Impact of Numerical Choices on Water Conservation in the E3SM Atmosphere Model

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Acknowledgement:
Andrew Gettelman, Erika Roesler, Anthony Craig, Peter Laurizen
All other E3SM team members

Motivation

- **Energy Exascale Earth System Model**
- **Water** is the other most important quantity that E3SM cares about:

  "How do the hydrological cycle and water resources interact with the climate system on local to global scales?"

- Climate projection simulations are often more than a century long
  - It is important to reduce accumulative errors (even they are small in short simulations)

Motivation

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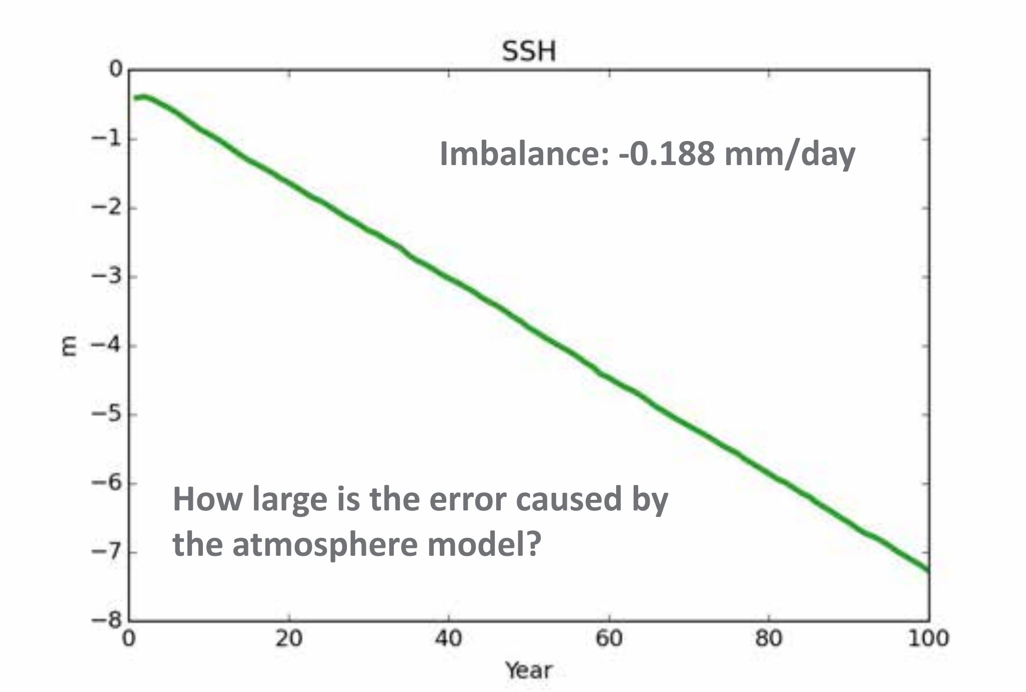
Evolution of simulated global mean Sea Surface Height (SSH) over 100 years using an old version of E3SM (alpha6_01 1850 CTRL)



Water budget terms

Evaporation
Sea ice fresh water
River runoff
Ice runoff
Rain
Snow
Frazil

https://acme-climate.atlassian.net/wiki/spaces/SIM/pages/79823075/2016-07-11+Coupled+-+Tune+and+validate+Task+meeting+notes

Sea Level Rise and Water Conservation

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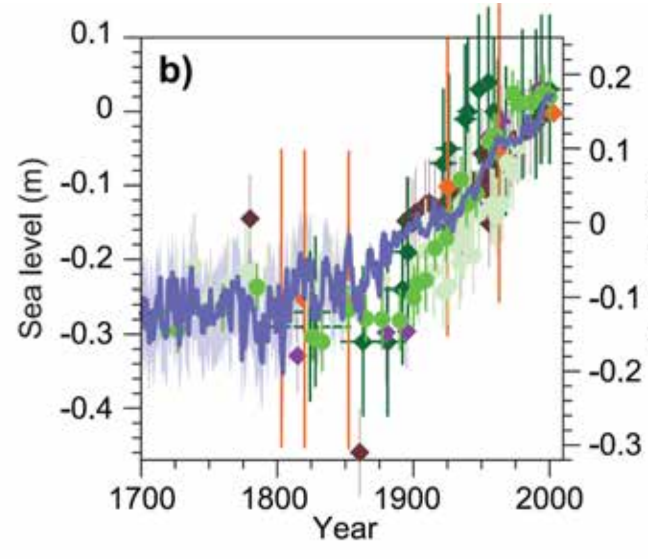
Observed Sea Level Rise
~ 30 cm from 1900 to 2000



Reconstructed from tide gauges
Source: IPCC AR5 Report

With a relative total water conservation error (to total precipitation) of about **0.3%** (per year), the model will simulate the same amount of sea level rise in a century-long simulation as we observed in the past century.

Small errors are not always trivial !!

Small Errors Often Come along with Model Development

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- New features/capabilities bring new challenges
- They might be incompatible with other components
- Fixing one problem might cause a further problem
- Sometimes these errors are not obvious

Small errors can cause big problems.

