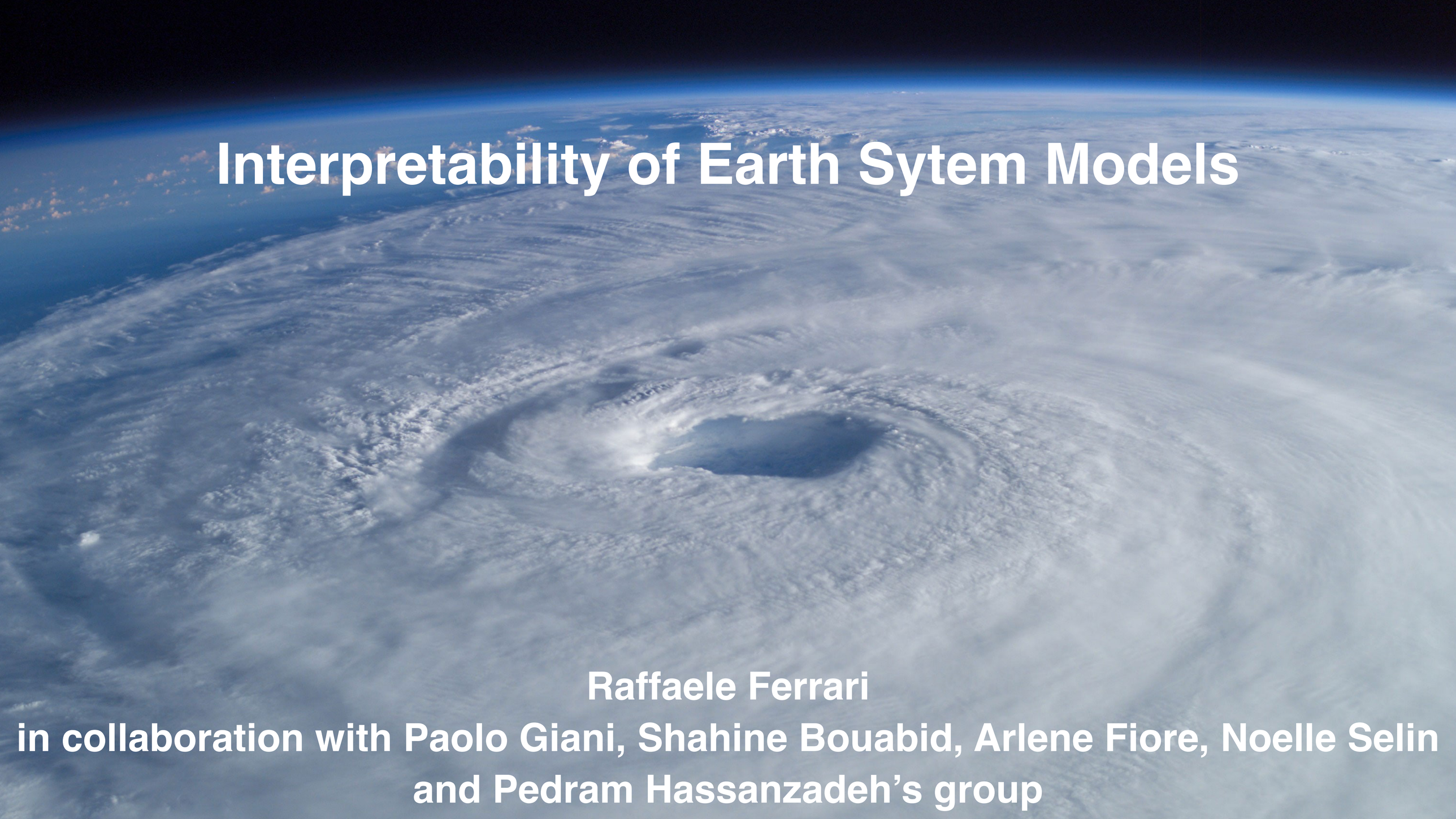


Interpretability of Earth Sytem Models

Raffaele Ferrari

in collaboration with Paolo Giani, Shahine Bouabid, Arlene Fiore, Noelle Selin and Pedram Hassanzadeh's group

