February 03, 2026

Extending CAMulator for Subseasonal Prediction

Simulations, Applications, and Performance

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Scientist IV; CGD ESP

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This material is based upon work supported by the NSF National Center for Atmospheric Research, a major facility sponsored by the U.S. National Science Foundation and managed by the University Corporation for Atmospheric Research. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of NSF.

Subseasonal Timescales: ~2 weeks - 2 months

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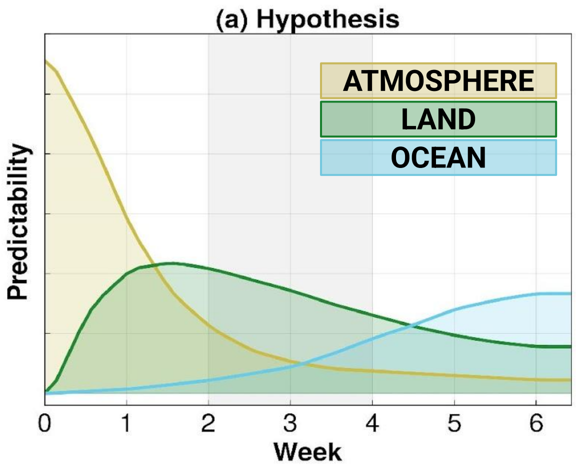
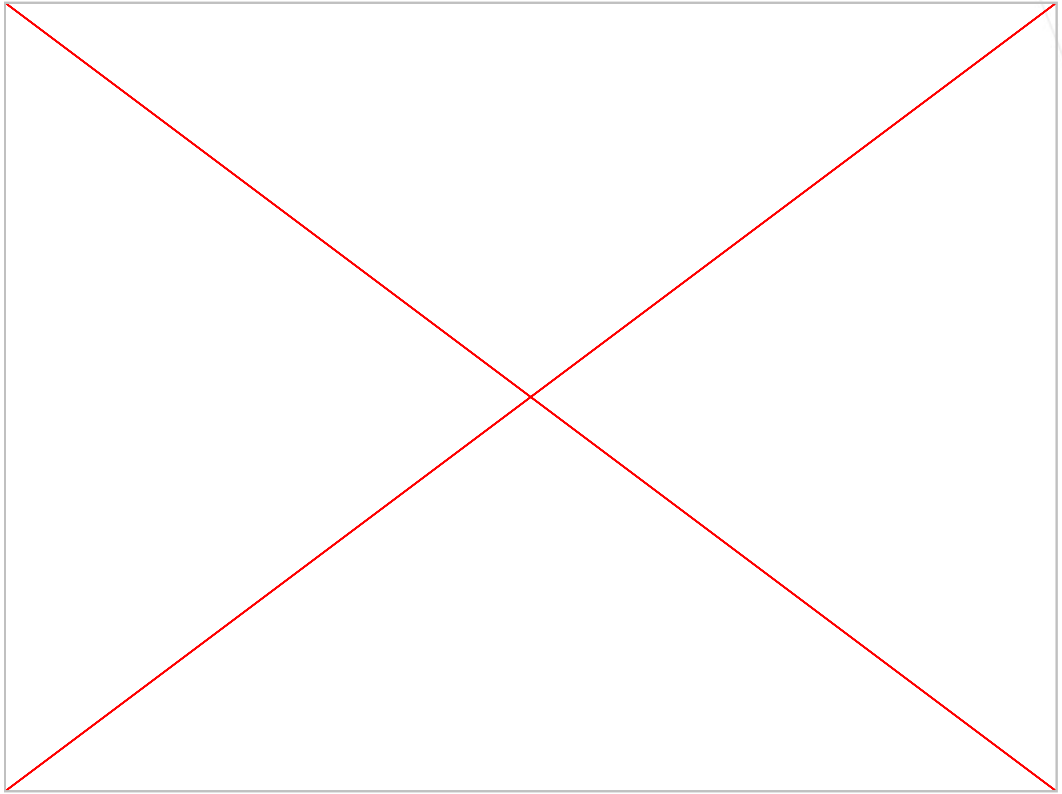


Richter et al. 2024

CAMulator: Emulator of the Community Atmosphere Model

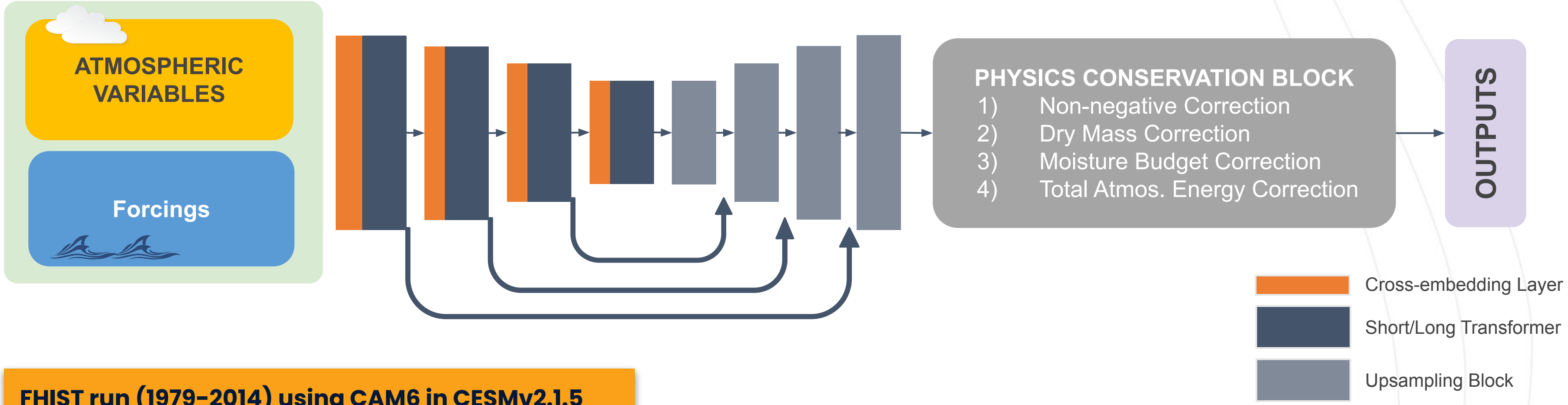


specific humidity
(lowest model level)

Chapman et al. 2025. “CAMulator: Fast Emulation of the Community Atmosphere Model.” *arXiv [Physics.Ao-Ph]*. arXiv. http://arxiv.org/abs/2504.06007.