Fire mainly caused by the insufficient insulation tape between the positive and negative sides of the battery
Source: https://www.cnet.com/news/why-is-samsung-galaxy-note-7-exploding-overheating/

Results from An Earlier Version of E3SM

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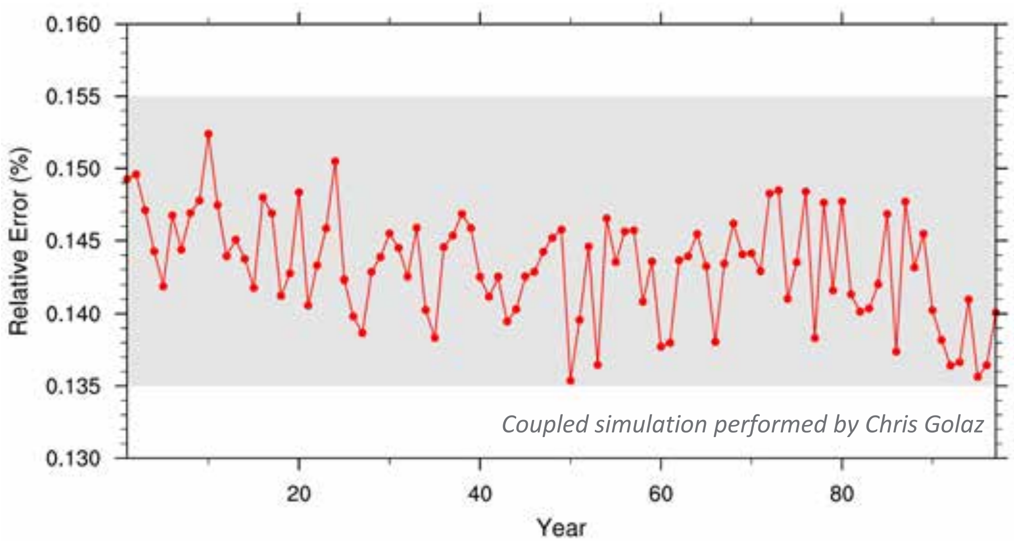
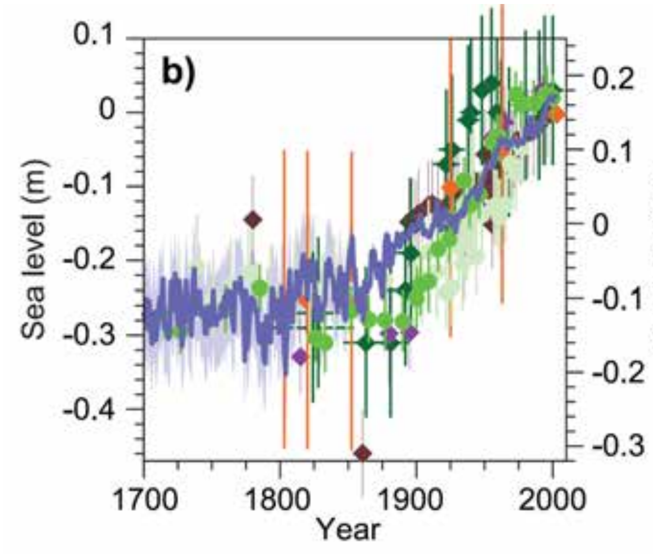
Implied sea level rise due to water conservation error caused by the atmosphere model in 100 years: 14.5 cm



Water conservation error relative to the annual mean precipitation flux

Observed Sea Level Rise
~ 30 cm from 1900 to 2000



Reconstructed from tide gauges
Source: IPCC AR5 Report

Water Conservation Error

For a given period: (t-1) to (t)