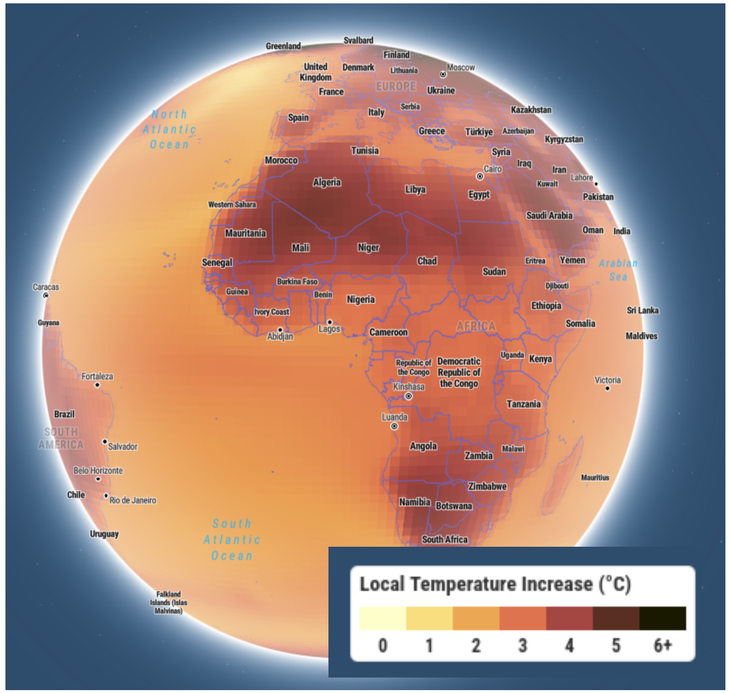


Paolo Giani

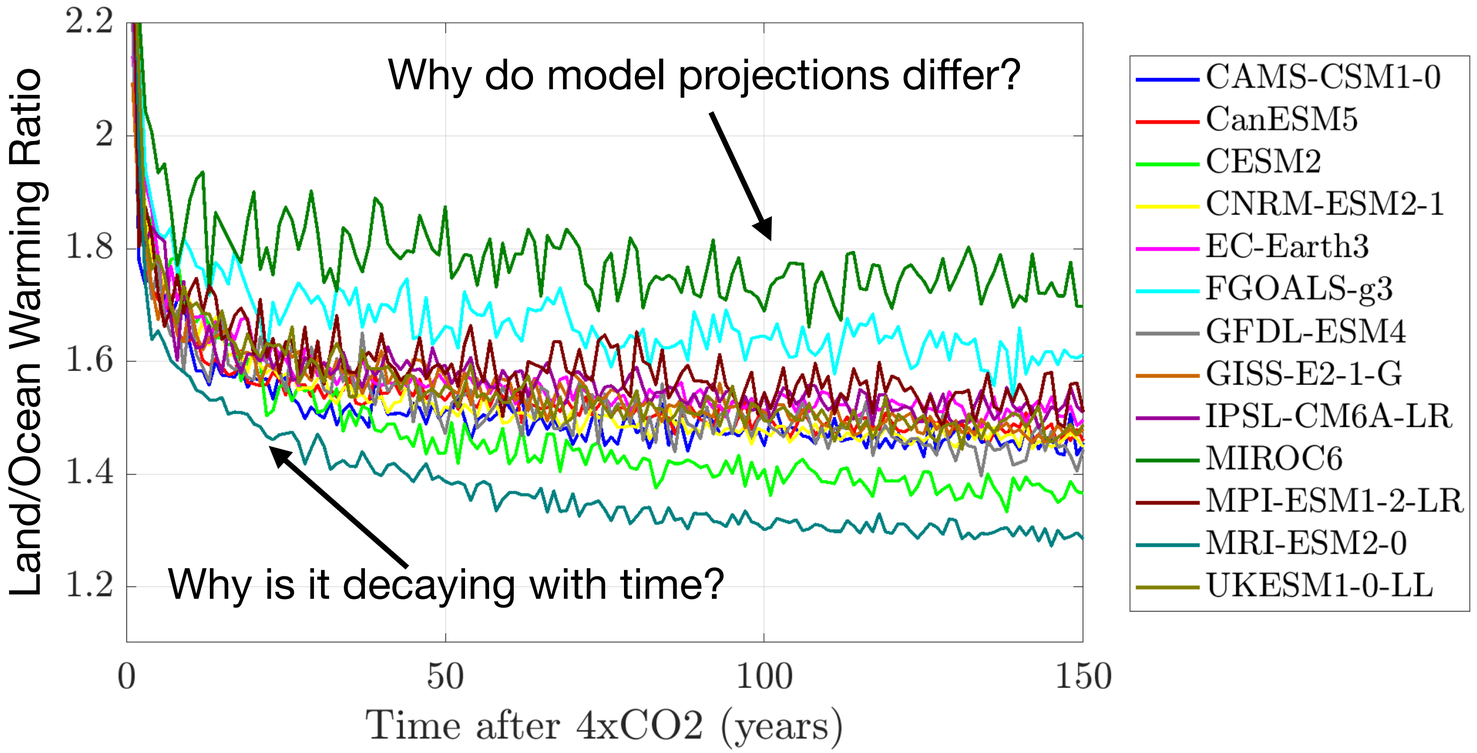
Interpretability of ESMs: algorithmic transparency does not guarantee interpretability

Learning physics with emulators of climate models

Projected end-of-century warming



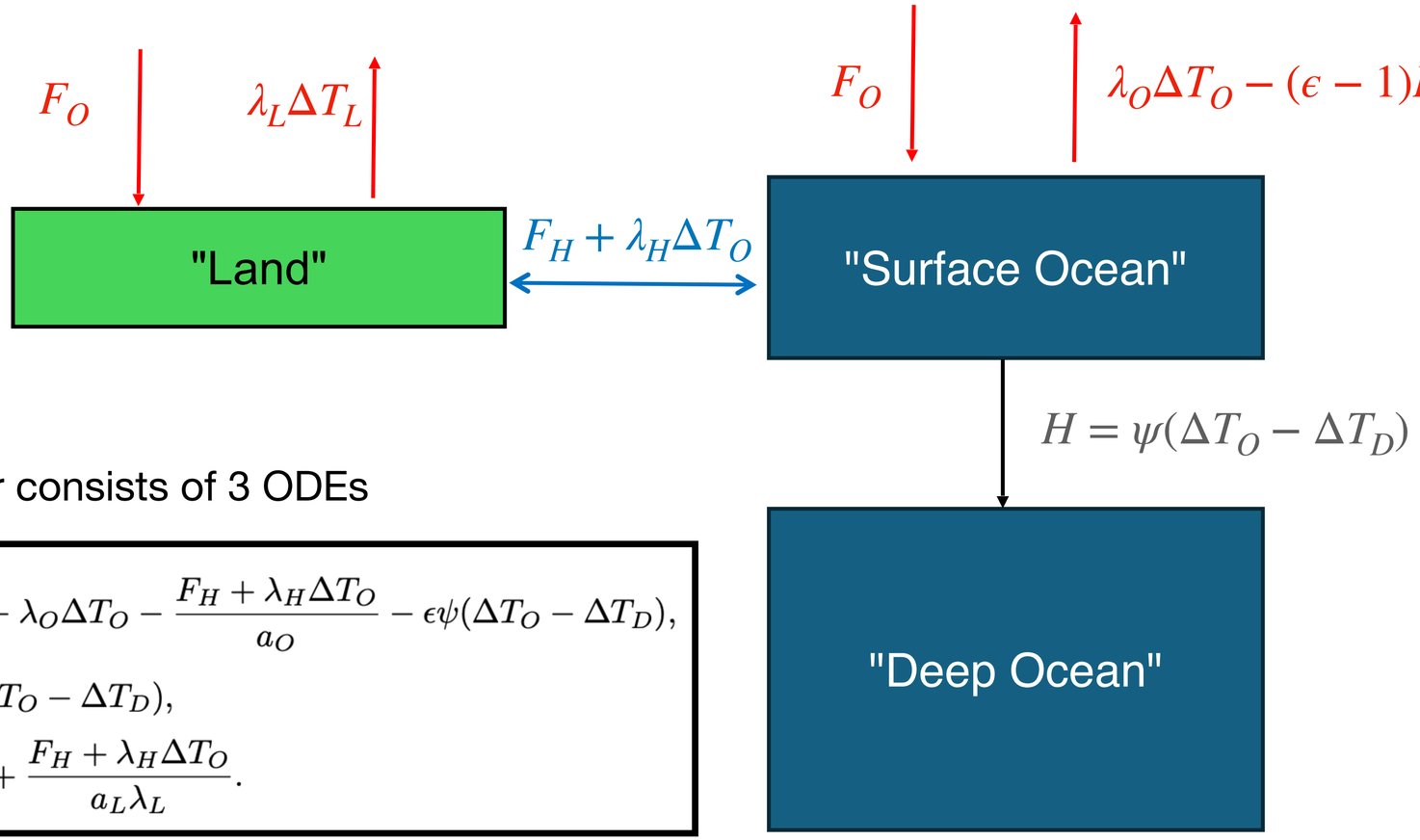
Why is Land/Ocean Contrast larger than 1?