CAMulator: Emulator of the Community Atmosphere Model

350x speed up over CAM6



FHIST run (1979-2014) using CAM6 in CESMv2.1.5

- O1000 lines of code
- 751,134,146 parameters
- 0.43% of GPT-3
- 2.86535 GB

Chapman et al. 2025. “CAMulator: Fast Emulation of the Community Atmosphere Model.” *arXiv [Physics.Ao-Ph]*. arXiv. http://arxiv.org/abs/2504.06007.

CAMulator: Emulator of the Community Atmosphere Model

Variable	Description	Units	Single Level/Levels
	Prognostic Variables (Input and Output)		
U	Zonal Wind	m/s	32 levels
V	Meridional Wind	m/s	32 levels
T	Temperature	K	32 levels
Qtot	Specific Total Water	kg/kg	32 levels
PS	Surface Pressure	Pa	Single Level
TREFHT	Near-Surface Air Temperature	K	Single Level
	Dynamic Forcing Variables (Input Only)		
SOLIN	Incoming Solar Radiation	J/m^2	Single Level
SST	Sea Surface Temperature	K	Single Level
	Static Forcing Variables (Input Only)		
Surface Geop.	Normalized Surface Height	m^2/s^2	Single Level
Land-Sea Mask	Land Mask × Cosine Latitude	unitless	Single Level

CAMulator

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	Prognostic Variables (Input and Output)		
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T	Temperature	K	32 levels
Qtot	Specific Total Water	kg/kg	32 levels
PS	Surface Pressure	Pa	Single Level
TREFHT	Near-Surface Air Temperature	K	Single Level
	Diagnostic Variables (Output Only)		
PRECT	Precipitation Rate	m	Single Level
CLDTOT	Total Cloud Cover	fraction	Single Level
CLDHGH	High Cloud Cover	fraction	Single Level
CLDLOW	Low Cloud Cover	fraction	Single Level
CLDMED	Medium Cloud Cover	fraction	Single Level
TAUX	Zonal Wind Stress	N/m^2	Single Level
TAUY	Meridional Wind Stress	N/m^2	Single Level
U10	10m Wind Speed	m/s	Single Level
QFLX	Surface Moisture Flux	m	Single Level
FSNS	Net Solar Flux at Surface	J/m^2	Single Level
FLNS	Net Longwave Flux at Surface	J/m^2	Single Level
FSNT	Net Solar Flux at TOA	J/m^2	Single Level
FLNT	Net Longwave Flux at TOA	J/m^2	Single Level
SHFLX	Sensible Heat Flux	J/m^2	Single Level
LHFLX	Latent Heat Flux	J/m^2	Single Level

Prognostic: input & output
Forcing Variables: input
Diagnostic: output

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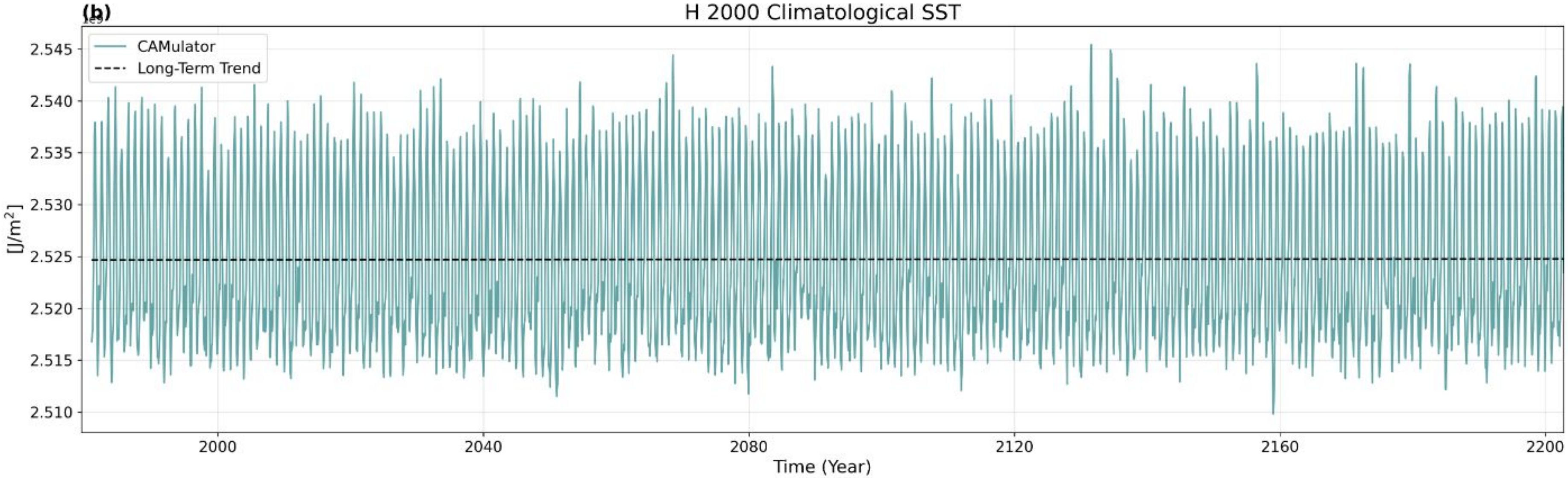
CAMulator: Emulator of the Community Atmosphere Model

What if we rolled it out for more than 200 years?