Error = W_modeled - W_expected

W_expected = W(t-1) - PRECT*dt + QFLX*dt

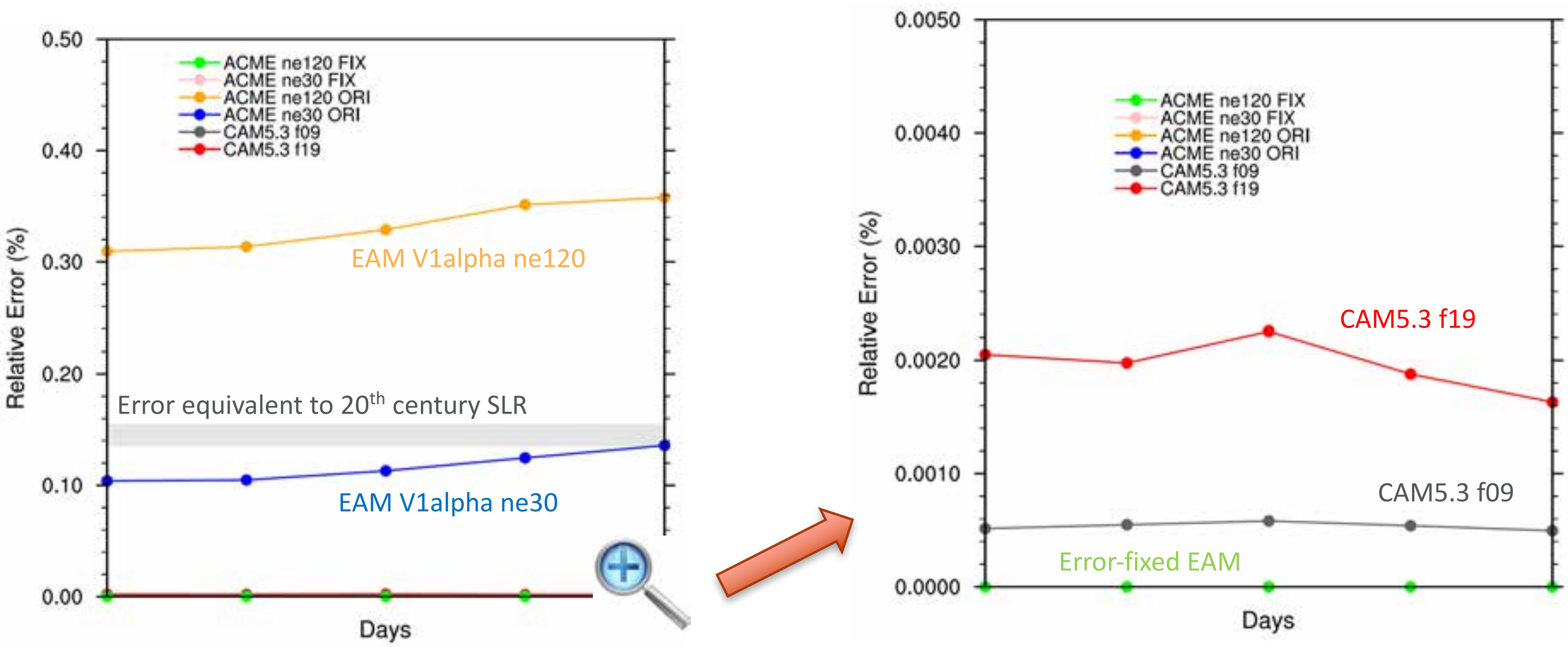
W_modeled = W(t)

W: *the total water storage in the atmosphere (kg m^{-2}), including water vapor, cloud liquid, cloud ice, rain, and snow.*