Simple emulators can be helpful in answering these questions

Simple "emulator" for land/ocean temperature contrast

We balance radiative and dynamical energy fluxes, which are highly parameterized and rely on a few easy-to-interpret and tunable parameters

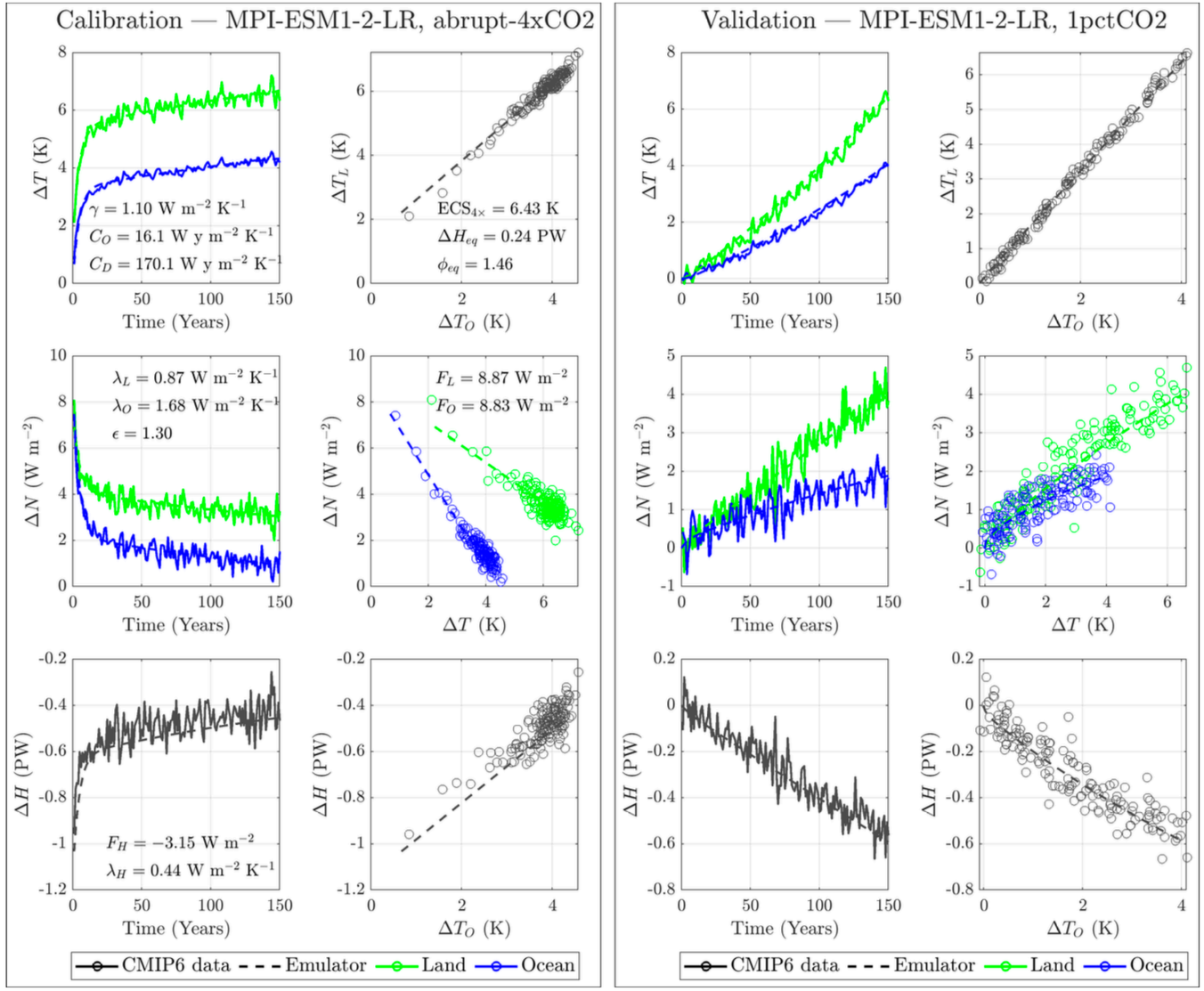


Emulator consists of 3 ODEs

$$C_O \frac{d\Delta T_O}{dt} = F_O - \lambda_O \Delta T_O - \frac{F_H + \lambda_H \Delta T_O}{a_O} - \epsilon\psi(\Delta T_O - \Delta T_D),$$
$$C_D \frac{d\Delta T_D}{dt} = \psi(\Delta T_O - \Delta T_D),$$
$$\Delta T_L = \frac{F_L}{\lambda_L} + \frac{F_H + \lambda_H \Delta T_O}{a_L \lambda_L}.$$

Paolo Giani , *Arlene Fiore, Raffaele Ferrari,* Paul O'Gorman, Vincent Cooper, *Noelle Selin, submitted*

