Generating large ensembles of precipitation extremes from CESM simulations using score-based diffusion models

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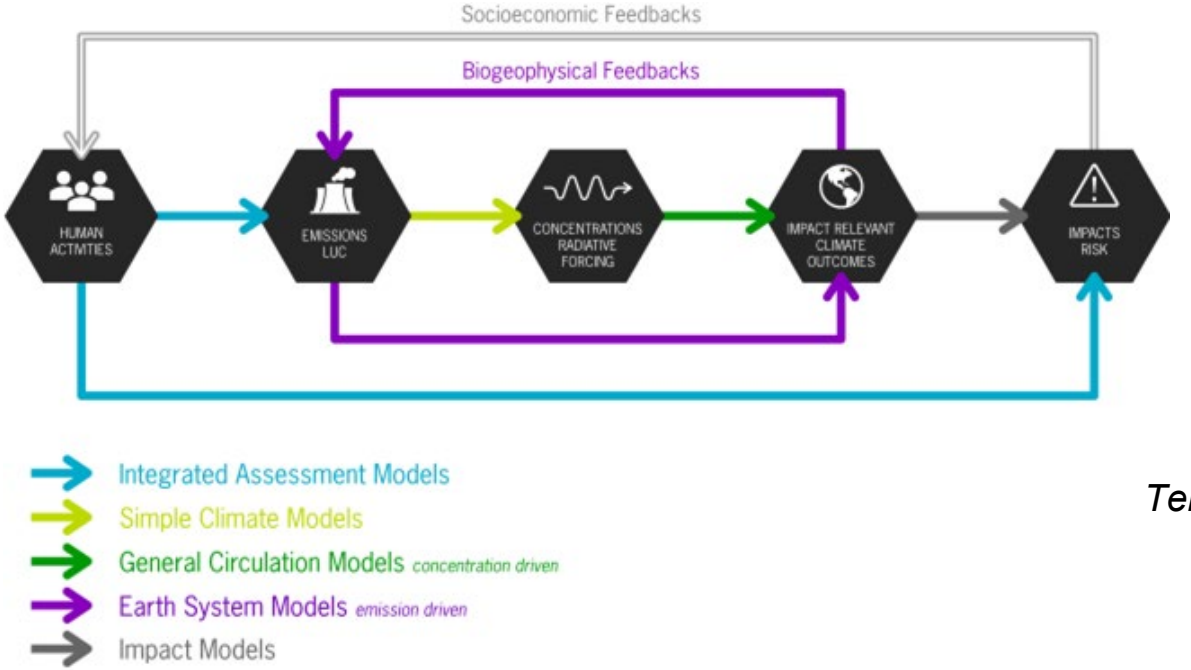
Background & motivation