Column-integrated heat content in CAMulator to fixed year-2000 climatological SSTs

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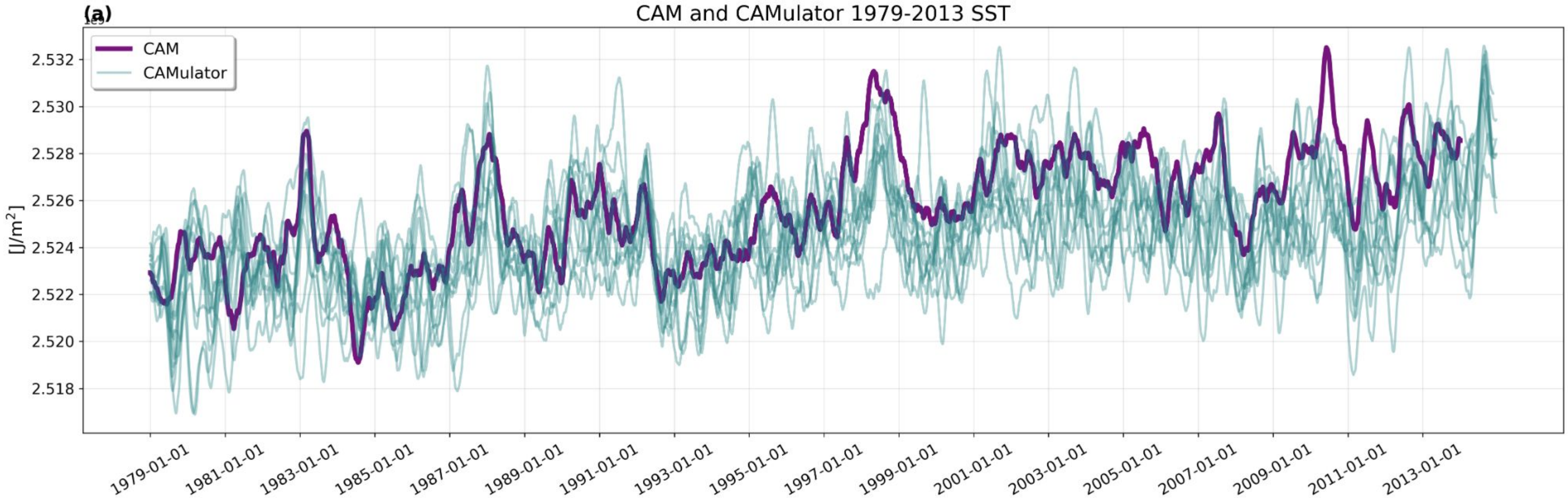
CAMulator: Emulator of the Community Atmosphere Model

What if we force it with observed SSTs?



A 12-member CAMulator ensemble (teal) is compared to the CAM6 simulation (purple) using observed SSTs from 1979–2014. CAMulator successfully captures the long-term warming trend and interannual variability.

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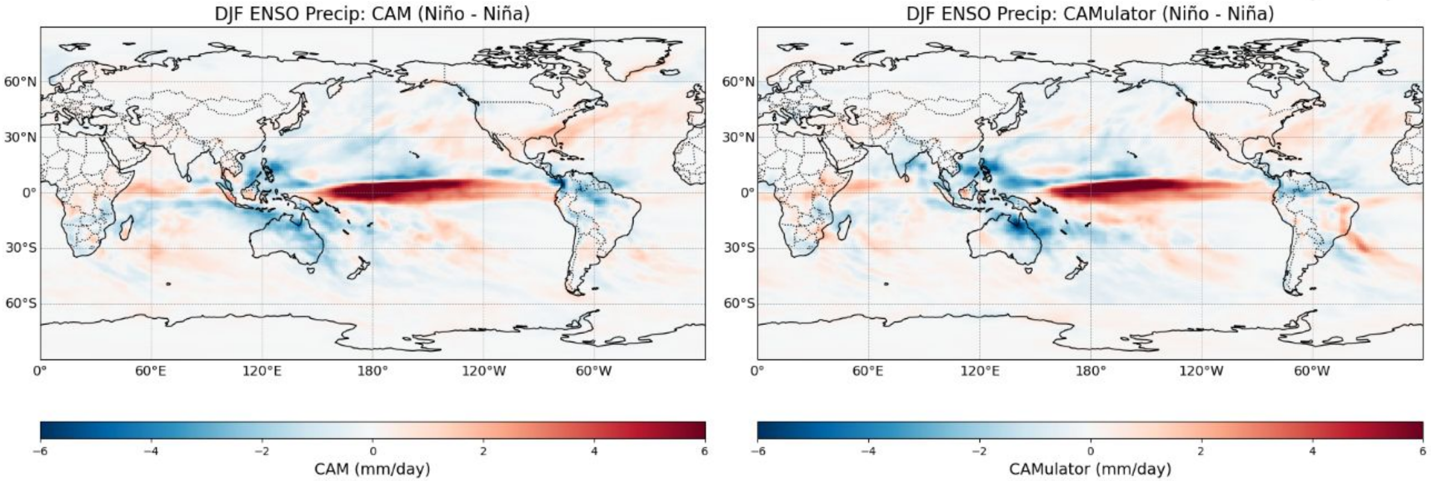
CAMulator: Emulator of the Community Atmosphere Model

ENSO Precip Response (8 strongest Nino-Nina):

CAM6 DJF **CAMulator DJF**



Precipitation Anomaly [mm/day]

Pattern Correlation: ~0.9

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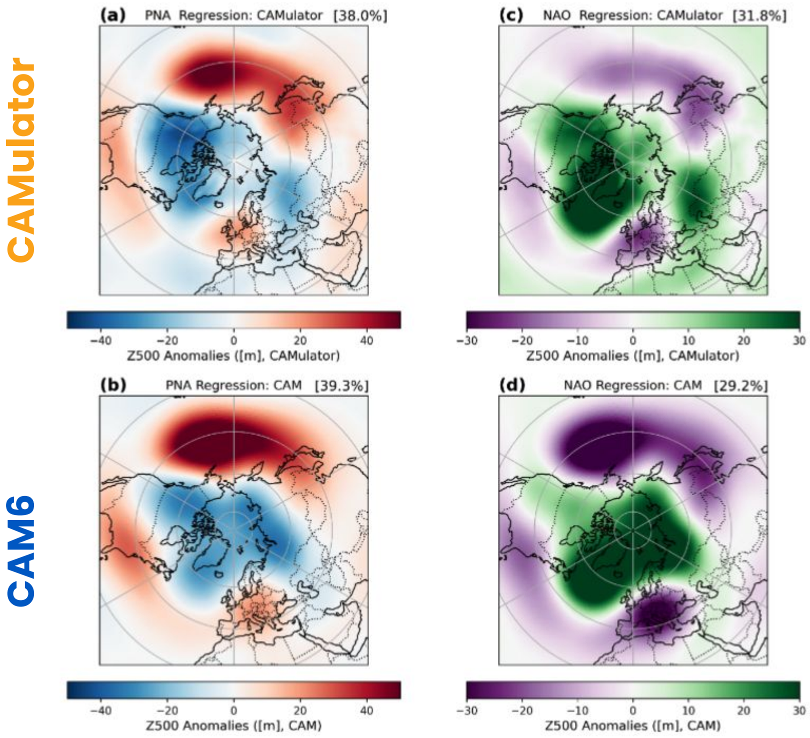
CAMulator: Emulator of the Community Atmosphere Model



