Frequently used acronyms:

CESM = Community Earth System Model
CAM = Community Atmosphere Model

Center update for NCAR

Peter Hjort Lauritzen (NCAR)

Working Group on Numerical Experimentation (WGNE) 40, November 3-7, 2025, Beijing, China

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Overview

- CESM3/CAM7 development
- New high resolution coupled CESM1.5 dataset released
- Update on software modernization effort
  (CCPP = Common Community Physics Package)
- Emulating CAM: CAMulator

CAM “manifesto”

Scope of CAM

CAM is a community model used by academia, national labs, research centers, and industry across a wide range of temporal and spatial scales.

Our “bread and butter” is
- Provide a flexible, configurable modeling system supporting coupled climate, paleo-climate, isotope, geospace (space weather), and chemistry simulations.
- Deliver community datasets, such as the CESM Large Ensemble.

Increased focus on S2S and ultra-high resolution applications!

Model versions/releases CMIP driven!

Education & Support

Bulletin board run by staff.

Yearly CESM tutorial at NCAR, tutorial yearly at AGU as well as individual tutorials at Universities (for that, CESM is usually run in the cloud).

CESM Simpler Models effort supports idealized configurations from baroclinic waves, simplified physics forcing, single-column to Aqua-planet configurations (*it used to take a gradutent students weeks to months to set up simple configurations*). CESM is used in the classrooms at Universities!

Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3
PBL Scheme				
Shallow convection				
Deep convection Scheme				
Microphysics Scheme				
Macrophysics Scheme				
Radiation Model				
Drag/Gravity wave source				
Chemistry Package				
Aerosols Model				
Dynamical cores				
Model top / #levels				
Land/Ocean Model				

Table: Evolution of CAM in terms of parameterizations, dynamical cores and model/#levels and surface components

Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3
PBL Scheme				
Shallow convection				
Deep convection Scheme				
Microphysics Scheme				
Macrophysics Scheme				
Radiation Model				
Drag/Gravity wave source				
Chemistry Package				
Aerosols Model				
Dynamical cores	**FV** EUL SLD	**FV** EUL SLD SE	**FV** EUL SE FV3	**SE-CSLAM** MPAS (SE-NH) FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model				

Default CMIP dynamical core in bold font

No horizontal resolution entry in this table since CAM has been "stuck" at ~100km horizontal grid spacing for decades!

Why? See next slide

FV/FV3 - finite-volume dycore lat-lon/cubed-sphere

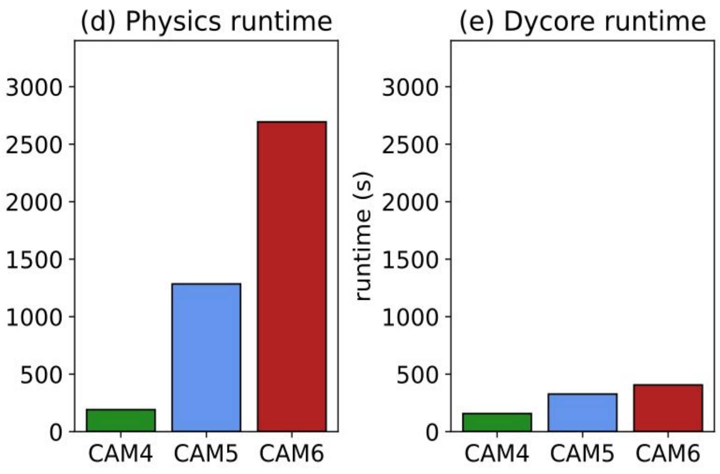
SE - spectral-element dynamical core on GLL grid
SE-CSLAM - SE with CSLAM and physics grid

EUL/SLD - spectral-transform dycore
MPAS - Model for Precition Across Scales

Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3

Figure: Computational performance metrics for CAM4 (26 levels), CAM5 (30 levels) and CAM6 (32 levels) at ~100km horizontal resolution using 144 processors and finite-volume (FV) dynamical core

Significant cost increase with model version!



Dynamics and physics are becoming more expensive

-dynamics : mostly because of tracer count and vertical resolution but also more advanced solvers!

-physics : increased complexity of process representation, aerosols, chemistry, …

Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3
PBL Scheme				
Shallow convection				
Deep convection Scheme				
Microphysics Scheme				
Macrophysics Scheme				
Radiation Model				
Drag/Gravity wave source				
Chemistry Package				
Aerosols Model				
Dynamical cores	**FV** EUL SLD	**FV** EUL SLD SE	**FV** EUL SE FV3	**SE-CSLAM** MPAS (SE-NH) FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model				

With CAM7 the model top has been moved from ~40km to ~80km and number of vertical levels from 30ish to 93 (~3x increase in cost everything else kept the same since cost scales linearly with number of levels)

We now have prognostic greenhouse gases in specified oxidants (SO) and climate chemistry (T4S) versions