Calibration/validation of emulator parameters with CMIP6



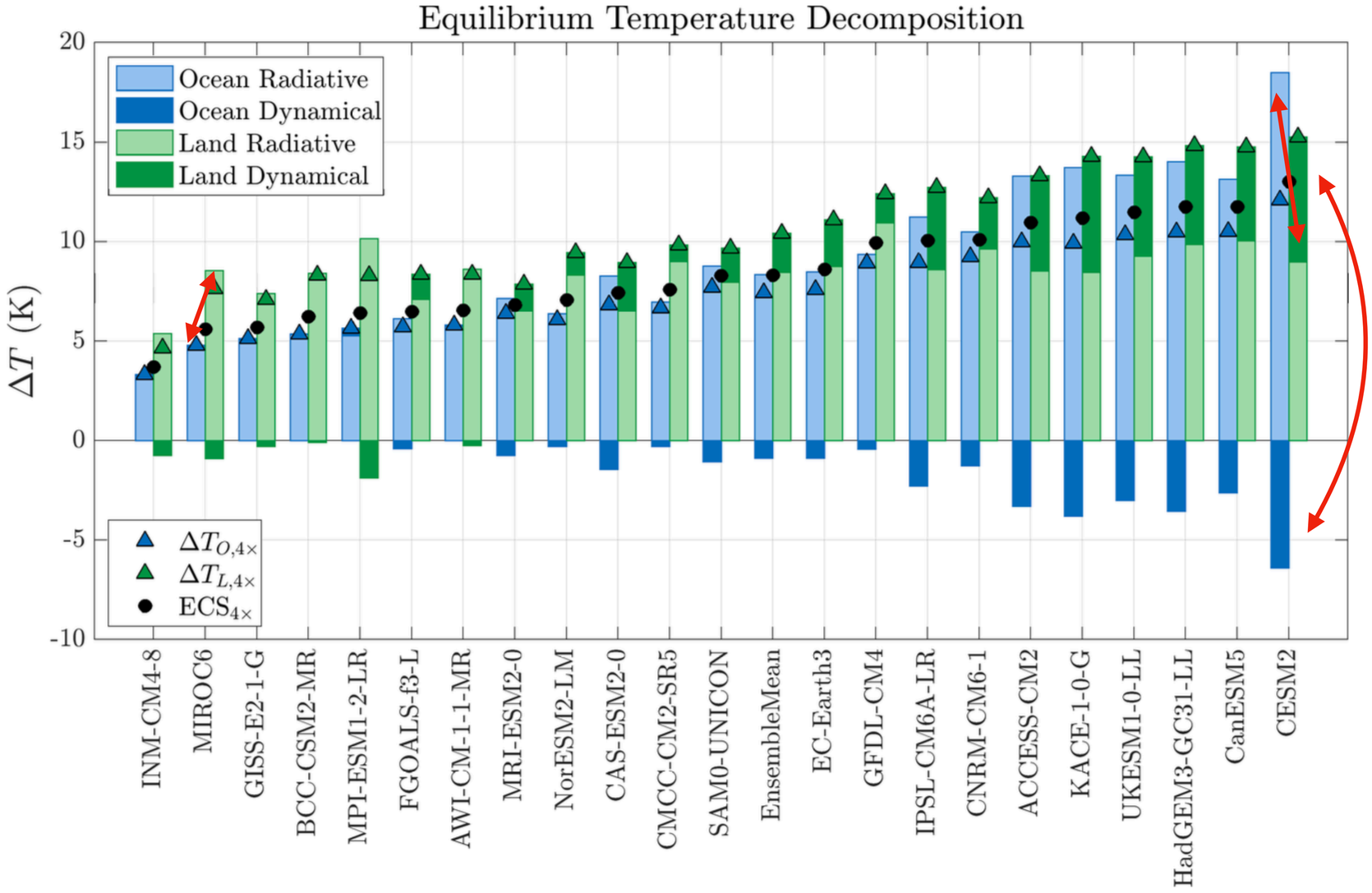
Paolo Giani , *Arlene Fiore, Raffaele Ferrari,* Paul O'Gorman, Vincent Cooper, *Noelle Selin, submitted*

Calibration/validation of emulator parameters with CMIP6

	$F_{O,4\times}$	$F_{L,4\times}$	$F_{H,4\times}$	λ_O	λ_L	λ_H	ψ	ϵ	$\mathrm{ECS}_{4\times}$	ϕ_{eq}
Ensemble Average	7.26	8.09	-0.99	0.87	0.96	0.17	1.00	1.36	8.31	1.40
ACCESS-CM2	7.07	7.60	-0.89	0.53	0.89	0.15	0.86	1.38	10.97	1.33
AWI-CM-1-1-MR	7.87	8.99	-1.13	1.37	1.04	0.19	0.86	1.32	6.57	1.44
BCC-CSM2-MR	6.09	7.55	-0.94	1.15	0.90	0.17	1.21	1.22	6.21	1.55
CAS-ESM2-0	6.99	8.03	-0.90	0.84	1.23	0.20	0.86	1.33	7.45	1.31
CESM2	7.55	9.05	-1.09	0.41	1.01	0.17	0.95	1.63	13.02	1.26
CMCC-CM2-SR5	7.85	8.68	-1.07	1.11	0.97	0.18	0.94	1.37	7.67	1.47
CNRM-CM6-1	7.08	7.71	-0.91	0.67	0.80	0.13	0.94	1.06	10.11	1.32
CanESM5	7.49	7.74	-0.96	0.57	0.77	0.14	0.85	1.11	11.75	1.40
EC-Earth3	7.47	6.99	-0.85	0.88	0.80	0.15	0.84	1.21	8.62	1.46
FGOALS-f3-L	9.31	8.17	-1.00	1.51	1.15	0.21	1.01	1.46	6.52	1.46
GFDL-CM4	8.49	6.92	-0.89	0.91	0.63	0.12	1.00	1.88	9.95	1.39
GISS-E2-1-G	7.92	8.93	-1.06	1.57	1.21	0.20	1.20	1.16	5.71	1.38
HadGEM3-GC31-LL	6.66	8.08	-0.98	0.47	0.82	0.15	0.84	1.19	11.75	1.41
INM-CM4-8	5.46	6.48	-0.81	1.75	1.20	0.20	0.94	1.20	3.71	1.40
IPSL-CM6A-LR	7.18	7.35	-0.85	0.64	0.85	0.15	0.62	1.33	10.06	1.42
KACE-1-0-G	7.10	6.87	-0.89	0.52	0.81	0.16	1.49	1.38	11.23	1.44
MIROC6	7.87	7.10	-0.88	1.71	0.83	0.16	1.11	1.31	5.62	1.60
MPI-ESM1-2-LR	8.83	8.87	-1.14	1.68	0.87	0.16	1.10	1.30	6.43	1.46
MRI-ESM2-0	5.97	7.38	-0.91	0.83	1.13	0.18	1.29	1.10	6.83	1.23
NorESM2-LM	10.00	8.21	-1.05	1.57	0.99	0.20	1.26	2.42	7.07	1.55
SAM0-UNICON	7.85	10.75	-1.25	0.89	1.35	0.21	1.01	1.44	8.29	1.25
UKESM1-0-LL	7.58	7.67	-0.88	0.57	0.83	0.14	0.83	1.19	11.49	1.38

Paolo Giani , *Arlene Fiore, Raffaele Ferrari,* Paul O'Gorman, Vincent Cooper, *Noelle Selin, submitted*