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CAMulator: Emulator of the Community Atmosphere Model

CAMulator v1
Training Data-AMIP

CAMulator v2
Training Data-Coupled

Chapman et al. 2025. “CAMulator: Fast Emulation of the Community Atmosphere Model.” *arXiv [Physics.Ao-Ph]*. arXiv. http://arxiv.org/abs/2504.06007.

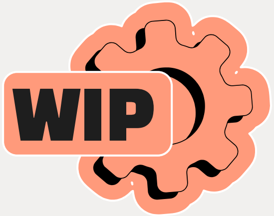
XXXmulator: ML Emulators to date

CAMulator v1

Training Data-AMIP

CAMulator v2

Training Data-Coupled



subCESMulator

+ ocean & land

subCESMulator: ML Emulator for S2S Prediction

WIP

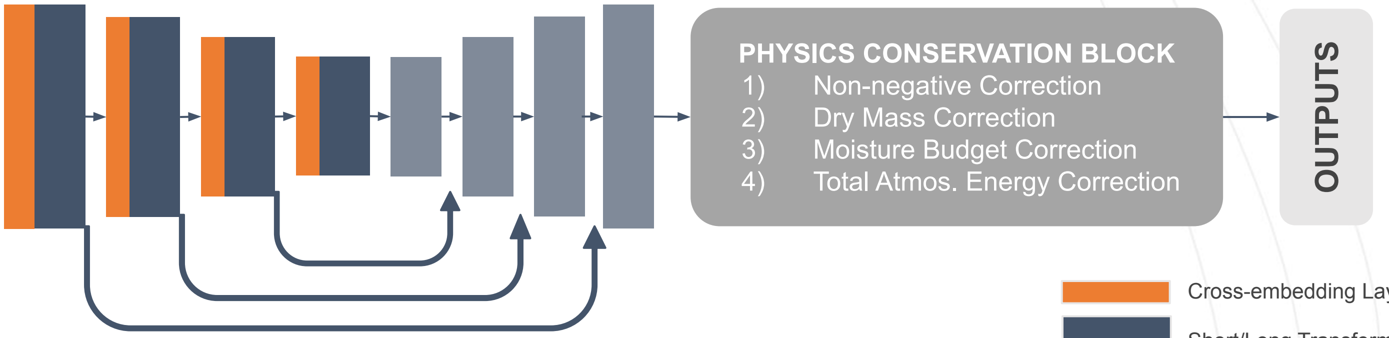
ATMOSPHERIC VARIABLES

Sea Surface Temperature

Soil Moisture
Surface Temp.

Sea Ice Fraction

CO2 Emissions



Cross-embedding Layer

Short/Long Transformer

Upsampling Block

Data: CESM2 Coupled Runs (1980-2050)
Training: 1980-2024
Validation: 2025-2030

Mayer et al. (in prep)

subCESMulator: ML Emulator for S2S Prediction

WIP

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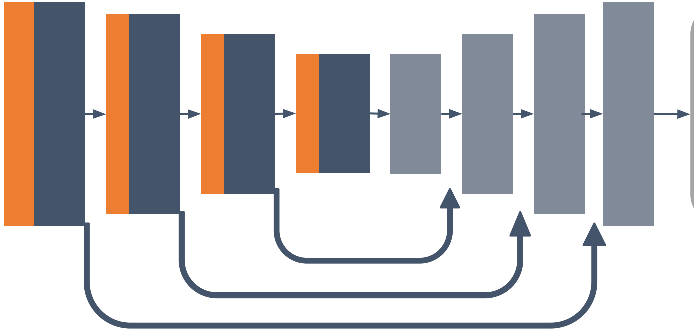


PHYSICS CONSERVATION BLOCK

1) Non-negative Correction
2) Dry Mass Correction
3) Moisture Budget Correction
4) Total Atmos. Energy Correction

OUTPUTS

- Cross-embedding Layer
- Short/Long Transformer
- Upsampling Block

Data: CESM2 Coupled Runs (1980-2050)
Training: 1980-2024
Validation: 2025-2030

Modified subCESMulator
Data: CESM2-LE
Training: 1990-2025 x 5 members = 175 years
(typical S2S models train on 1979-2025 = 46 years)

+ more land & ocean variables

Mayer et al. (in prep)

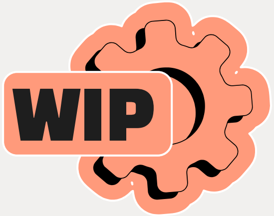
XXXmulator: ML Emulators to date

CAMulator v1

Training Data-AMIP

CAMulator v2

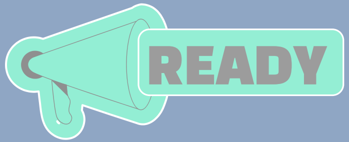
Training Data-Coupled



subCESMulator

+ ocean & land

...Mulator: ML Emulators to date



CAMulator v1

Training Data-AMIP

CAMulator v2

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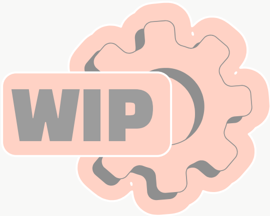