PRECT: *total precipitation flux (kg m^{-2} s^{-1}).*

QFLX: *surface moisture flux (kg m^{-2} s^{-1}).*

CAM5.3 versus EAM



What has been changed?

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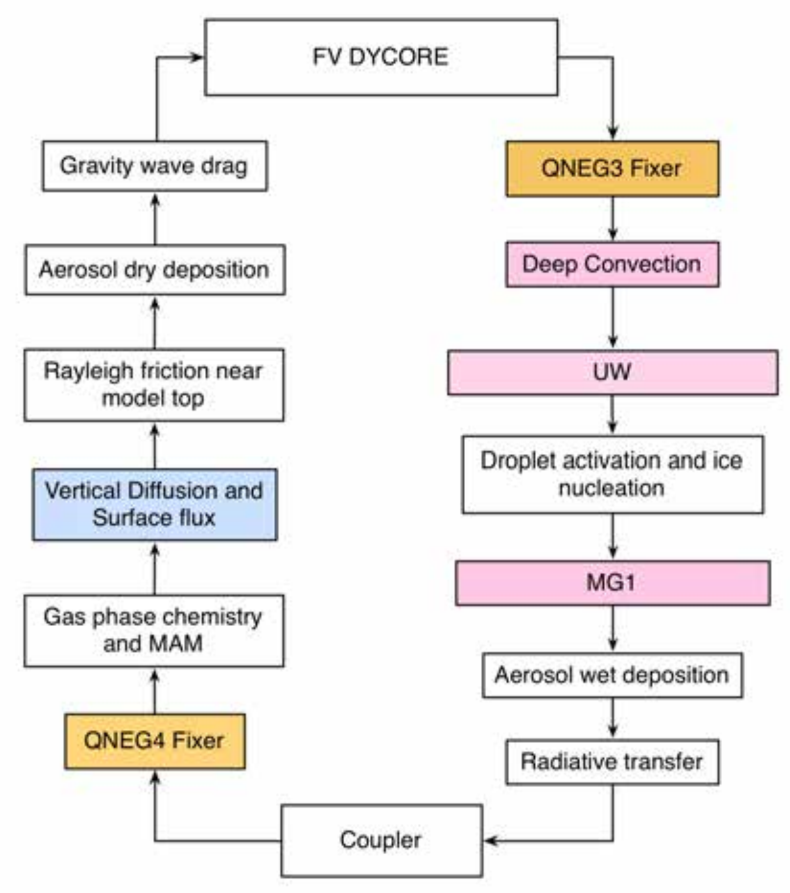
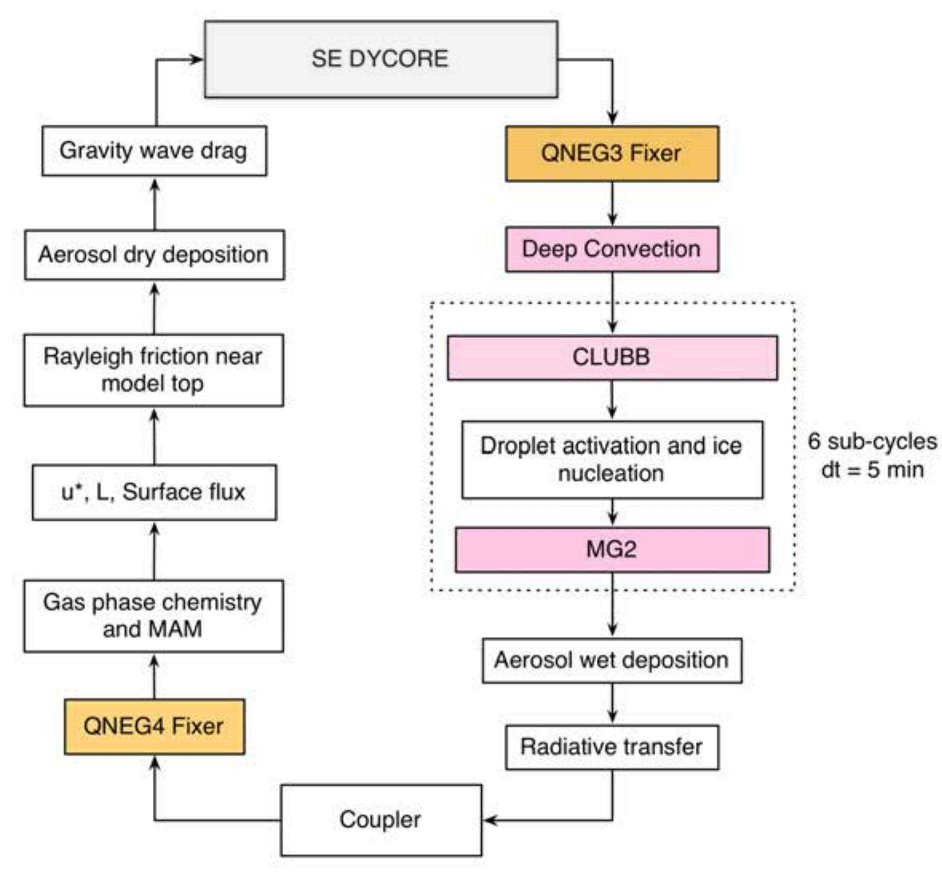
CAM5.3 FV L30



