

ClimForGe: A Diffusion-based Forcing–Response Climate Emulator on Daily Timescales

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Climate Emulation

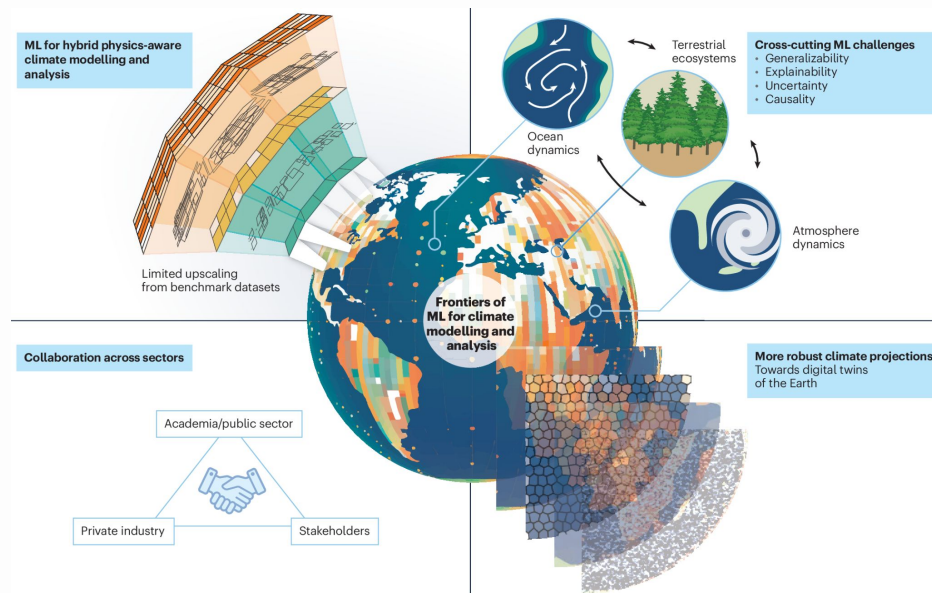
What are they?

Branch of climate models that approximate the behavior of full climate/Earth-system models without solving all the physics focusing on reproducing long term statistics.

Climate Emulators learn from observations and/or ESM outputs to map forcings (e.g., GHGs, aerosols) to targets (e.g global temperature/precipitation)

Why it matters

- Informs policy via long-term climate understanding
- Enables rapid scenario exploration
- Improves understanding of climate processes



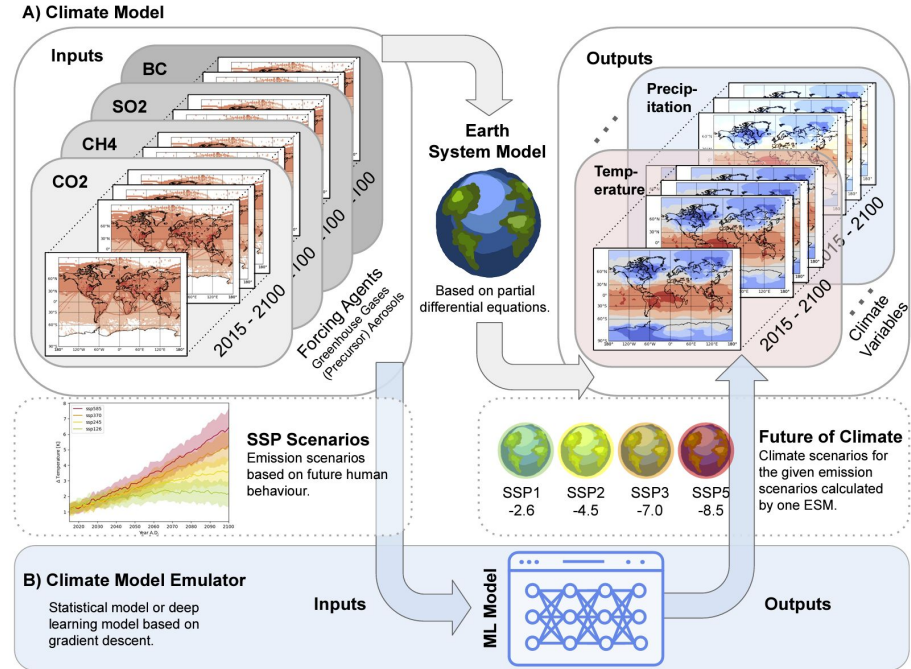
Source: Figure adapted from “Artificial intelligence for climate modeling,”
Nature Climate Change (2024), DOI: [10.1038/s41558-024-02095-y]