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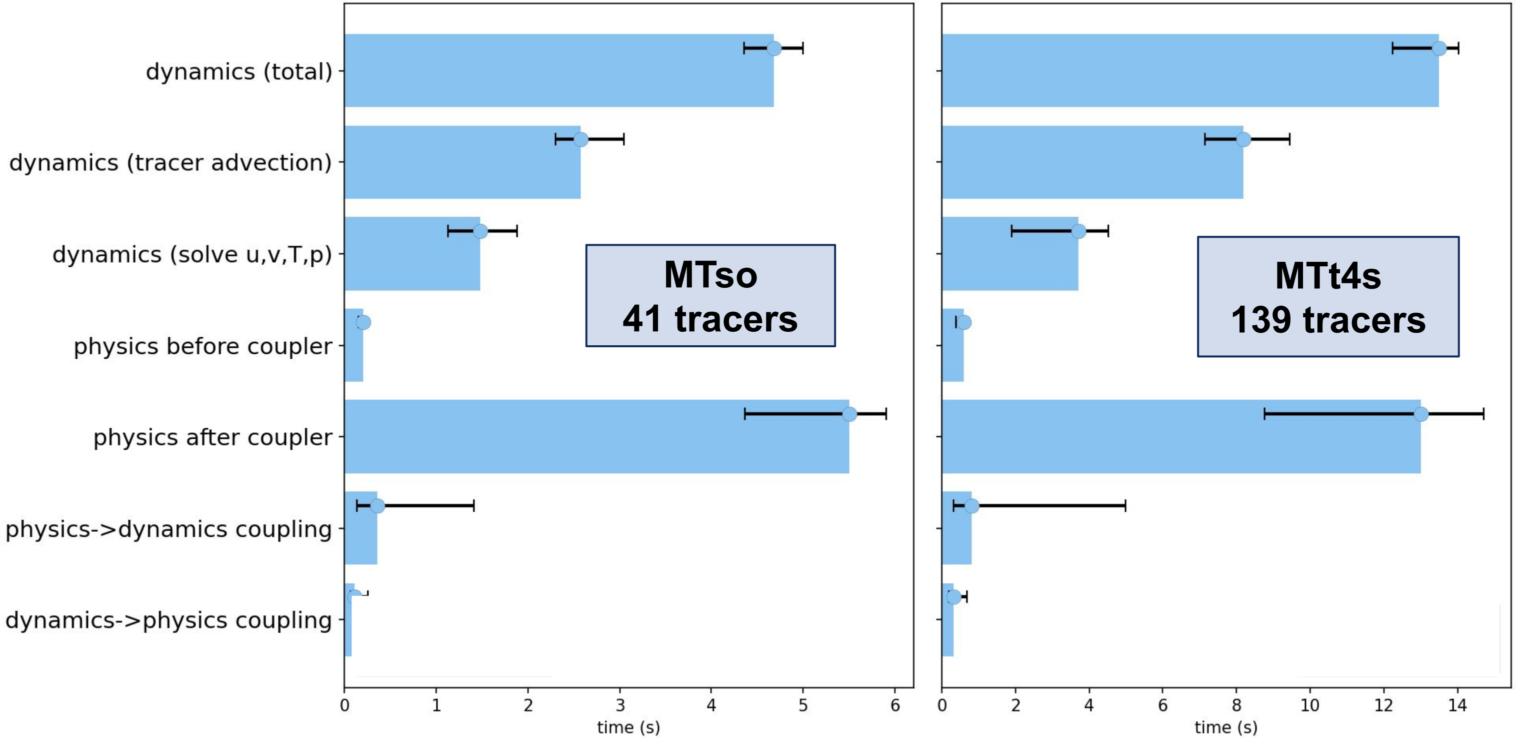
MPAS - Model for Precition Across Scales

Computational cost breakdown of CAM7 with SE-CSLAM dynamical core: MTso (specified oxidants; 41 tracers) and MTt4s (climate chemstry; 139 tracers) wth 93 levels/~80km top (5400 processors)



Blue bars: mean timing. Error bars: min/max timing

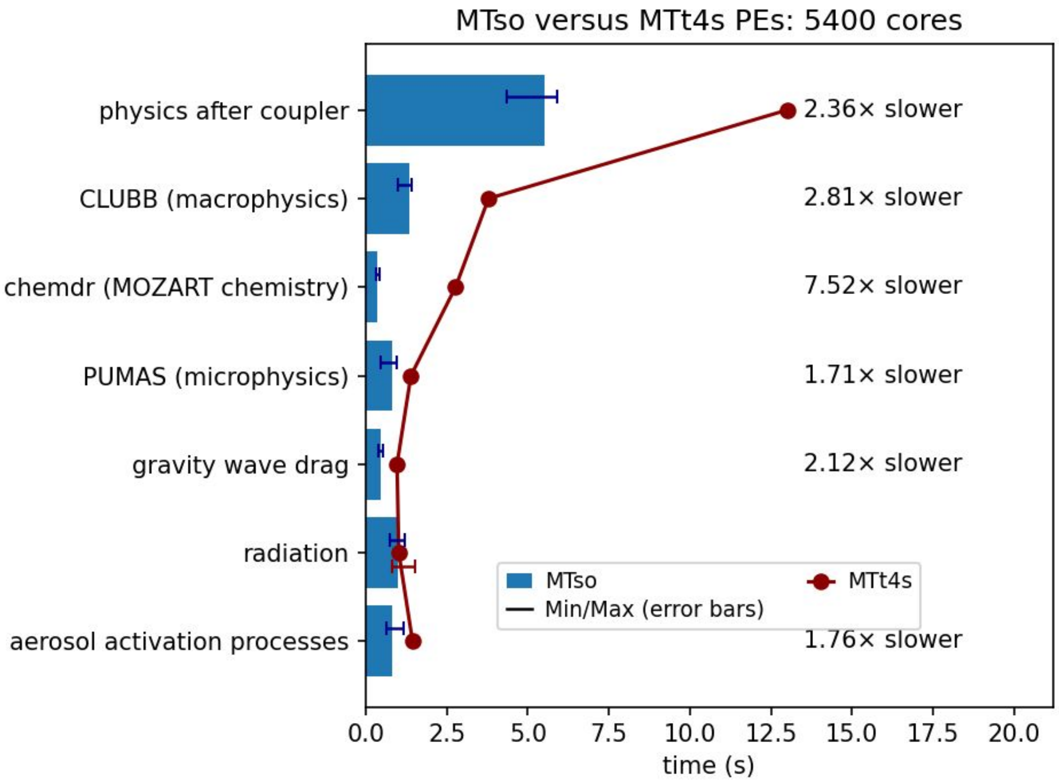
Contrary to CAM4,5,6, dynamics versus physics timings are similar …

… even between so and t4s despite 3x difference in tracer count!

Significant amount of load-imbalance

MTts4 is about 3x more expensive

Computational cost breakdown of CAM7 with SE-CSLAM dynamical core: MTso (specified oxidants; 41 tracers) and MTt4s (climate chemstry; 139 tracers) wth 93 levels/~80km top (5400 processors)



Parameterizations that perform vertical mixing of constituents (CLUBB,gravity wave scheme, …) scale (more or less) with number of tracers

Physics scheme timings (excl. deep convection which is comparatively very cheap)

Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3
PBL Scheme				
Shallow convection				
Deep convection Scheme				
Microphysics Scheme				
Macrophysics Scheme				
Radiation Model				
Drag/Gravity wave source				
Chemistry Package				
Aerosols Model				
Dynamical cores	**FV** EUL SLD	**FV** EUL SLD SE	**FV** EUL SE FV3	**SE-CSLAM** MPAS (SE-NH) FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model				

After 2+ decades we finally have a new default dynamical core!