EAM V1alpha SE L72

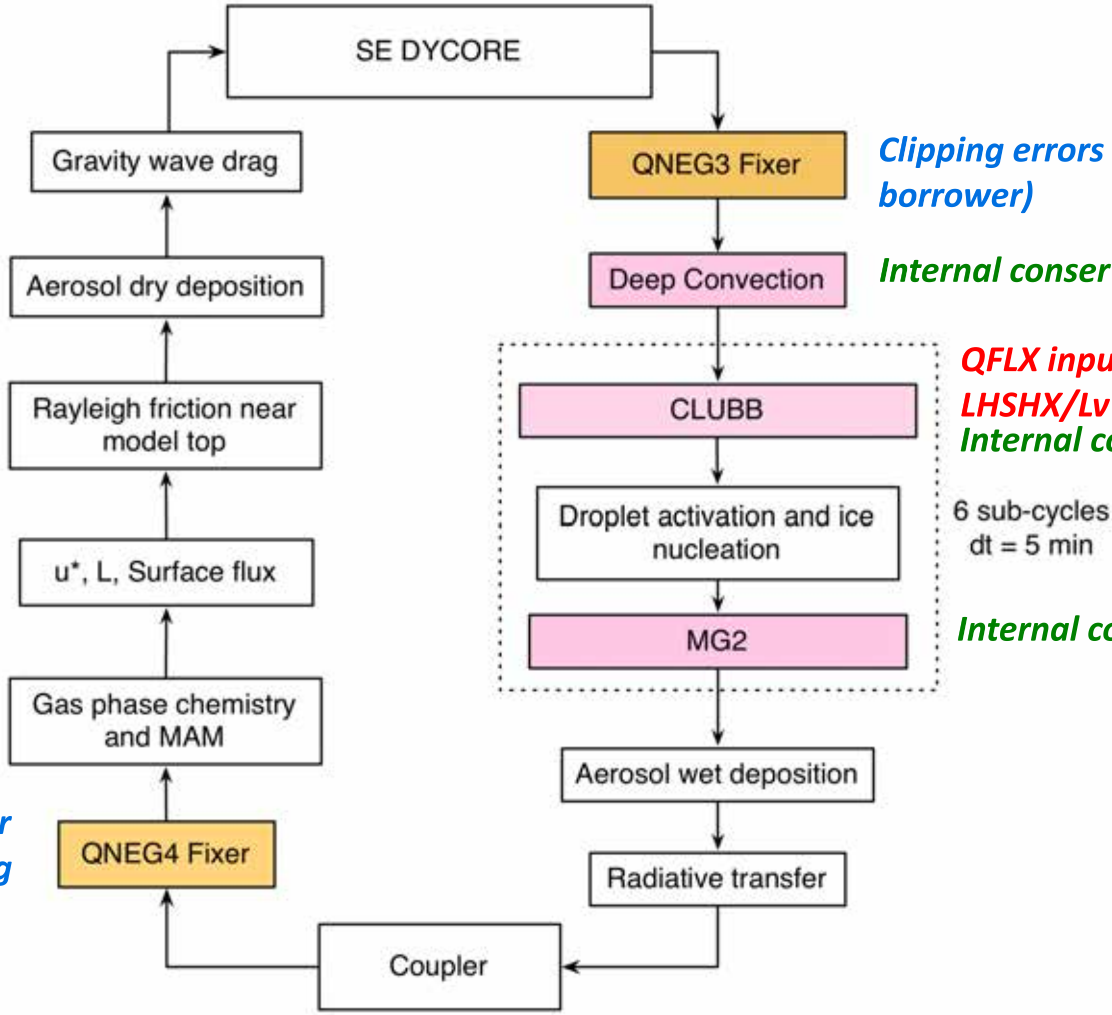


Problems Identified in ACME

Physics-Dynamics Coupling Errors (solution: ftype 0→ 2) (PDC)

- *Large and corrected*
- *Small and not corrected*
- *To be corrected in future versions*

The model is very frequently corrected by QNEG4 due to:
1. Reordering of the vdiff/CLUBB process
2. Very thin surface layer



Clipping errors (solution: mass borrower)

Internal conservation error (INT)

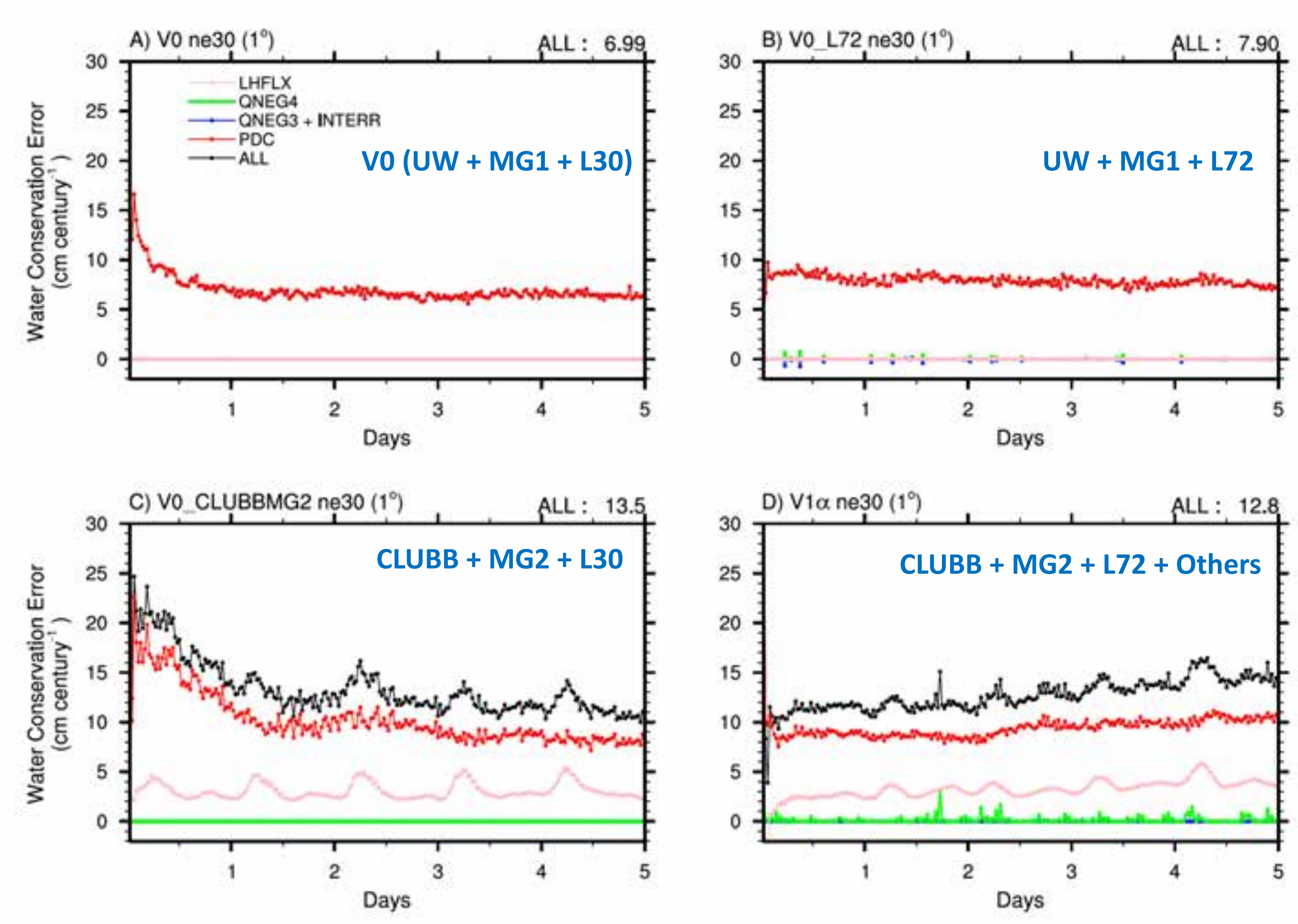
QFLX input error (solution: LHSHX/Lv → QFLX)
Internal conservation error

Internal conservation error

QFLX correction error (solution: adjust water vapor profile rather than correcting QFLX)
Moved to the place before CLUBB is called.