ML for Climate Emulation

Emerging branch of climate emulation, ML based emulators further improve on the ability to rapidly explore many different scenarios

Key approaches

- Force-Response modeling
- Autoregressive modeling
- Super-resolution/Downscaling



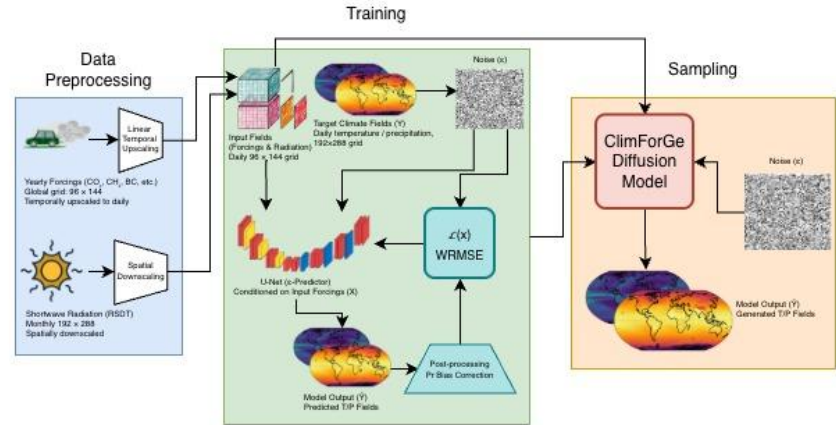
Source: KIT ClimateSet Project – “Climate Emulation Using Machine Learning,”

Karlsruhe Institute of Technology (<https://ki-klima.iti.kit.edu>)

ClimForGe (Climate Forcing Generator)

A Diffusion Model based forcing-response model, more specifically utilizing the EDM (Karras et al., 2022) diffusion architecture with a UNet Neural Network

- **Inputs:** GHGs + aerosol forcings, solar radiation (RSDT)
- **Targets:** daily global temperature and precipitation full fields
- **Speed:** 50 years (>18,000 days) of full global fields in approximately 1h 40m on a single Nvidia A100 GPU.



ClimForGe - Results

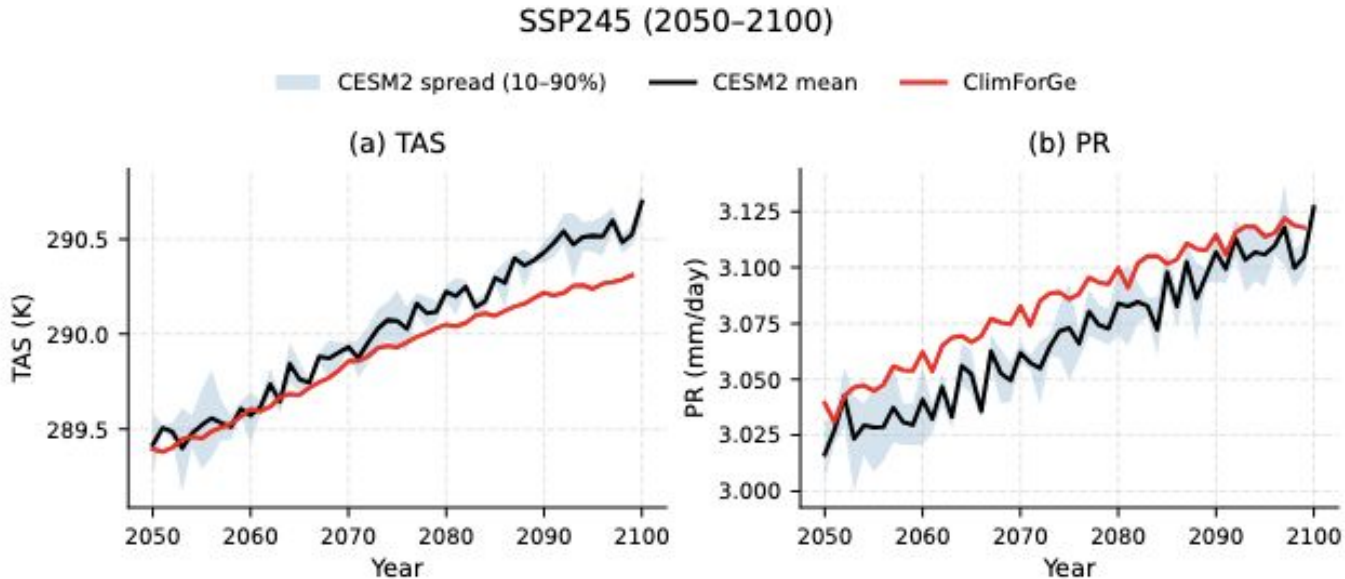
Area-weighted RMSE & CRPS on for means from 2080-2100 following the protocol from ClimateBench (Duncan-Watson Parris). ClimForGe matches baselines on RMSE and **beats GP on CRPS**—despite **2× finer spatial** and **365× finer temporal (daily)** resolution, demonstrating strong daily-scale probabilistic skill.