subCESMulator

+ ocean & land

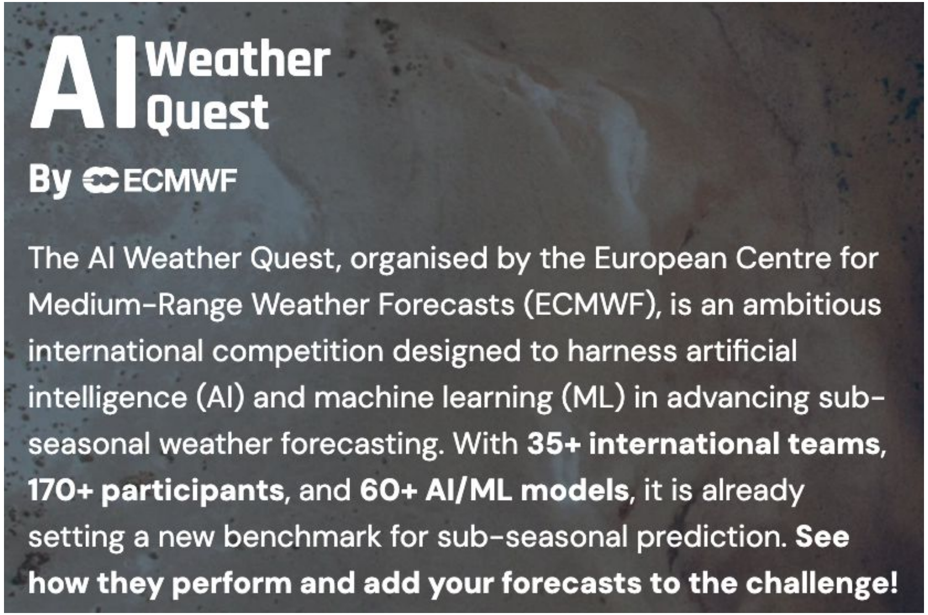
U.S. DEPARTMENT of ENERGY
Office of Science

NSF NCAR UCAR

AI Weather Quest Submission

Kirsten J. Mayer, Katherine Dagon, William E. Chapman, Charlie Becker, John Schreck, David John Gagne, Judith Berner, Abby Jaye, Sasha Glanville

Can we use a AI model trained on CESM for subseasonal forecasting?



Loegel et al. 2025

Participants provide **weekly, global forecasts** at a 1.5 degree resolution of **quintile probabilities** for weekly-mean (Days 19–25 and Days 26–32):

- **Temperature**
- **Precipitation**
- **Sea level pressure**

Evaluated against initial **ERA5** release data using ranked probability skill score (**RPSS**)

INITIALIZATION

We initialize with 11 perturbations of each 31 member of **GEFS initializations (341 members)**
→ Perturbation method based on CESM S2S hindcast method (see Section 2.b of Richter et al. 2022)

DYNAMICAL FORCING

SST and ICEFRAC are forcing variables in CAMulator, so we **persist their initial conditions** throughout forecast

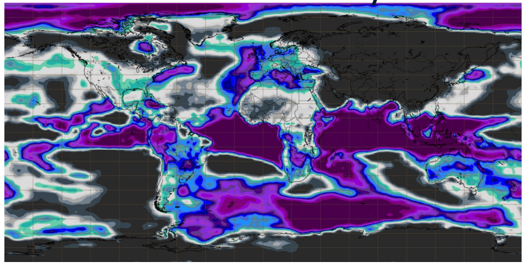
QUINTILES

CAMulator is trained on coupled runs, so we **calculate quintiles based on CESM training data** (2000-2025)