Error Quantification for EAM

Error Sources: PDC   LHFLX (only in C & D)   QNEG4   QNEG3   INTERR



Physics-Dynamics Coupling Errors

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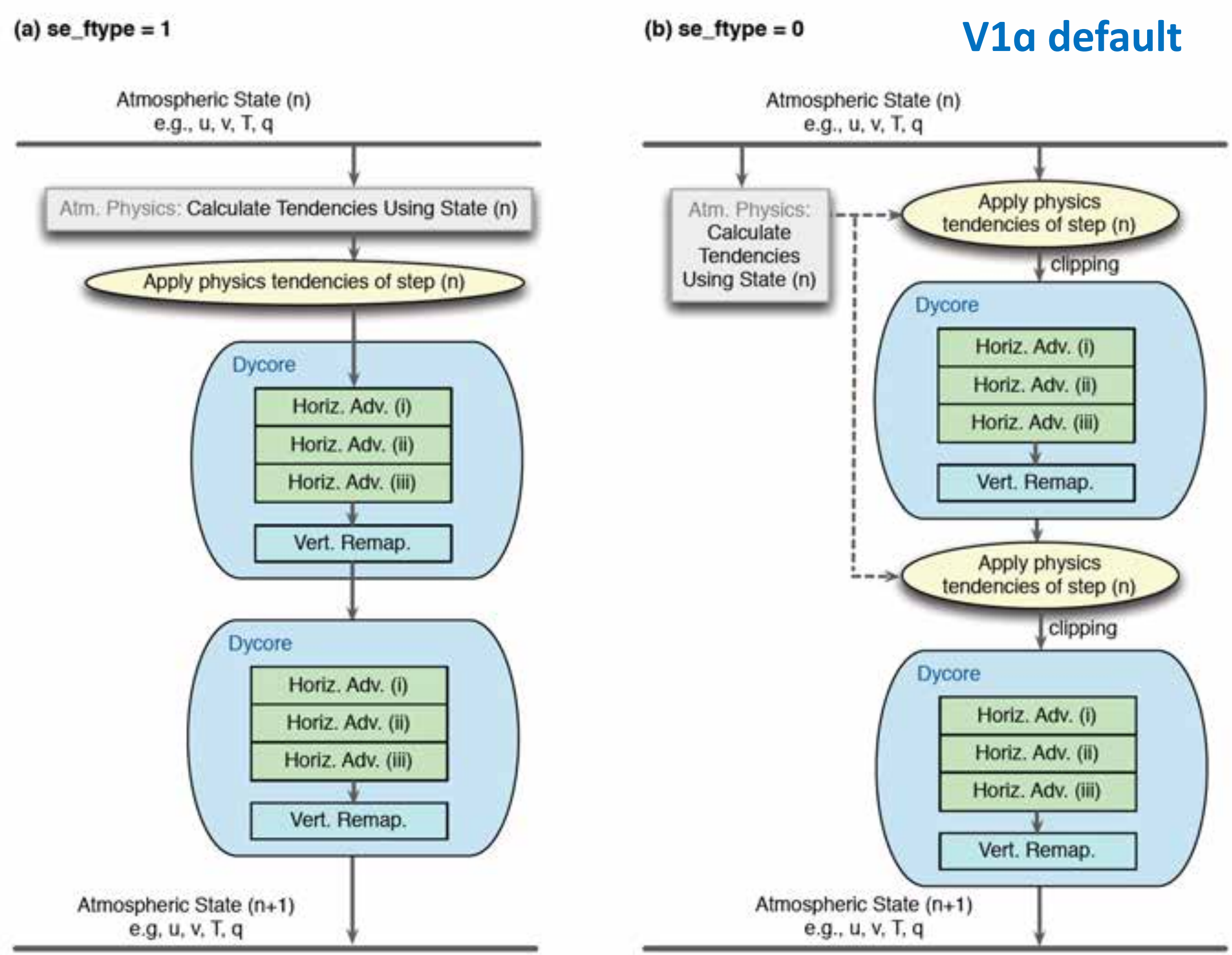
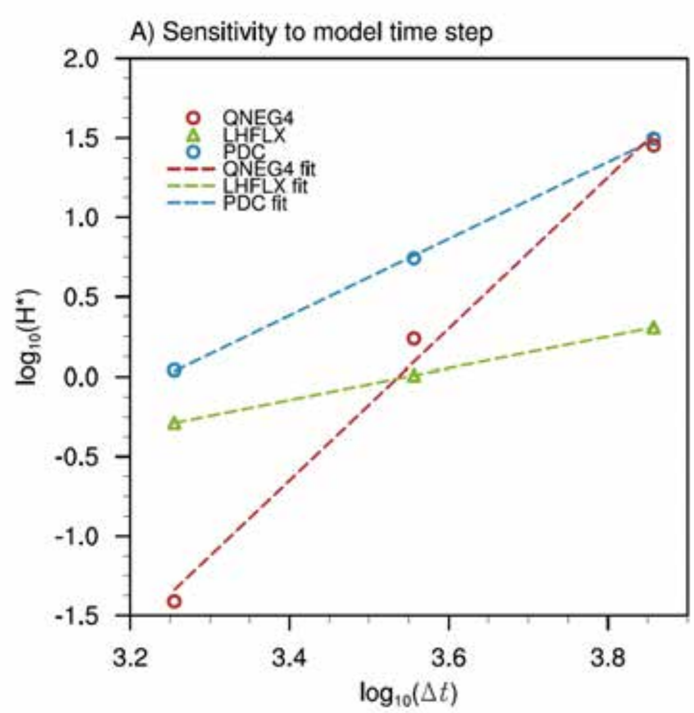