Less grid points towards the poles than regular lat-lon grids has likely degraded polar climate simulation

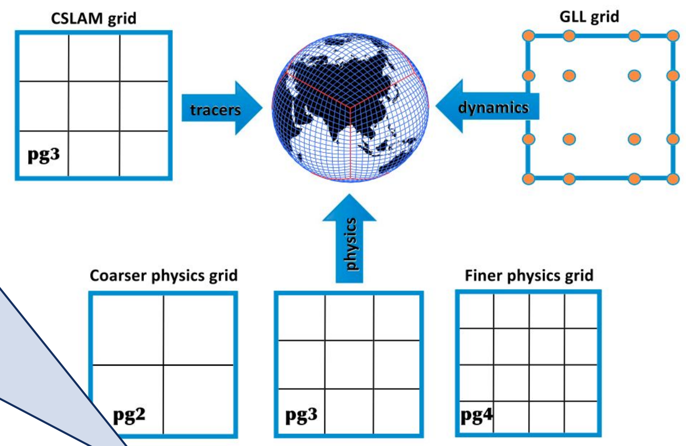


Figure 1. An overv... of the different grids in CAM-SE-CSLAM.

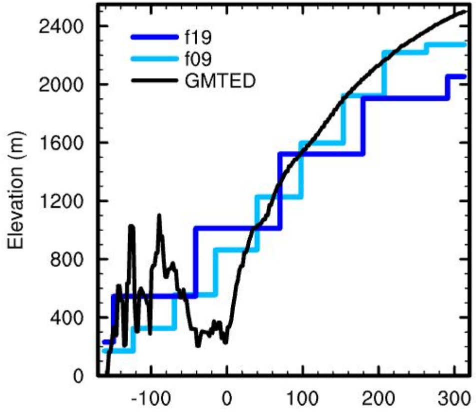
FV/FV3 - finite-volume dycore lat-lon/cubed-sphere

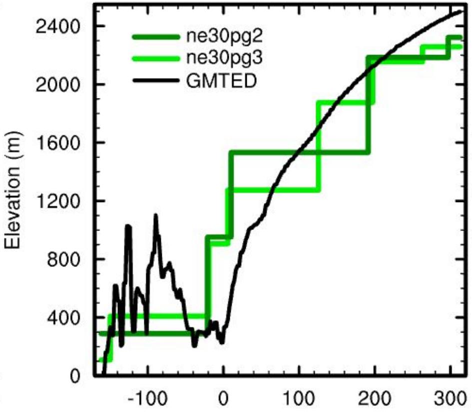
SE - spectral-element dynamical core on GLL grid
SE-CSLAM - SE with CSLAM and physics grid

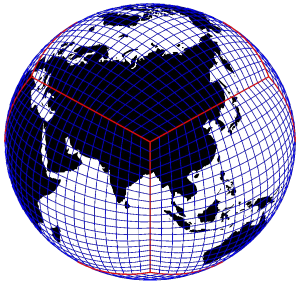
EUL/SLD - spectral-transform dycore
MPAS - Model for Precition Across Scales

Cubed-sphere versus regular lat-lon grid: Greenland

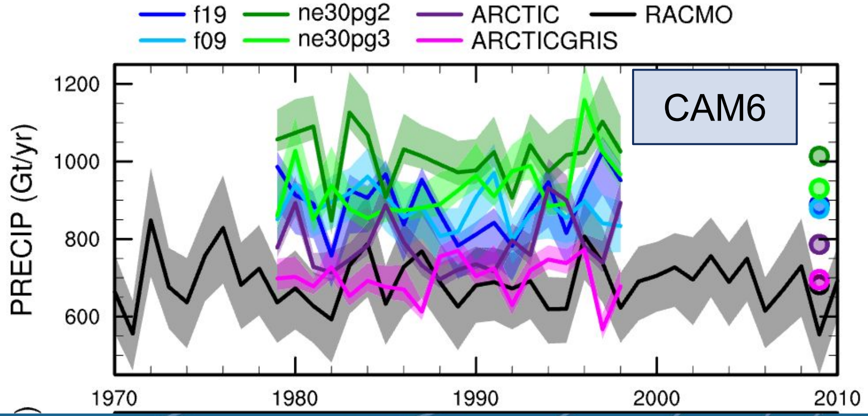
https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2022MS003192



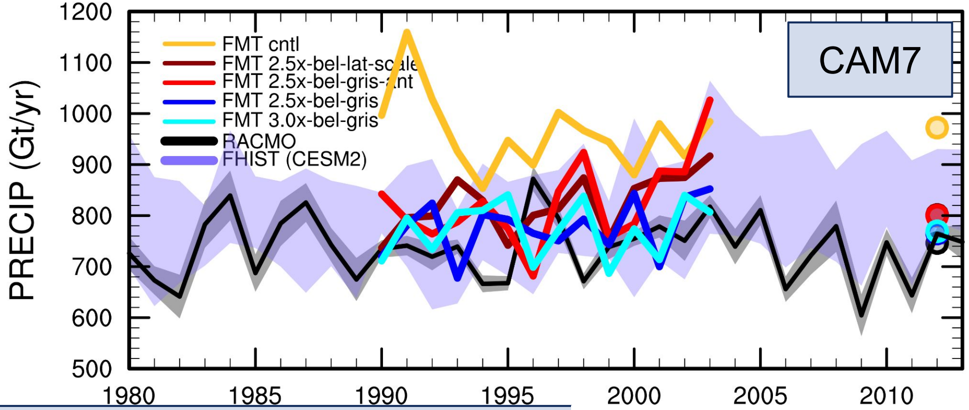




Less grid-points at Northern/Southern latitudes on cubed-sphere grid compared to lat-lon grid -> Greenland surface-mass balance biases increased when switching dynamical core/grid (blue -> green curves)!