Interpreting the ESM land/ocean warming difference



Paolo Giani , *Arlene Fiore, Raffaele Ferrari,* Paul O'Gorman, Vincent Cooper, *Noelle Selin, submitted*

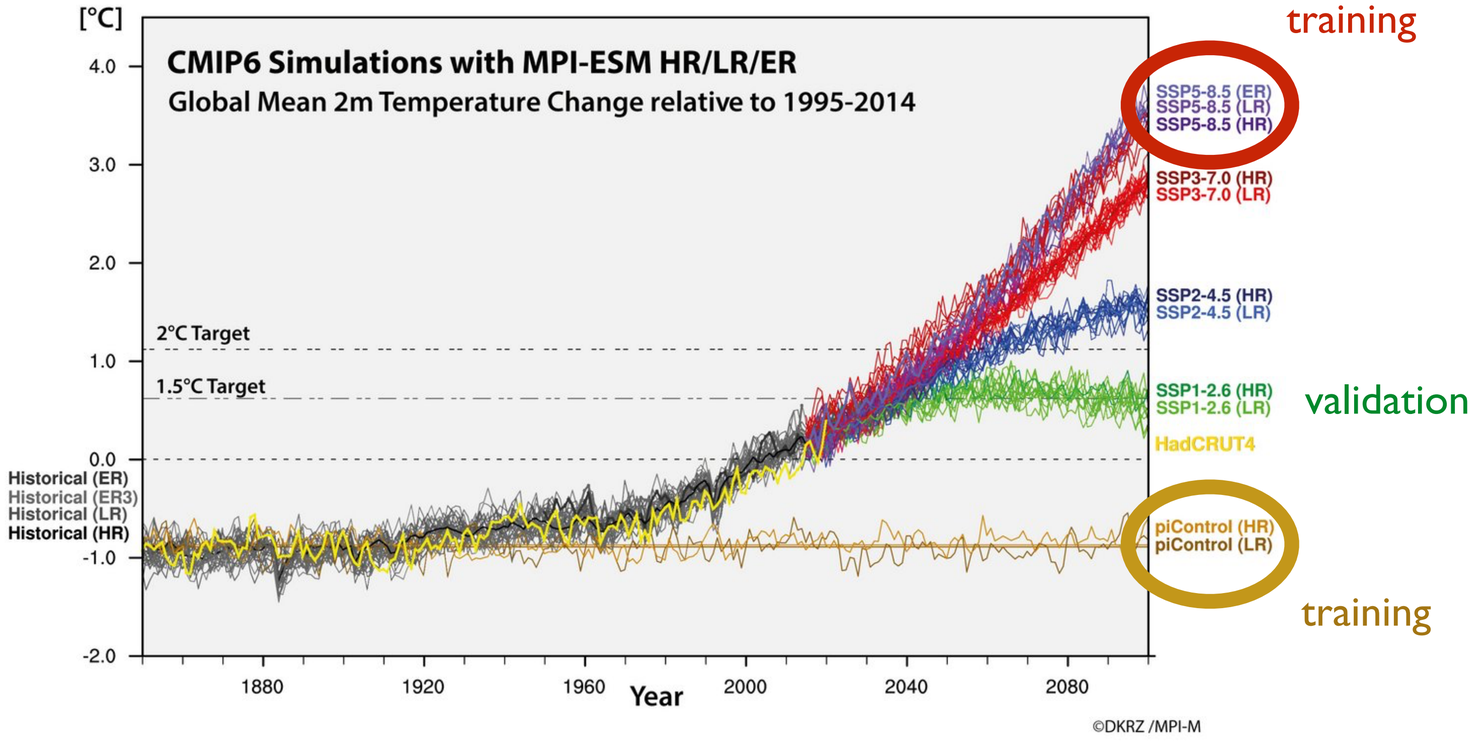


Shahine Bouabid

Interpretability of ESM emulators: validation on emergent properties

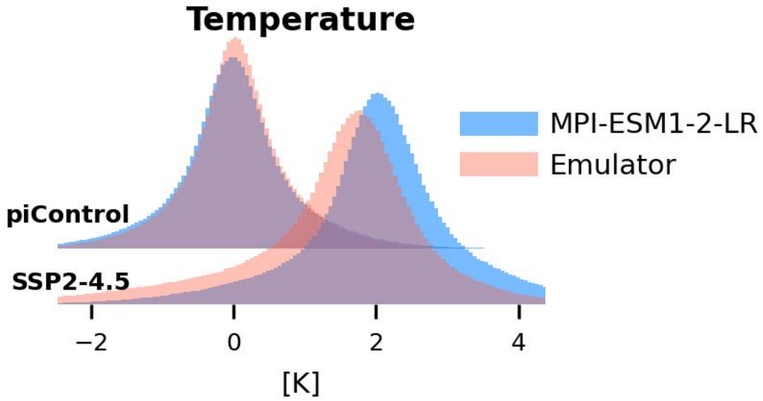
MIT Earthsampler: score-based diffusion emulator

Model: CMIP 6, Max-Planck Institute Model
Given Information: Global Mean Surface Temperature
Training: historical + SSP5-8.5
Testing: SSP1-2.6