V1α default

Old physics tendency is not consistent with the new state; negative tracer can appear, and be clipped

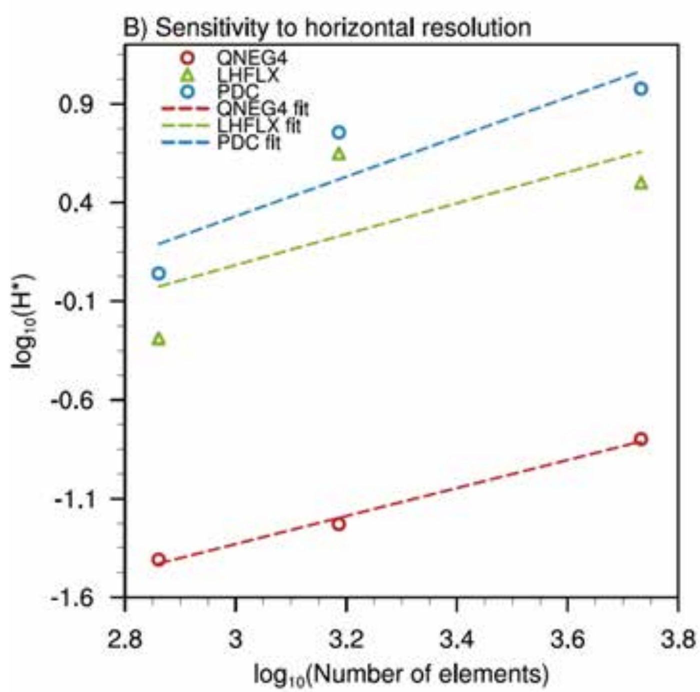
Sensitivity to temporal and spatial resolution

Time-step sensitivity (ne11)



1800s 3600s 7200s

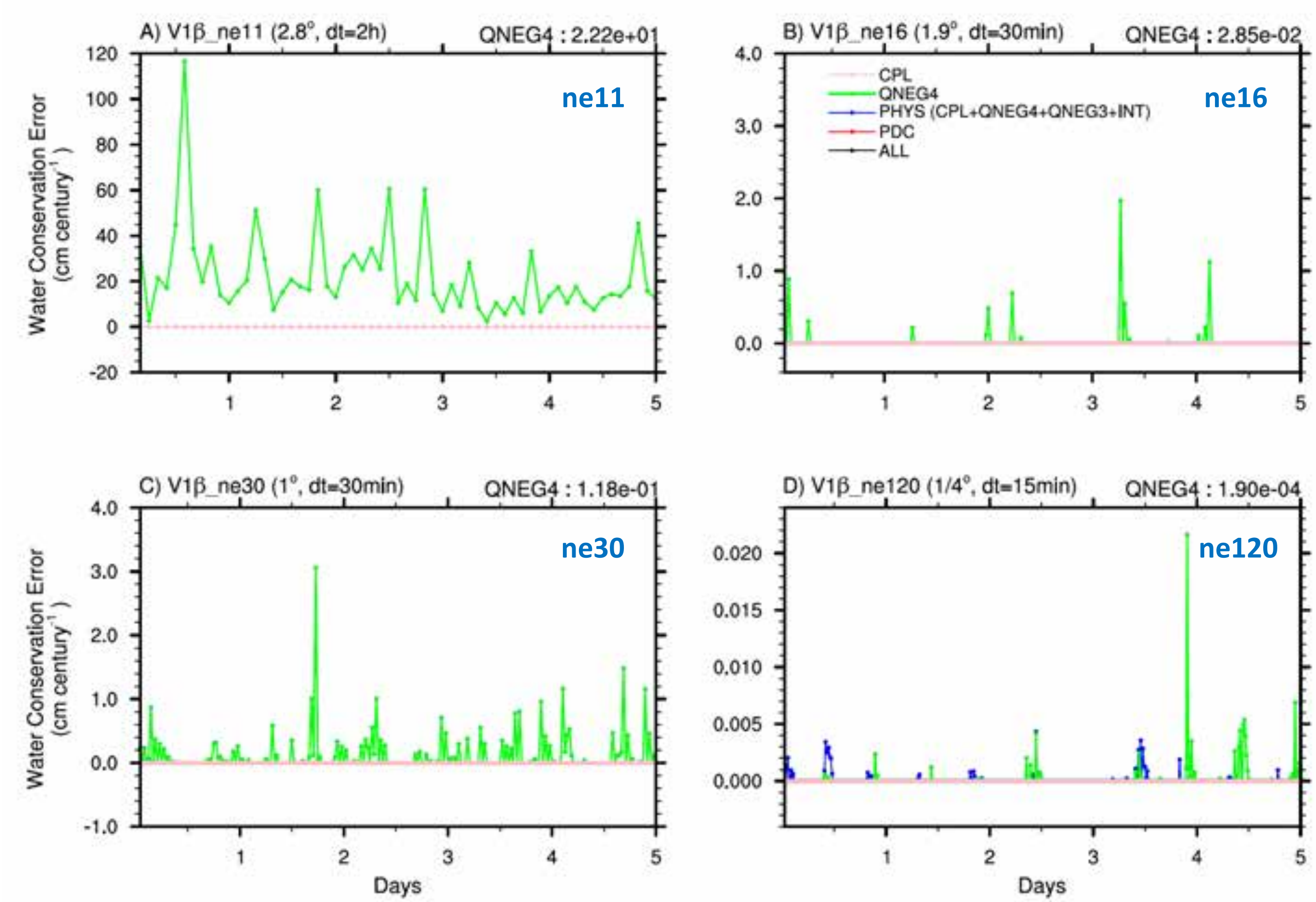
Resolution sensitivity (dt = 1800s)