Cubed-sphere versus regular lat-lon grid: Greenland



Artifically increasing SGH30 (=sub-grid-scale variance of topography on scales below ~5km) over Greenland (and Antartica) improves precipitation biases (yellow -> blue line in plot above)

NSF NCAR Operated by UCAR

Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3
PBL Scheme	HB	UW	CLUBB	CLUBB+ (progn. momentum fluxes)
Shallow convection	Hack	UW	CLUBB	CLUBB+ (progn. momentum fluxes)
Deep convection Scheme	ZM_mod1	ZM_mod1	ZM_mod2	ZM_mod3 / CLUBB-MF (ultra high res; ~3km)
Microphysics Scheme	RK	MG1	MG2	PUMAS
Macrophysics Scheme	Zhang	Park	CLUBB	CLUBB+ (prognostic momentum fluxes)
Radiation Model	CAMRT	RRTMG	RRTMG	RRTMG**P**
Drag/Gravity wave source	McFarlane orographic GW scheme	NOGW/TMS oro	Beljaars/NOGW/AnisoOGW	Beljaars/NOGW(+moving mountains source)/ AnisoOGW
Chemistry Package	-	MOZART	MOZART	MOZART
Aerosols Model	BAM	MAM3/CI	MAM4/CI	MAM4 (if using strat. chem. then MAM5)/CI
Dynamical cores	**FV** / EUL / SLD	**FV** / EUL / SLD / SE	**FV** / EUL / SE / FV3	**SE-CSLAM** / MPAS / (SE-NH) / FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model	CLM4/POP2	CLM4/POP2	CLM5/POP2	CLM6/MOM6

HB - Holtslag-Boville **TMS** – Turbulent Mtn Stress
NOGW – non-orographic gravity wave (**GW**); Sources: frontal and convective
{Iso/Aniso}OGW – isotropic/anisotropic orog. GW
CI - cloud droplet activation and ice nucleation
FV/FV3 - finite-volume dycore lat-lon/cubed-sphere

MG – Morrison Gettelman **UW** – U.Washington
ZM - Zhang-McFarlane
CLUBB - Cloud Layers Unified By Binormals
CLUBB-MF - Unified deep-shallow convection
SE - spectral-element dynamical core on GLL grid
SE-CSLAM - SE with CSLAM and physics grid

RT - Radiative Transfer
RRTMGP – Rapid Radiative Transfer Model
MAM – Model Aerosol Model
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Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3
PBL Scheme	HB	UW	CLUBB	CLUBB+ (progn. momentum fluxes)
Shallow convection	Hack	UW	CLUBB	CLUBB+ (progn. momentum fluxes)
Deep convection Scheme	ZM_mod1	ZM_mod1	ZM_mod2	ZM_mod3 | CLUBB-MF (ultra high res; ~3km)
Microphysics Scheme	RK	MG1	MG2	PUMAS
Macrophysics Scheme	Zhang	Park	CLUBB	CLUBB+ (prognostic momentum fluxes)
Radiation Model	CAMRT	RRTMG	RRTMG	RRTMG**P**
Drag/Gravity wave source	Mo[illegible] GV[illegible]	[illegible]	[illegible]	Beljaars/NOGW(+moving mountains source)/ AnisoOGW
Chemistry Package	-	MOZART	MOZART	MOZART
Aerosols Model	BAM	MAM3/CI	MAM4/CI	MAM4 (if using strat. chem. then MAM5)/CI
Dynamical cores	**FV** | EUL | SLD	**FV** | EUL | SLD | SE	**FV** | EUL | SE | FV3	**SE-CSLAM** | MPAS | (SE-NH) | FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model	CLM4/POP2	CLM4/POP2	CLM5/POP2	CLM6/MOM6

New sources of parameterized gravity waves

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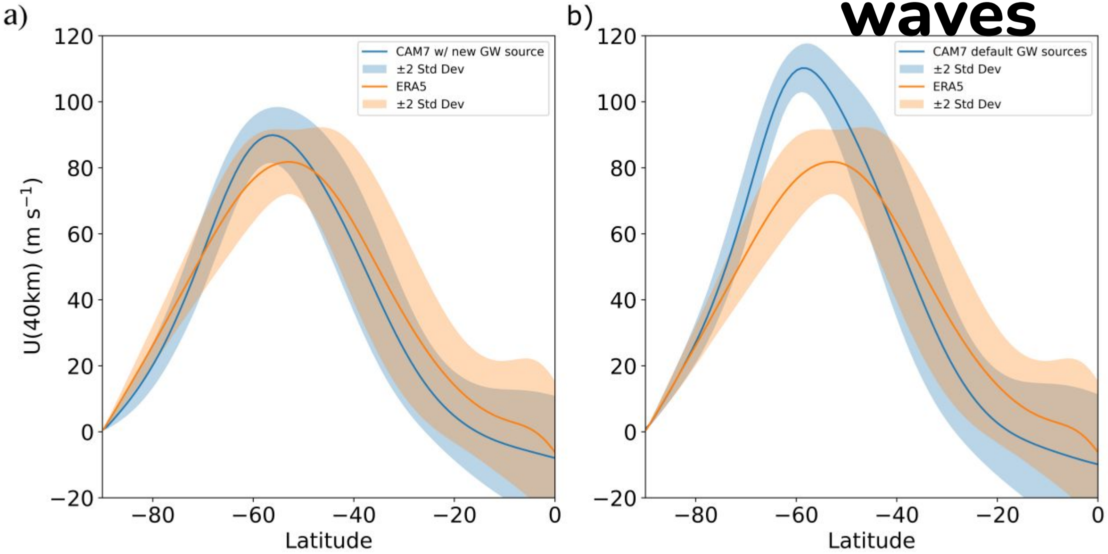
Improving representation of stratospheric Polar Vortex in Southern Hemisphere with low-frequency frontal waves



Mean zonal mean zonal wind speed for JJA at 45 km altitude of in: a) CAM7 with the new parameterization (blue) and ERA5 (orange) and b) CAM7 w/o the parameterization (blue) and ERA5 (orange). Shading in both panels shows ±2σ range.