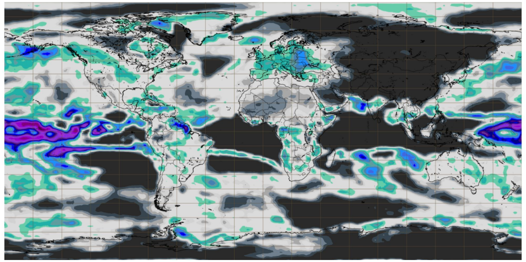
Takes ~7 hrs to submit

Week 3 Forecast: 02 February - 08 February 2m Temperature

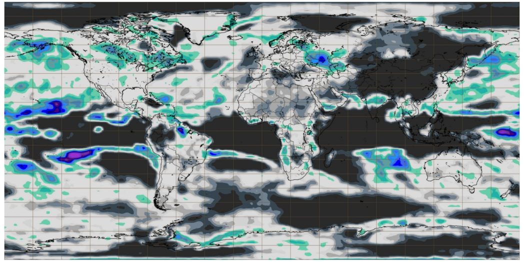
<20th: Anomalously Cold



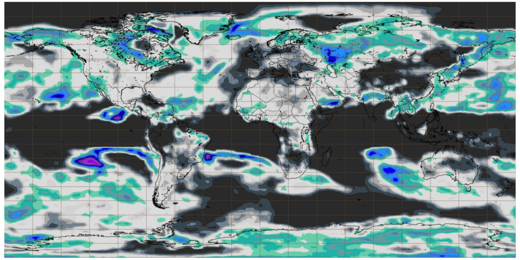
20th-40th



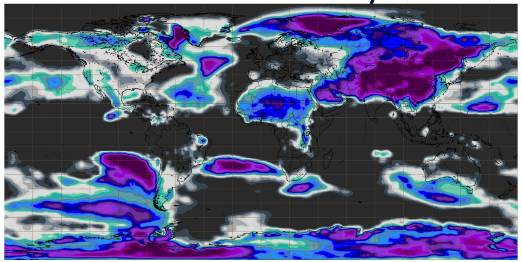
40th - 60th



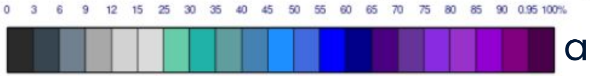
60th - 80th



>80th: Anomalously Warm



no members

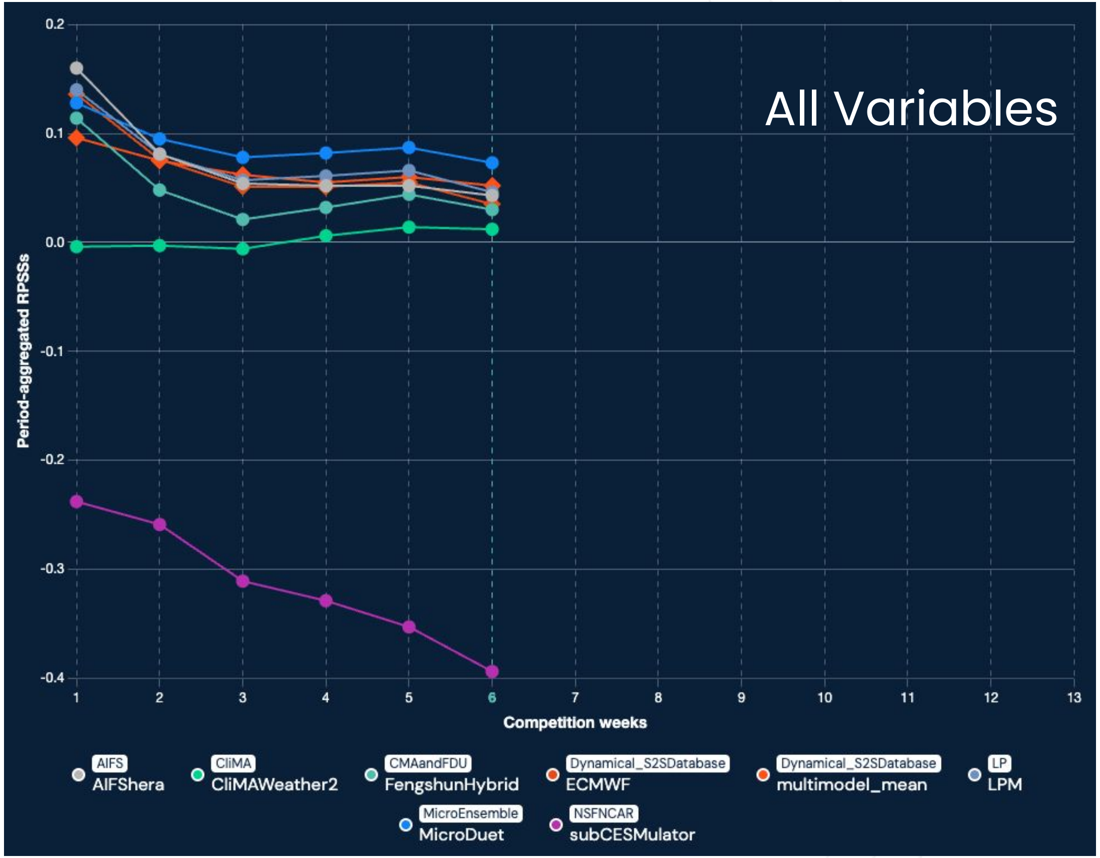


all members

CAMulator: AI Weather Quest DJF Skill

WEEK 3:

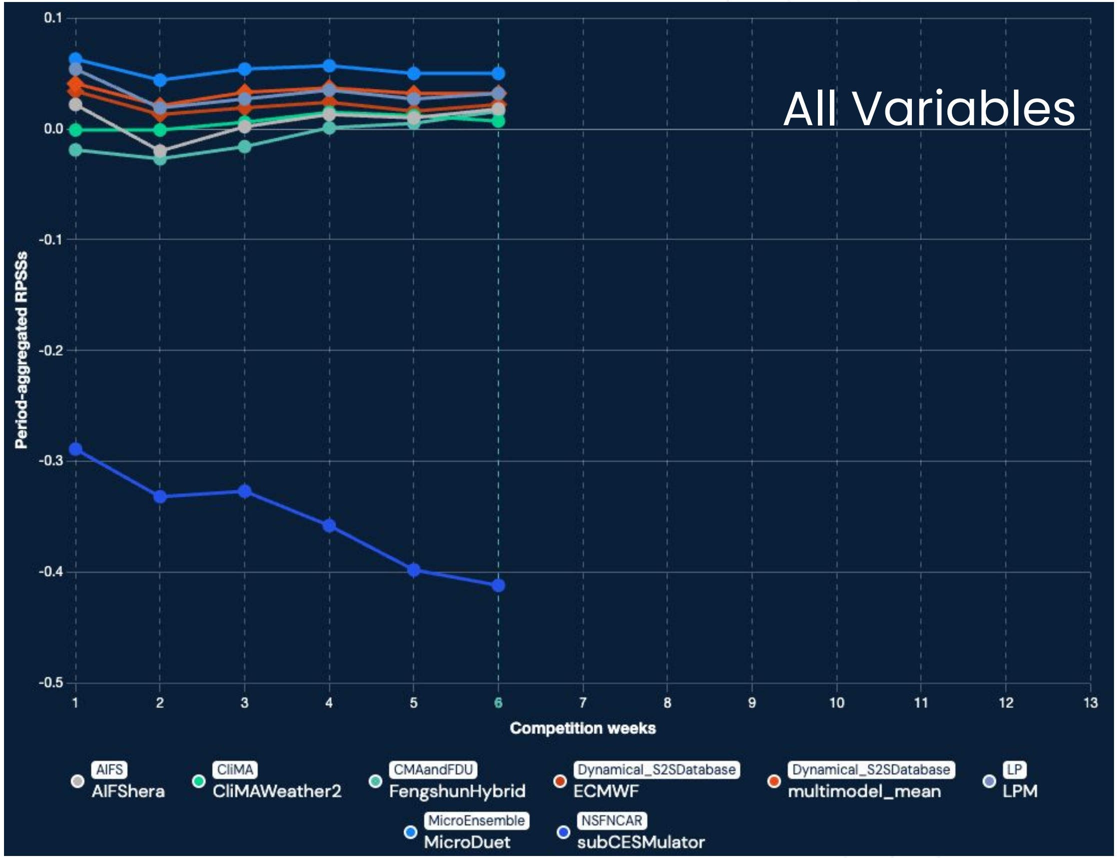
- All Variables
  - 14th out of 20 teams
  - 28th out of 36 models
- 2m Temperature
  - 20th out of 22 teams
  - 38th out of 40 models
- MSLP
  - 17th out of 20 teams
  - 34th out of 38 models
- Precipitation
  - 16th out of 21 teams
  - 33rd out of 40 models



CAMulator: AI Weather Quest DJF Skill

WEEK 4:

- All Variables
  - 14th out of 20 teams
  - 29th out of 37 models
- 2m Temperature
  - 20th out of 22 teams
  - 39th out of 41 models
- MSLP
  - 17th out of 20 teams
  - 34th out of 38 models
- Precipitation
  - 16th out of 21 teams
  - 33rd out of 40 models