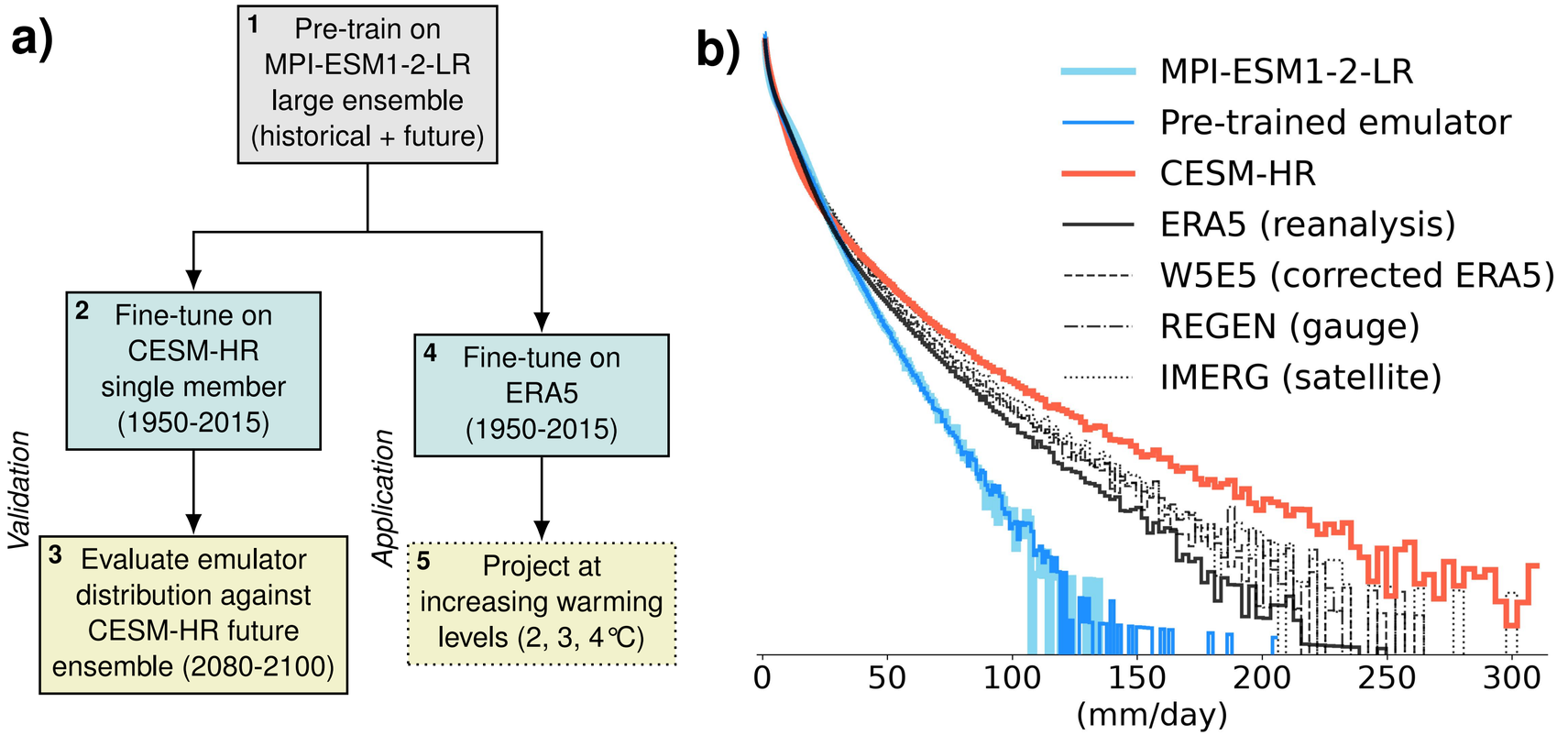
MIT Earthsampler formulation

$$PDF(T, q, , p, u, v \mid GMST)$$



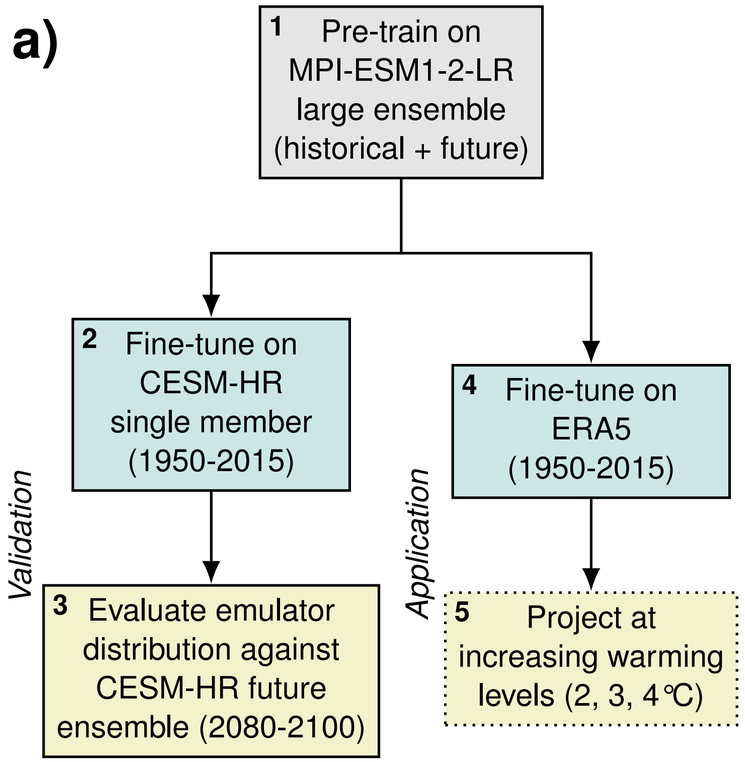
Shahine Bouabid, *Andre Souza, Raffaele Ferrari, JAMES, 2026*

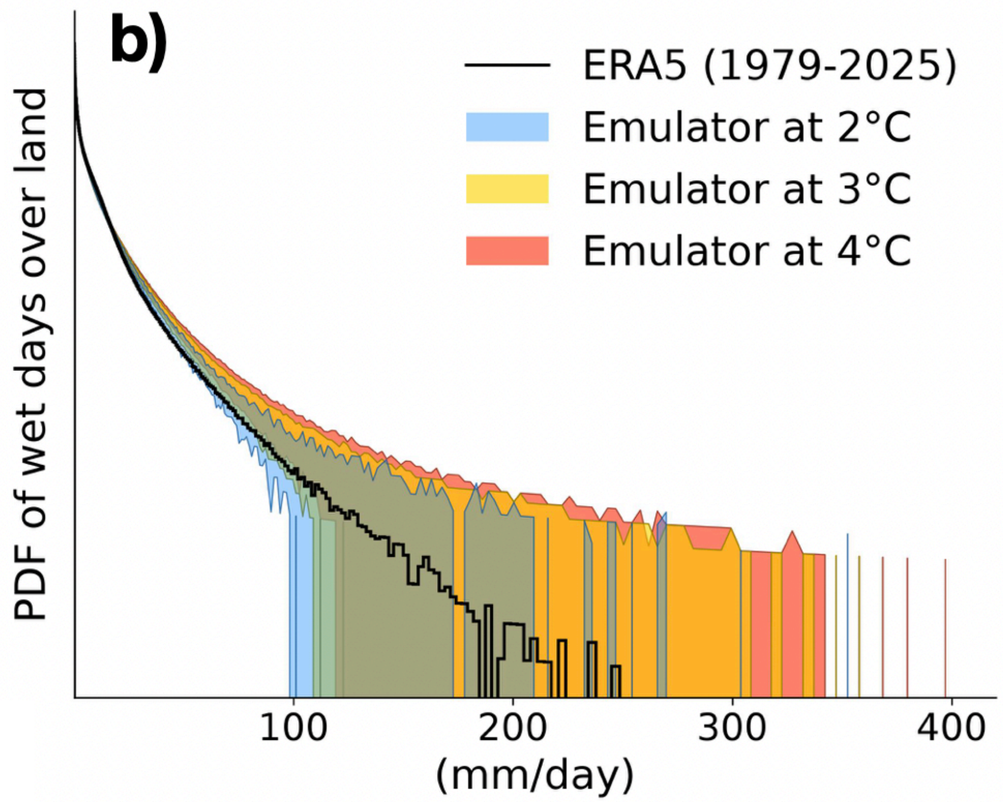
MIT Earthsampler: tail bias (extreme weather)