For the simulation of the polar vortex representation of the wind speed and the tilt of the jet axis has been a long-standing challenge. Inclusion of low-frequency frontal gravity waves (GWs) lead to major improvement in the representation of the Southern Hemisphere Polar Vortex. Both, the wind speed and the tilt of the jet axis have been improved by including this new parameterization. This may open up new possibilities for sub-seasonal to seasonal forecasting research.

Paper: Bramberger and Bacmeister, "Improving representation of stratospheric Polar Vortex in Southern Hemisphere with low-frequency frontal waves" , GRL, in rev.

Version (release date) Coupled Model version	CAM4 (April 2010) CCSM4	CAM5 (June 2011) CESM1	CAM6 (June 2017) CESM2	CAM7 CESM3
PBL Scheme	HB	UW	CLUBB	C... BB+ (progn. momentum fluxes)
Shallow convection				...progn. momentum fluxes)
Deep convection Scheme				CLUBB-MF (ultra high res; ~3km)
Microphysics Scheme				
Macrophysics Scheme	Zhang	Park	CLUBB	C... B+ (prognostic momentum fluxes)
Radiation Model	CAMRT	RRTMG	RRTMG	RRTMG**P**
Drag/Gravity wave source	McFarlane orographic GW scheme	NOGW/TMS oro	Beljaars/NOGW/AnisoOGW	Beljaars/NOGW(+moving mountains source)/ AnisoOGW
Chemistry Package	-	MOZART	MOZART	MOZART
Aerosols Model	BAM	MAM3/CI	MAM4/CI	MAM4 (if using strat. chem. then MAM5)/CI
Dynamical cores	**FV** / EUL / SLD	**FV** / EUL / SLD / SE	**FV** / EUL / SE / FV3	**SE-CSLAM** / MPAS / (SE-NH) / FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model	CLM4/POP2	CLM4/POP2	CLM5/POP2	CLM6/MOM6

When we run at ~3km horizontal resolution (using MPAS dynamical core) CAM7 physics optimized for ~100km leads to "pop corn" convection

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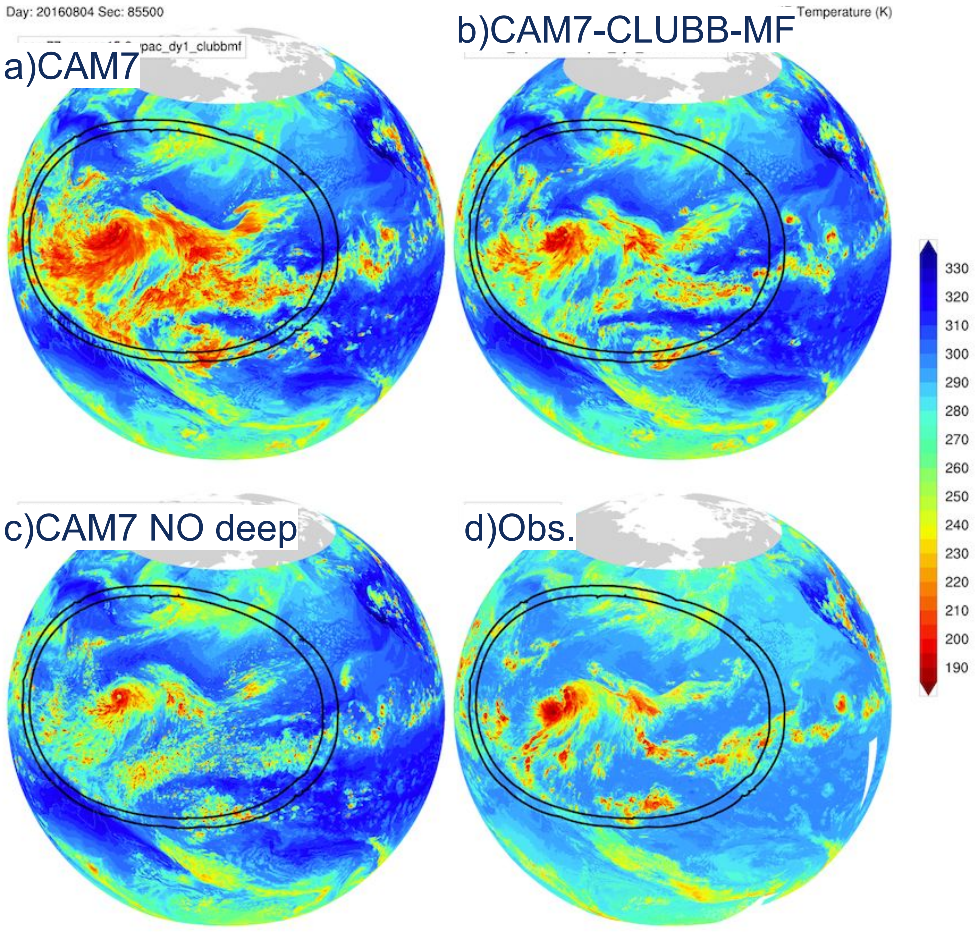

West Pacific Mesh (15→3 km)

- Cost 17M core hrs p sim. yr
- 8M grid columns (running on 16k pes)

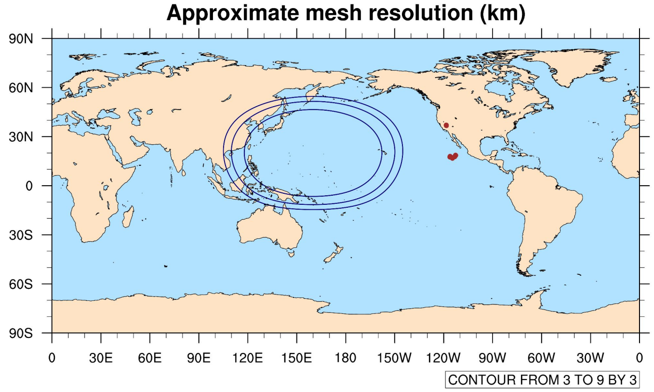

Figure: Brightness Temperature (K) snapshots from forecasts after 1 day for CAM7-MPAS with a global resolution of 15 km refined to 3 km within the black lined region for a) CAM7 optimized for low-resolution, b) CAM7 optimized for km-scale, c) CAM7 turning off parameterization of deep convection, and d) Observed geostationary IR channel brightness temperature

NSF funded project to import DOE's non-hydrostatic spectral-element dynamical core (SE-NH) into CAM. Why?