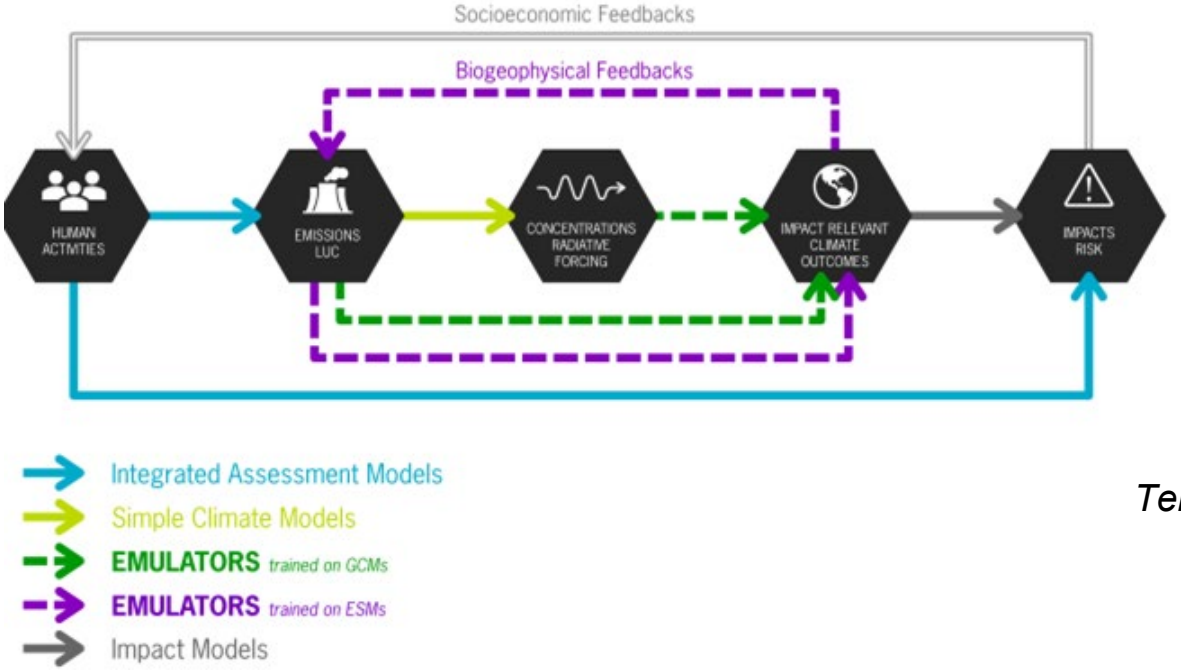
Earth system models (ESM) are only affordable for running a few scenarios



Tebaldi et al. (preprint)

Background & motivation

Emulators could increase accessibility, versatility, and fit-for-purposeness of climate information



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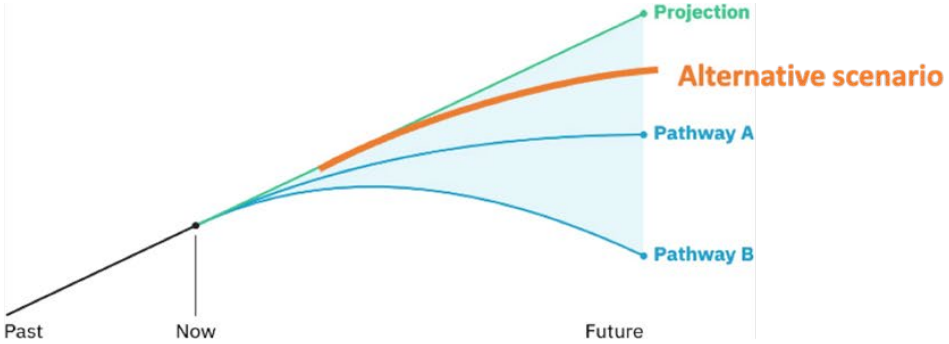
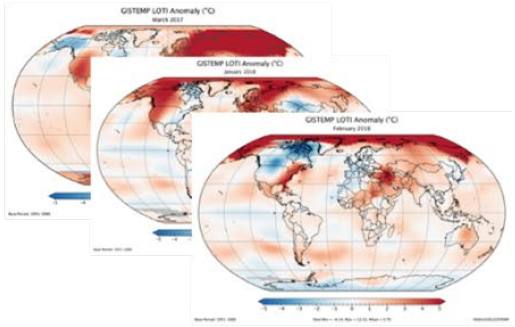
Background & motivation