Shahine Bouabid, *Pedram Hassanzadeh, Raffaele Ferrari, et al., in preparation*

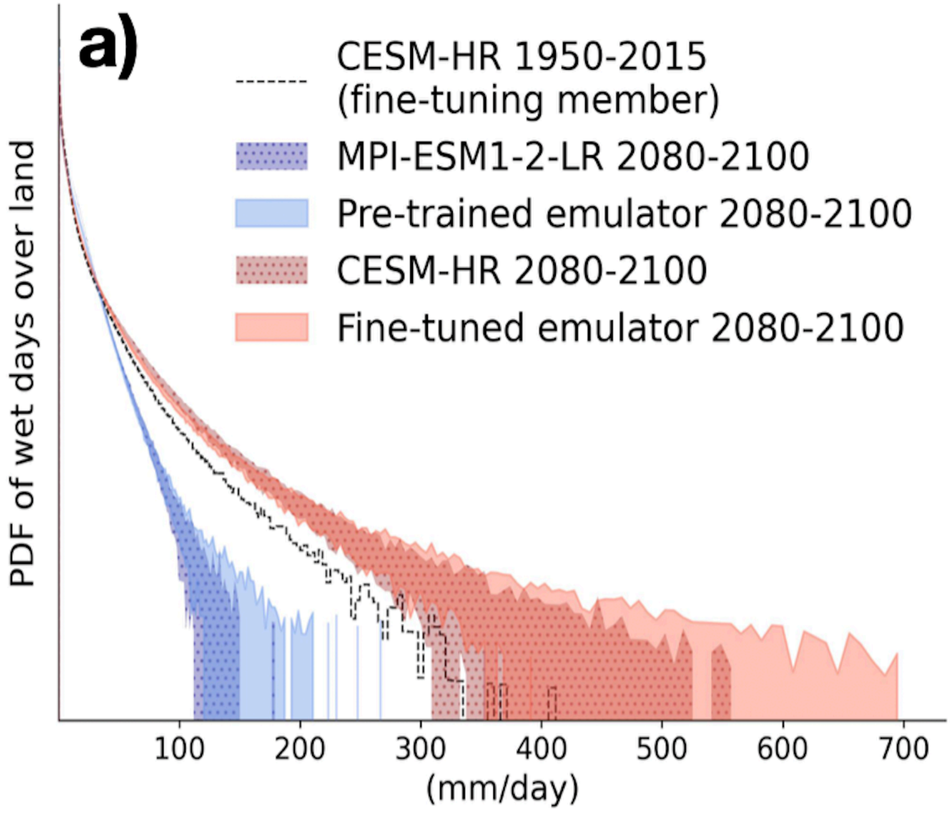
MIT Earthsampler: tail bias (extreme weather)