- SE-CSLAM is hydrostatic and will not be developed further after CESM3
- SE-NH is non-hydrostatic and uses ultra-fast semi-Lagrangian transport scheme (see presentation on WGNE physics-dynamics coupling effort)
- SE-NH is coded in C++/Kokkos, i.e. excellent GPU support
- Separate physics grid (like SE-CSLAM) but supports variable resolution!

Version (release date)	CAM4 (April 2010)	CAM5 (June 2011)	CAM6 (June 2017)	CAM7
Coupled Model ve				
PBL Scheme				
Shallow convecti				
Deep convection				h res; ~3km)
Microphysics Sch				
Macrophysics Sc				s)
Radiation Model				
Drag/Gravity wav				ource)/
Chemistry Packag				
Aerosols Model	BAM	MAM3/CI	MAM4/CI	MAM4 (if using ... n then MAM5)/CI
Dynamical cores	**FV** EUL SLD	**FV** EUL SLD SE	**FV** EUL SE FV3	**SE-CSLAM** MPAS (SE-NH) FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model	CLM4/POP2	CLM4/POP2	CLM5/POP2	CLM6/MOM6

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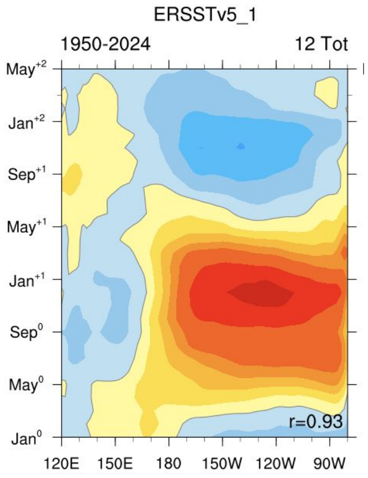
MPAS - Model for Precition Across Scales

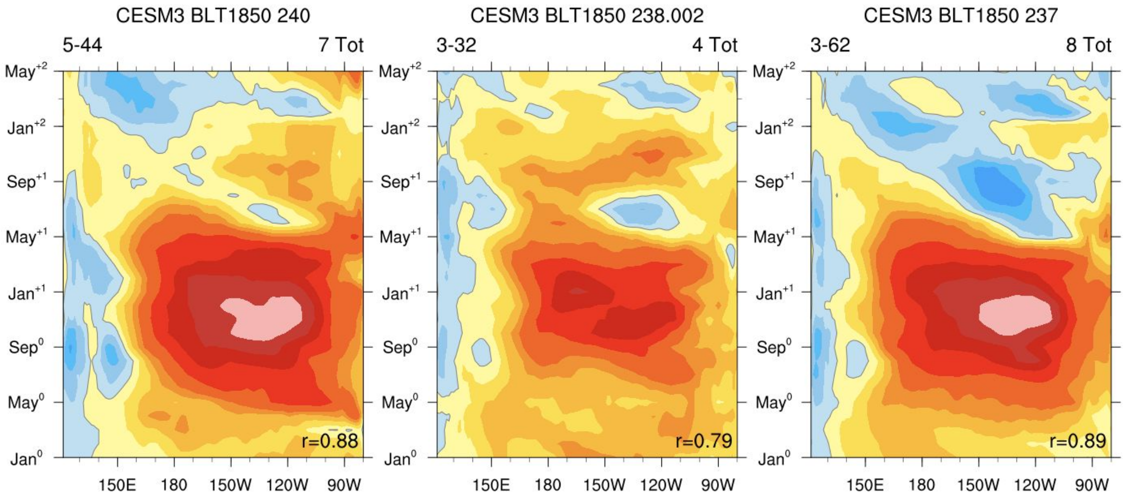
CESM3 issues: La Nina transition

Struggling with El Nino -> La Nina transition. And El Nino event amplitude is too large.

OBS

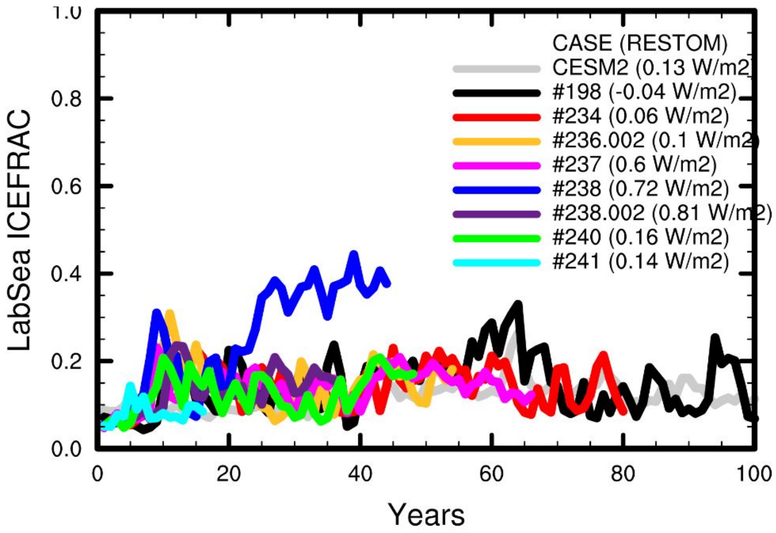


Different CESM3 candidate configurations



CESM3 issues: Lab sea freeze

Labrador Sea freeze is still haunting us: was an issue in CESM2 and despite switching ocean component and dynamical core/grid in atmosphere, it is still an issue!