Representing natural variability is key for fit-for-purposeness





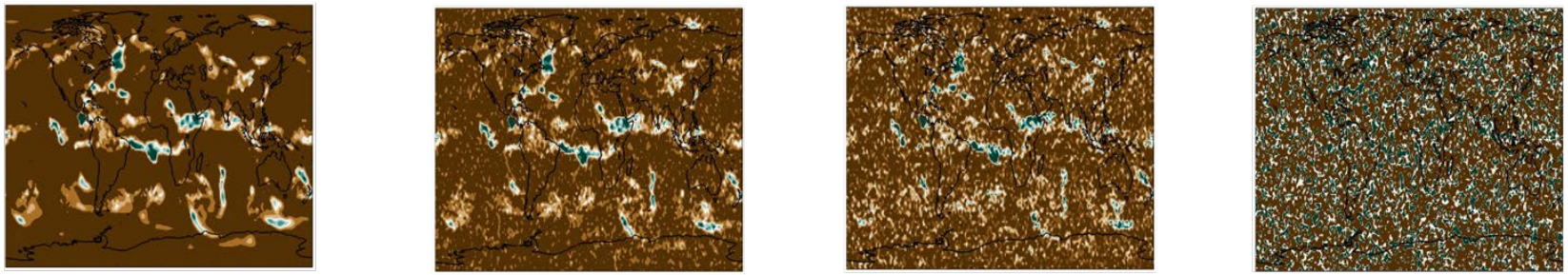
- Most existing emulators focus on modeling the annual/monthly **mean** $\bar{\mathbf{q}} = \mathbf{f}(T_g)$
- Here: emulate the **distribution** of daily variables conditioned on the scenario $p(\mathbf{q}|T_g)$

Image credit: climatescenarios.org; NASA

Method: score-based diffusion model

Key idea: find the transformation between $p(\mathbf{q}|T_g)$ and multivariate Gaussian distribution

$\mathbf{q}(\tau = 0) \sim p_{\text{data}}(\mathbf{q}|T_g)$ *Forward diffusion process* $\mathrm{d}\mathbf{q} = g(\tau)\mathrm{d}\mathbf{W}$ $\tau \in [0, 1]$



Reverse diffusion process $\mathrm{d}\mathbf{q} = -g(\tau)^2\mathbf{s}(\mathbf{q}, \tau)\mathrm{d}\tau + g(\tau)\mathrm{d}\mathbf{W}$

The score function $\mathbf{s}(\mathbf{q}, \tau) \equiv \nabla_{\mathbf{q}} \log p_{\text{data}}\ (\mathbf{q}|T_g)$ is modelled using neural networks (UNet)

