIP6 ScenarioMIP, 2020. URL http://cera-www.dkrz.de/WDCC/meta/CMIP6/CMIP6.ScenarioMIP.NASA-GISS.GISS-E2-1-G.

[19] Peter Good. MOHC HadGEM3-GC31-LL model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.10845.

[20] Laura Jackson. MOHC HadGEM3-GC31-MM model output prepared for CMIP6 ScenarioMIP, 2020. URL https://doi.org/10.22033/ESGF/CMIP6.10846.

[21] Kaoru Tachiiri, Manabu Abe, Tomohiro Hajima, Osamu Arakawa, Tatsuo Suzuki, Yoshiki Komuro, Koji Ogochi, Michio Watanabe, Akitomo Yamamoto, Hiroaki Tatebe, Maki A. Noguchi, Rumi Ohgaito, Akinori Ito, Dai Yamazaki, Akihiko Ito, Kumiko Takata, Shingo Watanabe, and Michio Kawamiya. MIROC MIROC-ES2L model output prepared for CMIP6 ScenarioMIP, 2019. URL http://cera-www.dkrz.de/WDCC/meta/CMIP6/CMIP6.ScenarioMIP.MIROC.MIROC-ES2L.

[22] Seiji Yukimoto, Tsuyoshi Koshiro, Hideaki Kawai, Naga Oshima, Kohei Yoshida, Shogo Urakawa, Hiroyuki Tsujino, Makoto Deushi, Taichu Tanaka, Masahiro Hosaka, Hiromasa Yoshimura, Eiki Shindo, Ryo Mizuta, Masayoshi Ishii, Atsushi Obata, and Yukimasa Adachi. MRI MRI-ESM2.0 model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.638.

[23] Øyvind Seland, Mats Bentsen, Dirk Jan Leo Oliviè, Thomas Toniazzo, Ada Gjermundsen, Lise Seland Graff, Jens Boldingh Debernard, Alok Kumar Gupta, Yanchun He, Alf Kirkevåg, Jörg Schwinger, Jerry Tjiputra, Kjetil Schanke Aas, Ingo Bethke, Yuanchao Fan, Jan Griesfeller, Alf Grini, Chuncheng Guo, Mehmet Ilicak, Inger Helene Hafsahl Karset, Oskar Andreas Landgren, Johan Liakka, Kine Onsum Moseid, Aleksi Nummelin, Clemens Spensberger, Hui Tang, Zhongshi Zhang, Christoph Heinze, Trond Iversen, and Michael Schulz. NCC NorESM2-LM model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.604.

[24] Peter Good, Alistair Sellar, Yongming Tang, Steve Rumbold, Rich Ellis, Douglas Kelley, Till Kuhlbrodt, and Jeremy Walton. MOHC UKESM1.0-LL model output prepared for CMIP6 ScenarioMIP, 2019. URL https://doi.org/10.22033/ESGF/CMIP6.1567.