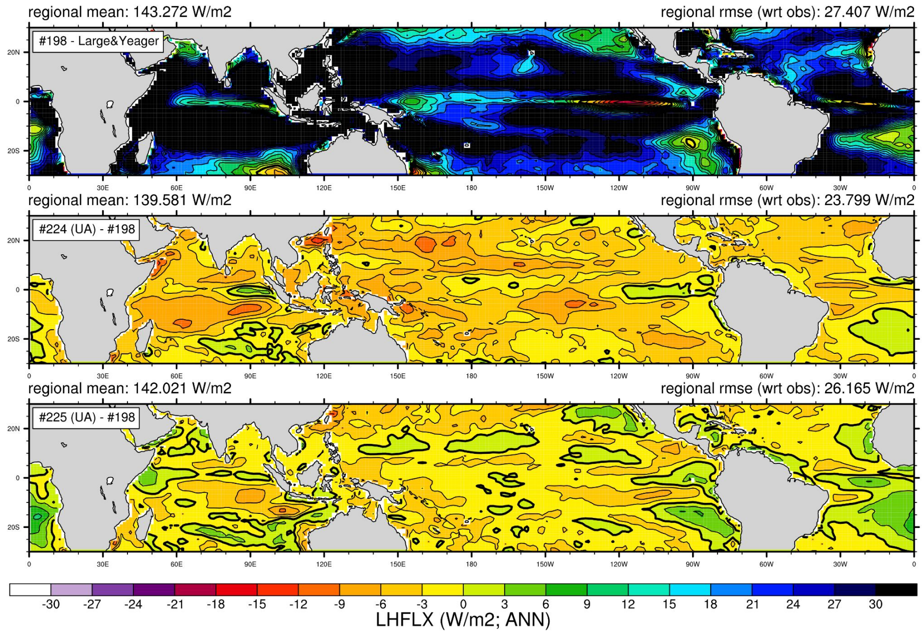


For run #238 and #238.002 the only difference is round-off pertubation in atmopshere -> prevents Lab sea freeze!

Ocean model mixing parameterizations are a factor!

CESM3 issues: latent heat flux

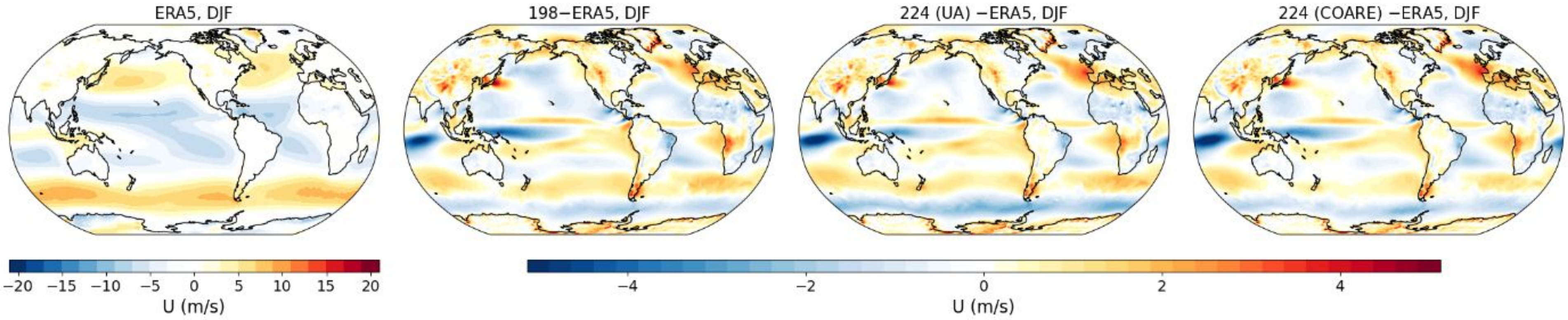
Our hydrological cycle is too vigorous: latent heat fluxes are larger than ERA5 (and ERA5 is likely overestimating latent heat fluxes)



Latent heat flux (upper) bias in run #198, difference between runs with different bulk schemes and #198 (middle, lower, respectvely).

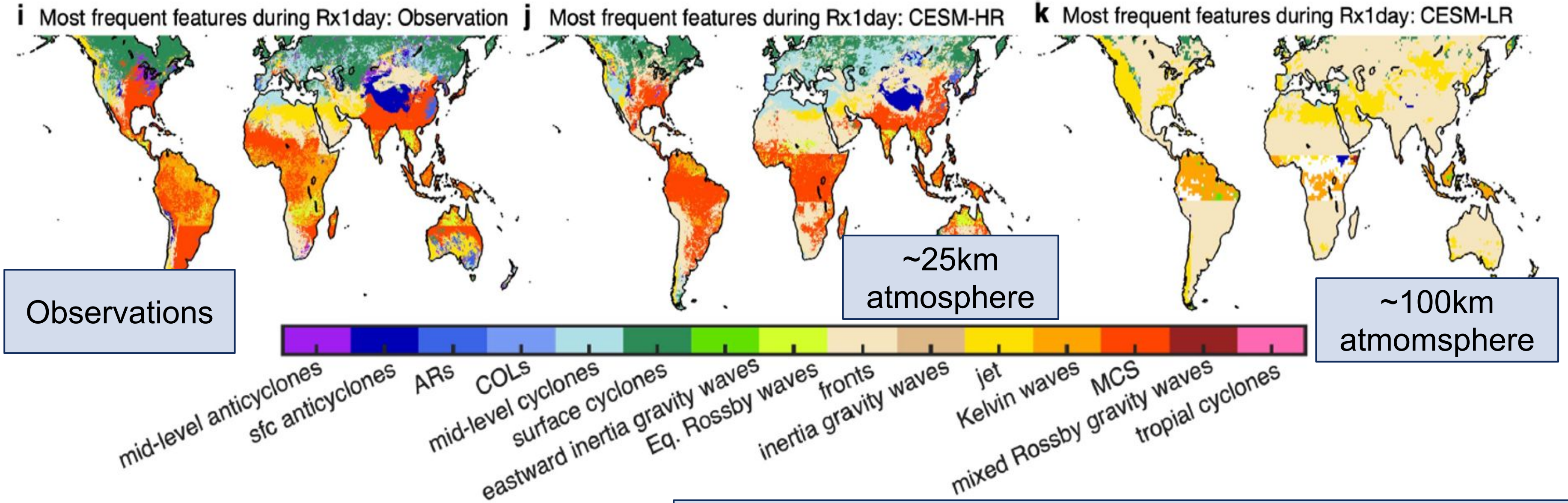
The large latent heat flux could be due to excessive surface winds (i.e. probably not enough drag). See next slide