Song et al. 2021, Bischoff & Deck 2024

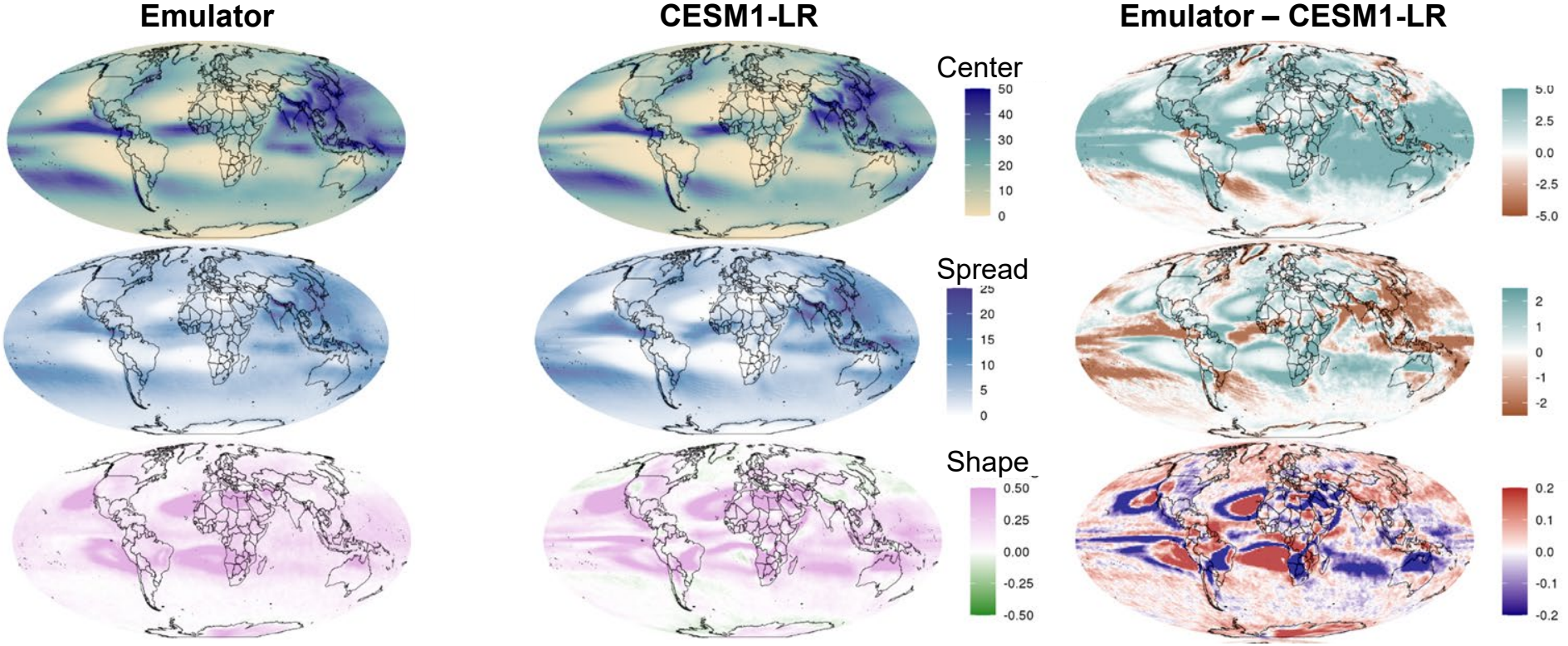
Dataset

- CESM1-LR (MESACLIP, for future HR extensions)
- Emulation: daily precipitation JJA
- 1950-2100 (RCP8.5)
- Training: 1 member; Testing: 10 members (full ensemble)
- Evaluation: seasonal (JJA) maximum daily precipitation, GEV-based

Questions

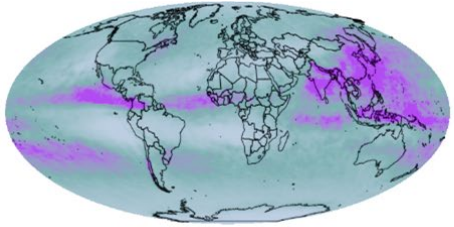
- [climate] Does the emulator reproduce the (most non-linear) part of the daily precipitation distribution → precipitation extremes?
- [weather] Does the emulator reproduce the spatial characteristics of individual extreme precipitation events?

(Preliminary) results: Rx1d GEV parameters

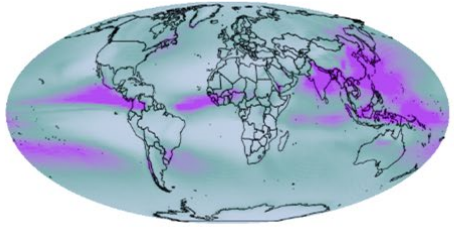


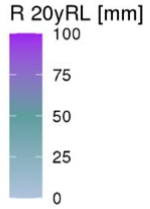
(Preliminary) results: 1-in-20year event