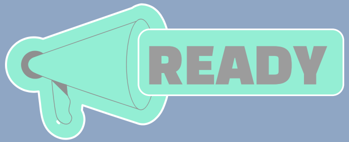
AIWQ Next Steps

MODEL	Move from CAMulator to subCESMulator
ENSEMBLE GENERATION	Switch to **Stochastic Decomposition Layers** which has shown good spread-skill ratios through medium-range forecasts in WxFormer (Schreck et al. 2025)
EVALUATION	Explore skill of real-time forecasts beyond quintiles & identify areas of improvement

ML S2S Hindcasts

Kirsten J. Mayer, Charlie Becker, Sasha Glanville, John Schreck, Judith Berner, Abby Jaye, Negin Sobhani

…Mulator: ML Emulators to date



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CAMulator v2
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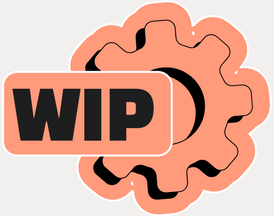
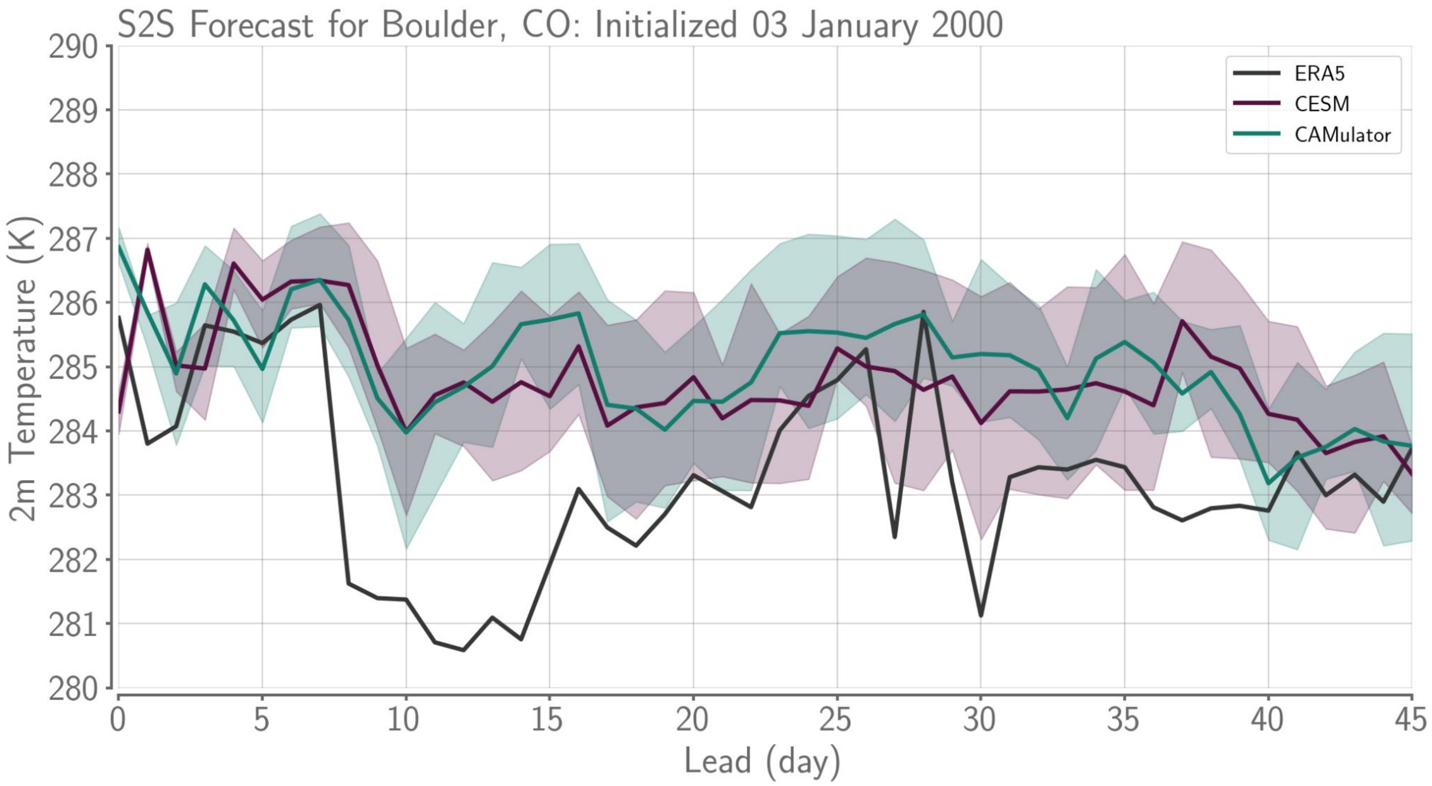


subCESMulator
+ ocean & land

ML-based S2S Hindcasts

1. CAMulator and subCESMulator
2. Use same initial conditions & ensemble generation as the CESM S2S Hindcasts
3. Explore additional ensemble generation approaches with >10 members
4. Run additional (and extended) initialization dates
5. Apply diagnostic package
6. Make available to the community


S2S Forecast for Boulder, CO: Initialized 03 January 2000
ERA5
CESM
CAMulator
2m Temperature (K)
290
289
288
287
286
285
284
283
282
281
280
0
5
10
15
20
25
30
35
40
45
Lead (day)

ML-Based Prediction

Coming Soon

CAMulator Hindcasts

subCESMulator Training

One trained on CESM coupled simulation and another using the CESM2-LE output

subCESMulator Hindcasts

Science!