	Temperature		Precipitation	
Model	RMSE (K)	CRPS (K)	RMSE (mm/day)	CRPS (mm/day)
Gaussian Process	0.225	0.477	0.153	1.075
CNN	0.222	-	0.139	-
ClimForGe (Ours)	0.377	0.282	0.239	0.128

RMSE and CRPS of global and time means for the years 2080-2100 of SSP245 for ClimForGe and Climatebench models. Note that because Climatebench emulates NorESM, these metrics are not directly comparable but the metrics provide a useful reference point for relative model skill.

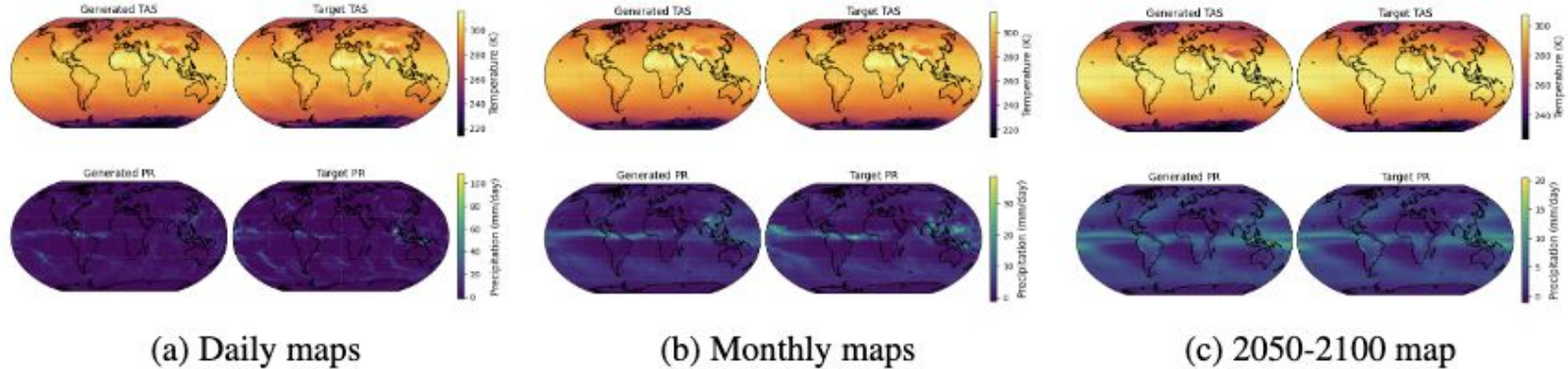
ClimForGe - Results

Comparing ClimForGe's yearly means for global temperature and precipitation against the CESM2 ensemble means under the SSP2-4.5 scenario from 2050 to 2100.



ClimForGe - Results

ClimForGe captures key spatial patterns like global warming regions and the tropical rainfall belt, showing strong consistency with CESM2 across daily, monthly, and long-term maps.



Conclusion

We introduced utilizing a diffusion architecture as a natural methods for climate emulation allowing:

- Fast scenario sweeps across multiple socioeconomic pathways
- Probabilistic skill capturing ESM uncertainty & internal variability

Limitations and Future Works

- Temporally disjoint as each daily sample is i.i.d
- Joint generation of Precipitation and Temperature
- Diffusion Guidance - allows for better exploration for extreme events



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Thanks!

Do you have any questions?

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