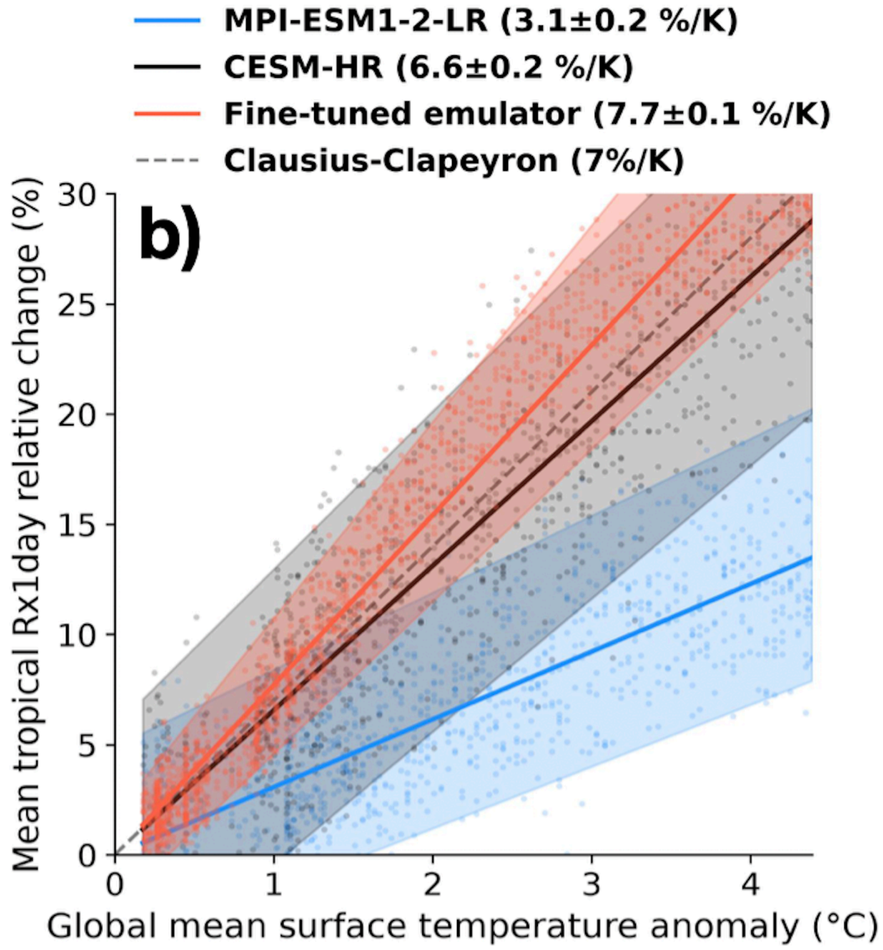




Shahine Bouabid, *Pedram Hassanzadeh, Raffaele Ferrari, et al., in preparation*

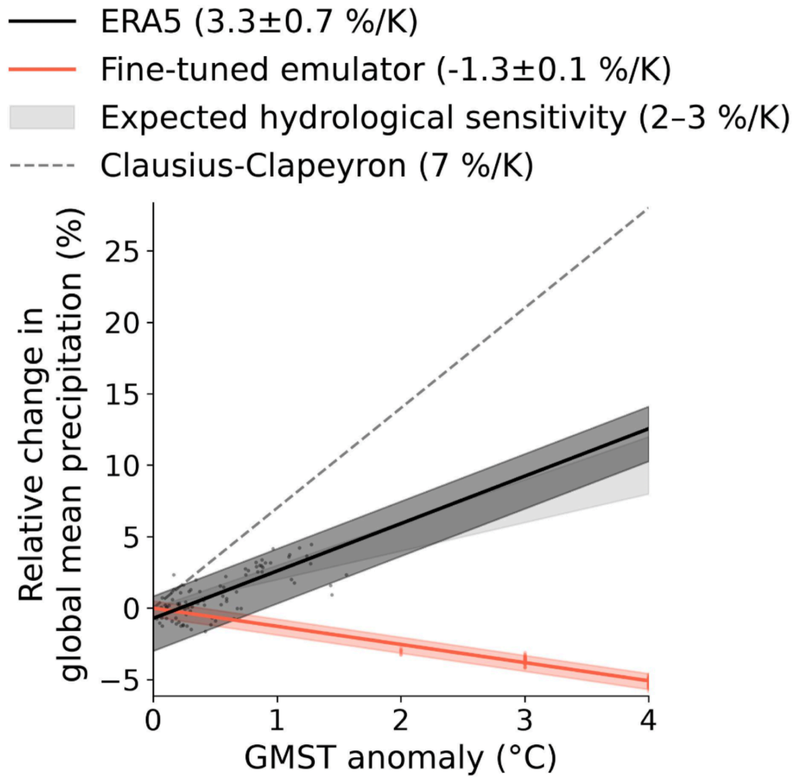
MIT Earthsampler: tail bias correction

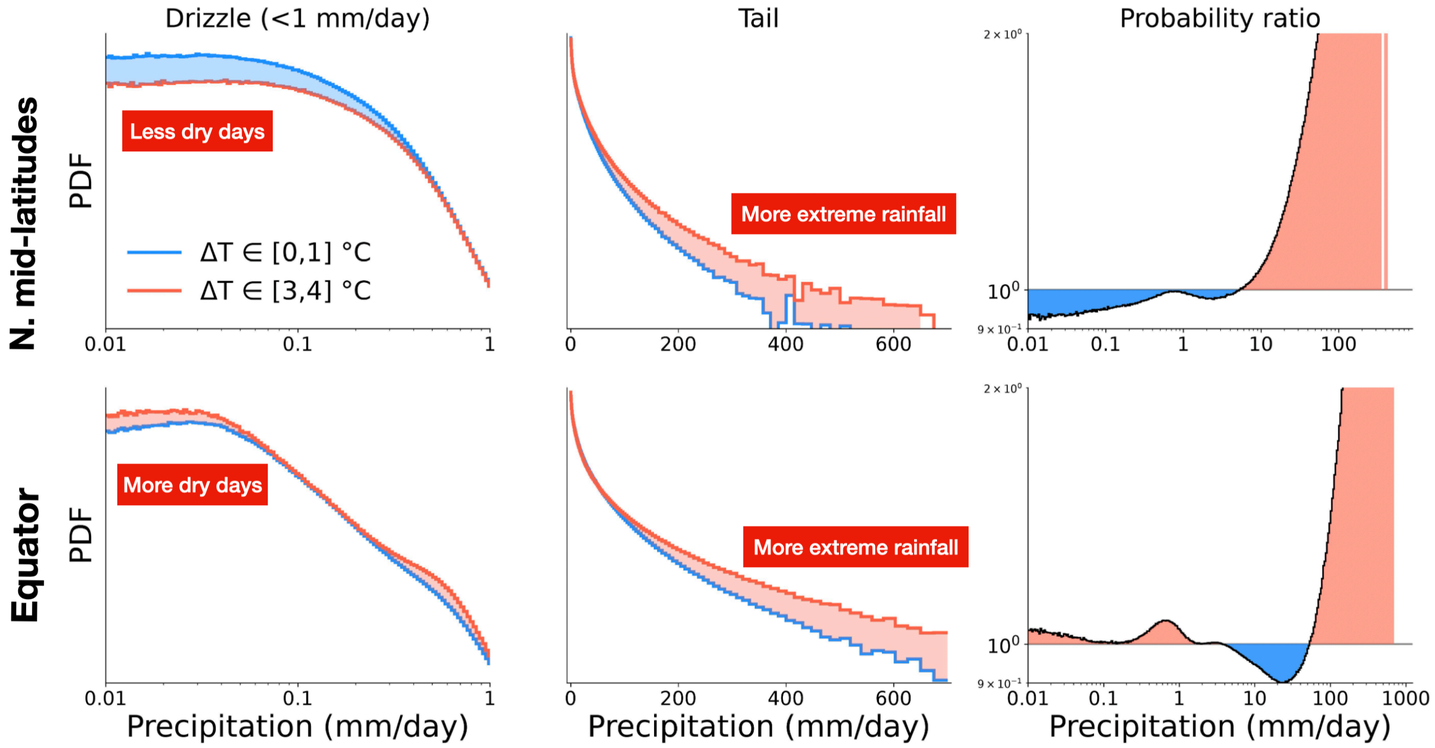




Shahine Bouabid, *Pedram Hassanzadeh, Raffaele Ferrari, et al., in preparation*

MIT Earthsampler: emergent trends





Shahine Bouabid, *Pedram Hassanzadeh, Raffaele Ferrari, et al., in preparation*

Concluding thoughts

Analogies between ESMs and AI emulators

- Algorithmic transparency does not necessarily lead to interpretability of complex systems
- Validating emerging properties helps establish trust in complex models

Differences between ESMs and AI emulators

- Biases in algorithmically transparent models provide a pathway to learn about physics
- Biases in black box models can only be addressed through additional training

In medio stat virtus (“virtue stands in the middle”)

- Embed AI modules in ESMs to represent specific processes
- Use AI emulators to identify the source of biases in ESMs