CESM3 issues: surface winds



DJF lowest model wind biases wrt to ERA5 for #198 with various bulk schemes
(see plot titles for details)

High resolution coupled climate model dataset: MESACLIP



Atmospheric Phenomena Associated with Extreme Precipitation Events

The CESM high-resolution (CESM-HR) simulations performed under the MESACLIP

MESACLIP: Understanding the Role of MESoscale Atmosphere-Ocean Interactions in Seasonal-to-Decadal CLImate Prediction

Chang, P., D. Fu, X. Liu, F. Castruccio, A. F. Prein, G. Danabasoglu, X. Wang, J. Bacmeister, Q. Zhang, N. Rosenbloom, T. King, and S. C. Bates, 2025: Atmospheric dynamical amplification intensifies future extreme precipitation events. *Nature Geoscience* (in press).

Hard coded physics scheme order

cam_development = current "operational" CAM code base in CESM

Old framework using Fortran physics driver (physpkg.F90), pbuf for passing variables between schemes, old I/O, build namelist using Perl (old), …

CAM-SIMA = new CAM code base

New framework to support CCPP convention, modularized I/O, modernized (Python) namelist handling, …

Generalized suites (shared between modeling systems)

Generalized constituents handling (object)

Shared CCPP'ized physics schemes located in https://github.com/ESCOMP/atmospheric_physics/tree/main/schemes

Non-CCPP'ized physics schemes and utility modules

Host model utility functions/modules, grid, composition, I/O functionality, thermal functions …

dycores

SE-CSLAM, FV, FV3
MPAS (external)
[SE-NH is on a fork of cam_development not in cam_development]

Each have their own tailored physics-dynamics coupling layer

dycores

Copy(ish) of SE-CSLAM dycore
with dynamic allocation of vertical levels and tracers

Similar for MPAS though MPAS is brought in as an external

Each have their own tailored physics-dynamics coupling layer

Version Coupled Model version	CAM-SIMA CAM4ish CESM3	CAM-SIMA CAM5ish CESM3	CAM-SIMA CAM6ish CESM3	CAM-SIMA CAM7 CESM3
PBL Scheme	HB	UW	CLUBB	CLUBB+ (progn. momentum flux)
Shallow convection	Hack	UW	CLUBB	CLUBB+ (progn. momentum flux)
Deep convection Scheme	ZM_mod1	ZM_mod1	ZM_mod2	ZM_mod3 / CLUBB-MF (ultra high res; ~3km)
Microphysics Scheme	RK	PUMAS (~~MG1~~)	PUMAS (~~MG2~~)	PUMAS
Macrophysics Scheme	Zhang	Park	CLUBB	CLUBB+ (prognostic momentum fluxes)
Radiation Model	RRTMG**P** (~~CAM-RT~~)	RRTMG**P**(~~RRTMG~~)	RRTMG**P** (~~RRTMG~~)	RRTMG**P**
Drag/Gravity wave source	McFarlane orographic GW scheme	NOGW/TMS oro	Beljaars/NOGW/AnisoOGW	Beljaars/NOGW(+moving mountains source)/ AnisoOGW
Chemistry Package	-	MOZART	MOZART	MOZART
Aerosols Model	BAM	MAM3/CI	MAM4/CI	MAM4 (if using strat. chemistry then MAM5)/CI
Dynamical cores	**FV** / EUL / SLD	**FV** / EUL / SLD / SE	**FV** / EUL / SE / FV3	**SE-CSLAM** / MPAS / (SE-NH) / FV
Model top / #levels	~42km /26	~42km / 30	~42km / 32	~80km/93 (Mid Top: **MT**) & ~42km/58 (Low Top: **LT**)
Land/Ocean Model	CLM4/POP2	CLM4/POP2	CLM5/POP2	CLM6/MOM6

Color key:

Green	Ported to CCPP
Yellow	Actively being ported

CCPP = Common Community Physics Package

CAMulator: Fast Emulation of the Community Atmosphere Model

William E. Chapman, John S. Schreck, Yingkai Sha, David John Gagne II, Dhamma Kimpara, Laure Zanna, Kirsten J. Mayer, Judith Berner

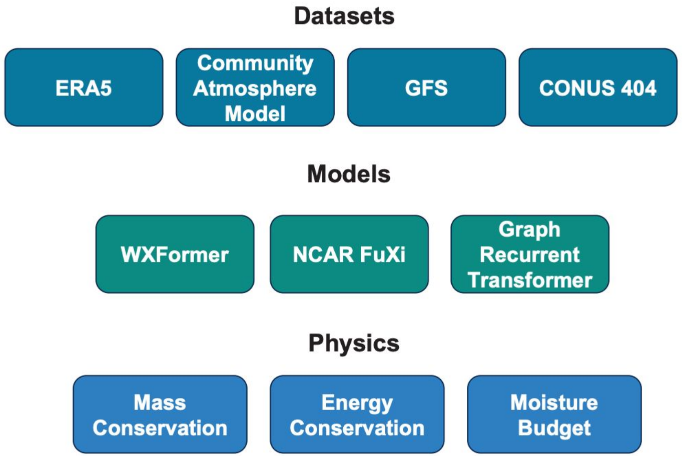
Our Framework: CREDIT

What is CREDIT?

An open foundational platform for developing and deploying AI weather and Earth system prediction models.

CREDIT enables users to build custom data and modeling pipelines to load data, train configurable AI forward models, and deploy them for real-time forecasting, hindcasting, or scenario projections.

CREDIT offers both scientifically validated model configurations and endless customization for any use case.



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