CREDIT: Community Research Earth Digital Intelligence Twin

CREDIT Platform for ML Emulation

- a research platform for training, operating, & conducting research with ML models for Earth System science
- **Platform Features**
    - Integrated pre-processing
    - Library of neural network architectures
    - Scalable training and inference on NCAR HPC
    - Physics constraints
    - Analysis tools and plotting

https://miles.ucar.edu/software/credit/


Will Chapman


John Schreck


DJ Gagne


Judith Berner


Kyle Sha


Arnold Kazadi


Dhamma Kimpara


Peter Lauritzen


Ben Kirk


Negin Sobhani

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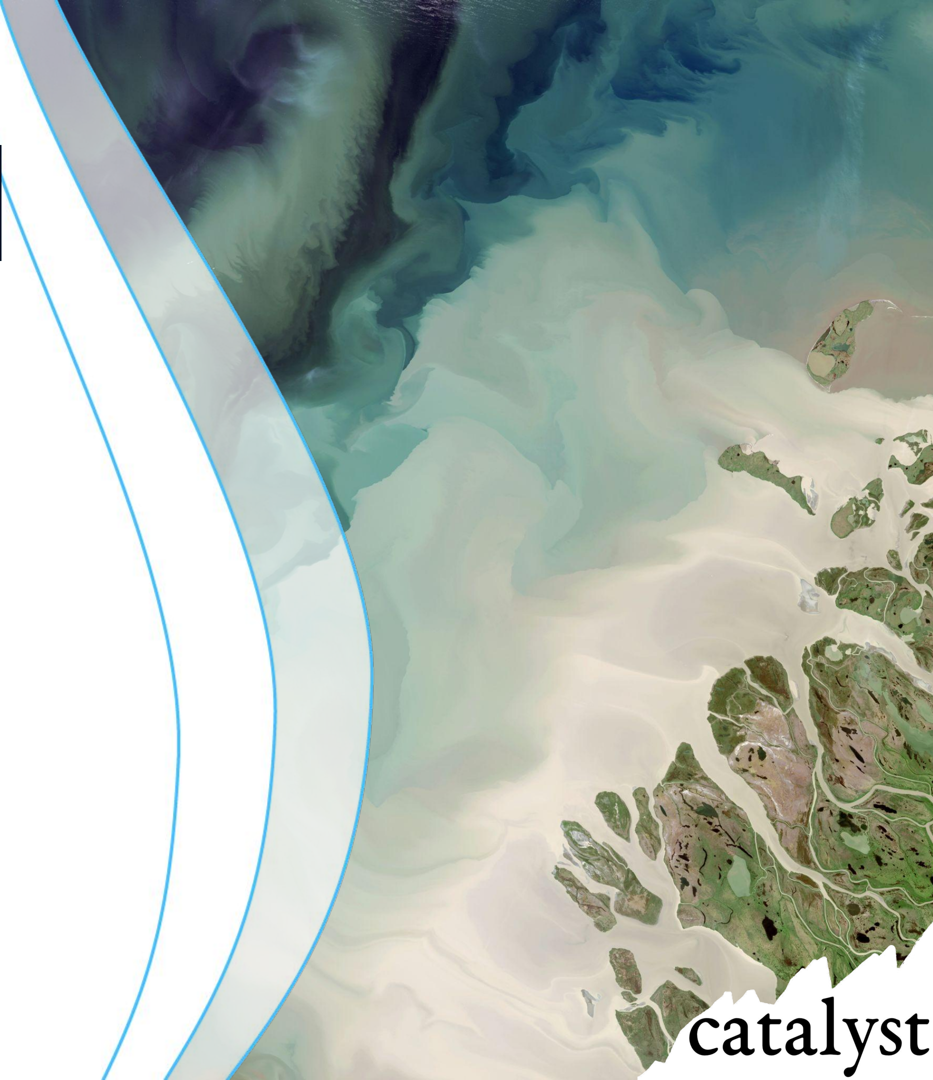
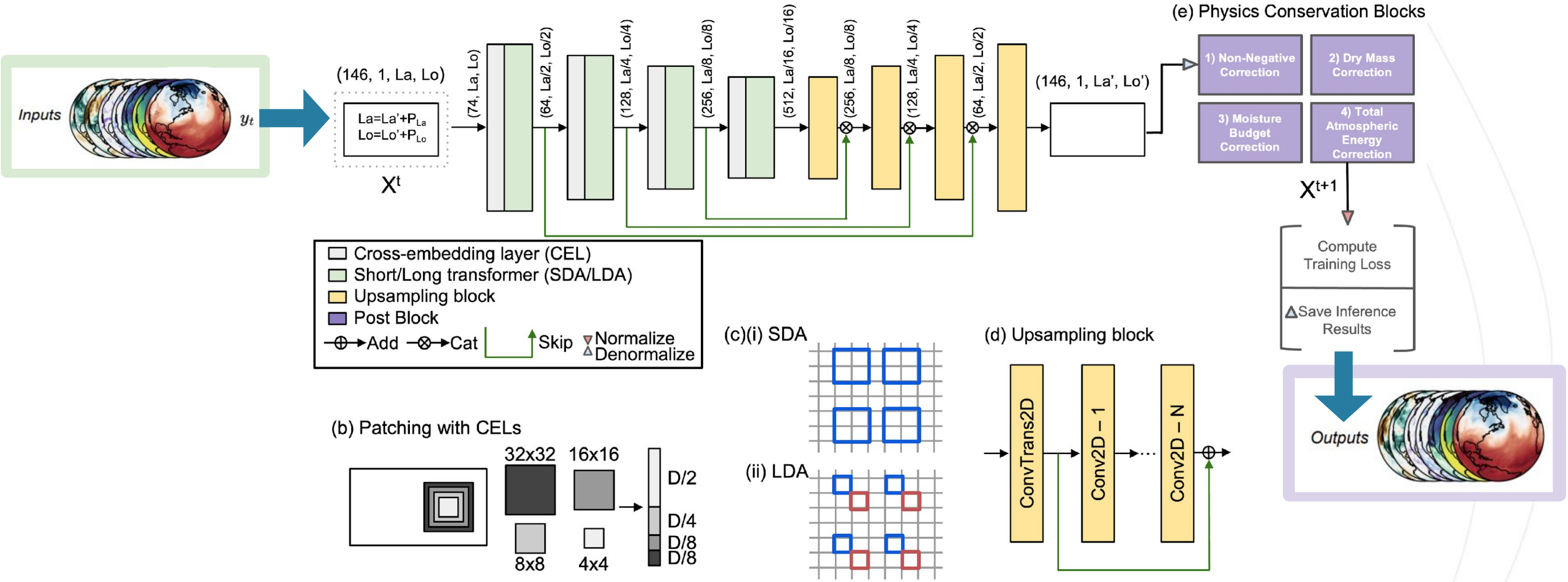


CAMulator: Emulator of the Community Atmosphere Model

Slide from Will Chapman



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