Emulator

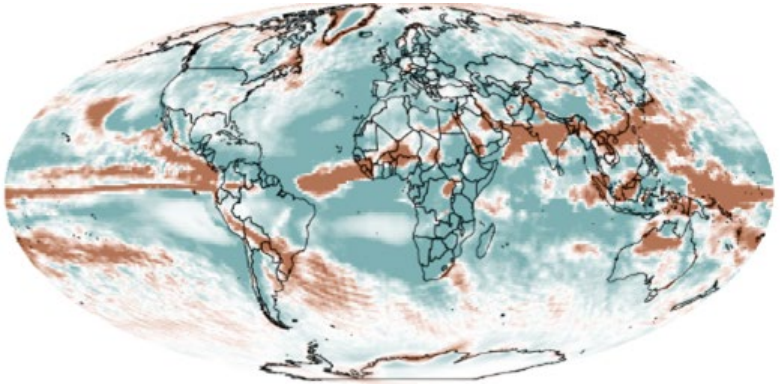


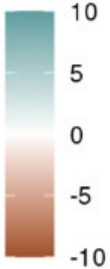
CESM1-LR



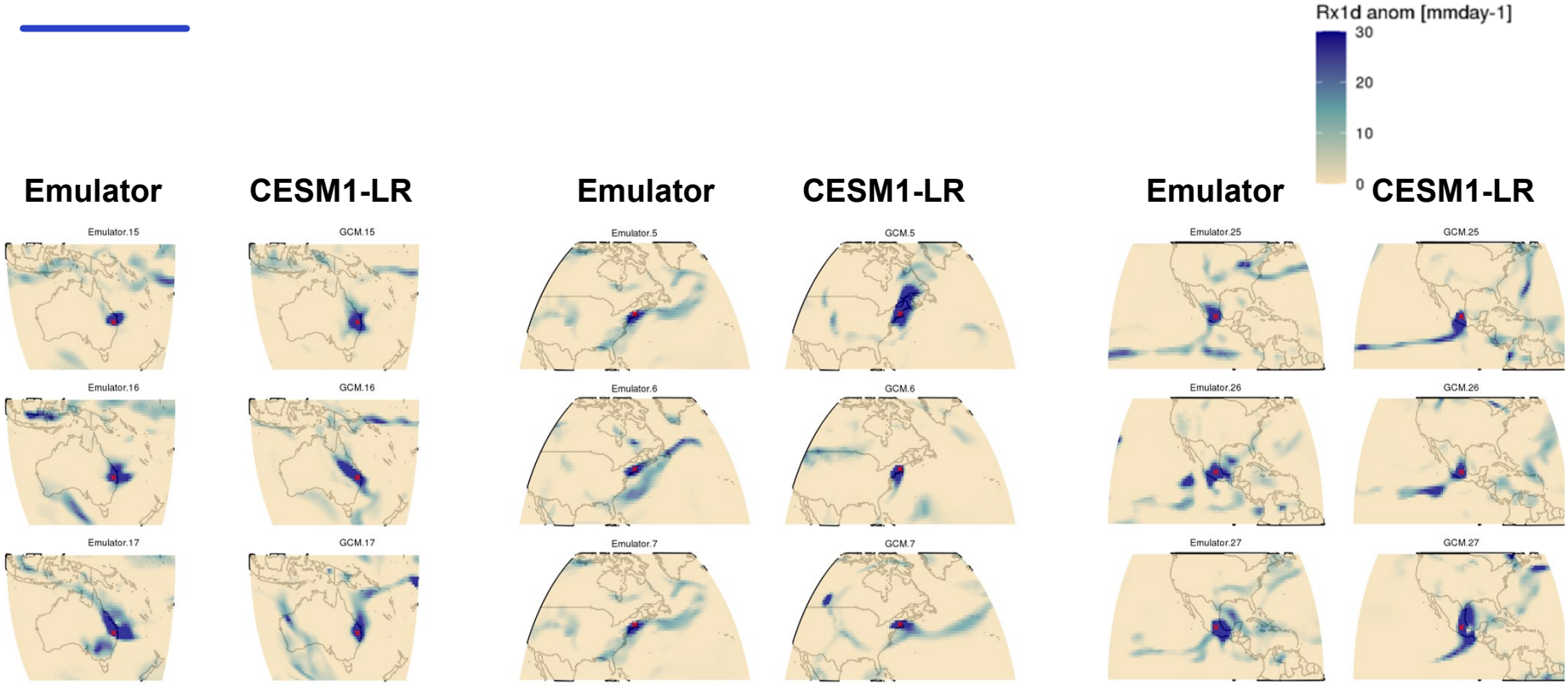


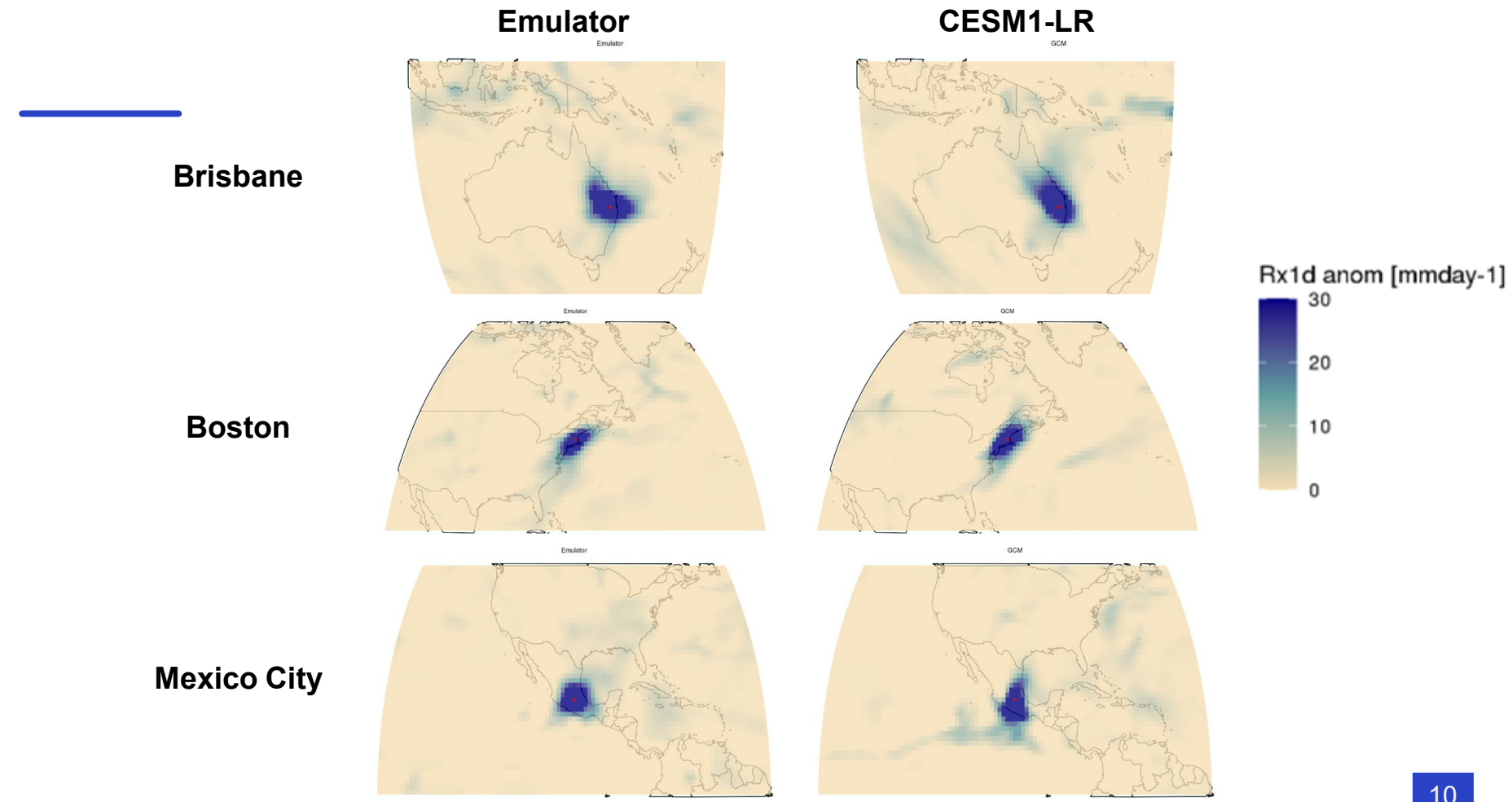
Emulator – CESM1-LR





(Preliminary) results: spatial event characteristics




Emulator
CESM1-LR
Brisbane
Boston
Mexico City
Emulator
GCM
Rx1d anom [mmday-1]
30
20
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Conclusions and outlook

Score-based diffusion models do (reasonably) well at

- Capturing highly non-linear daily precipitation (extreme) statistics*
- Capturing spatial characteristics of individual extremes

Towards usefulness of emulators for extremes

- Scenario interpolation/tailoring → more/different predictors
- Extrapolation to unseen events
- Multivariate (compound) extremes
- …

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