ne11 ne16 ne30

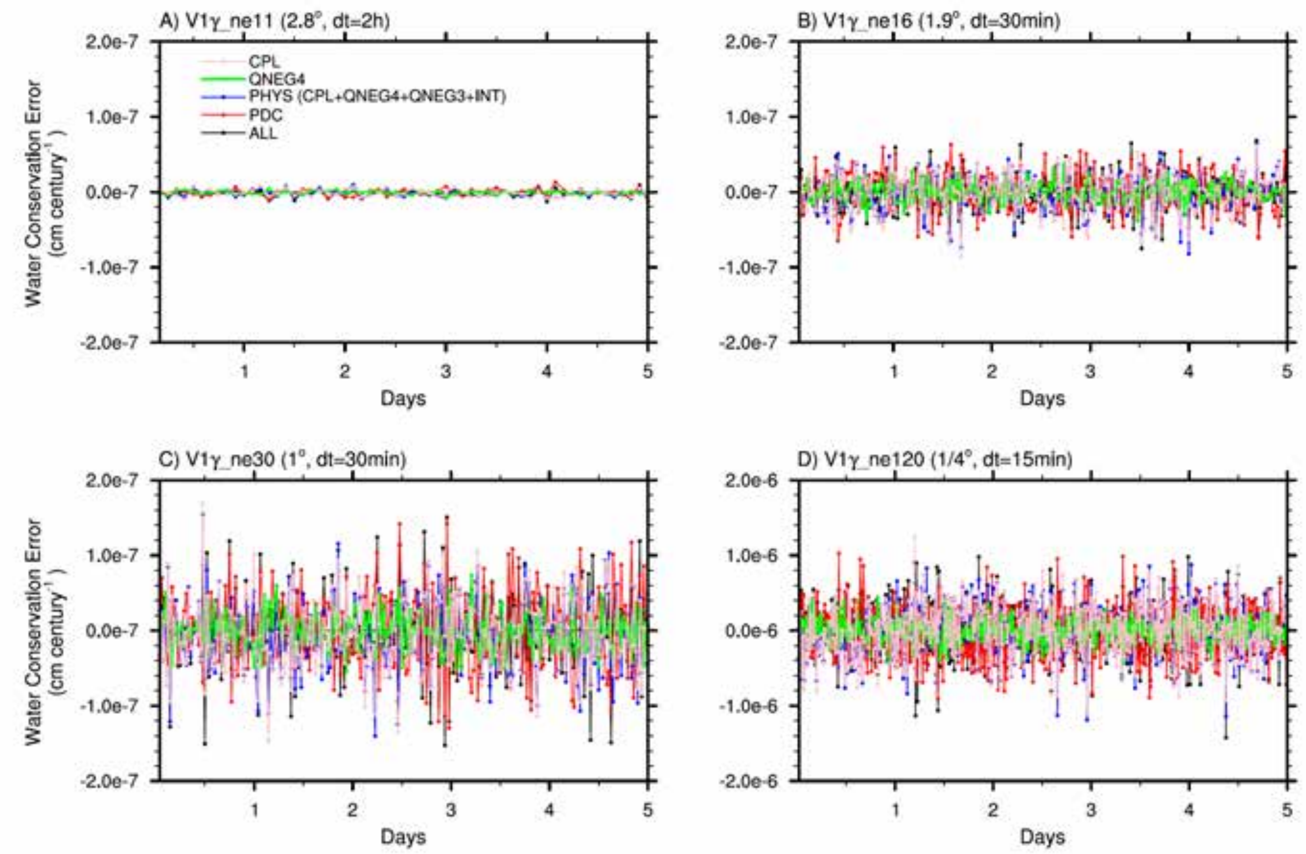
Remaining Errors in V1β

Error Sources: PDC LHFLX **QNEG4** **QNEG3** **INTER**



Further Error Reduction (V1γ, not official)

Error Sources: PDC LHFLX QNEG4 QNEG3 **INT**



Conservation Error in the New Coupled Model (E3SM beta)

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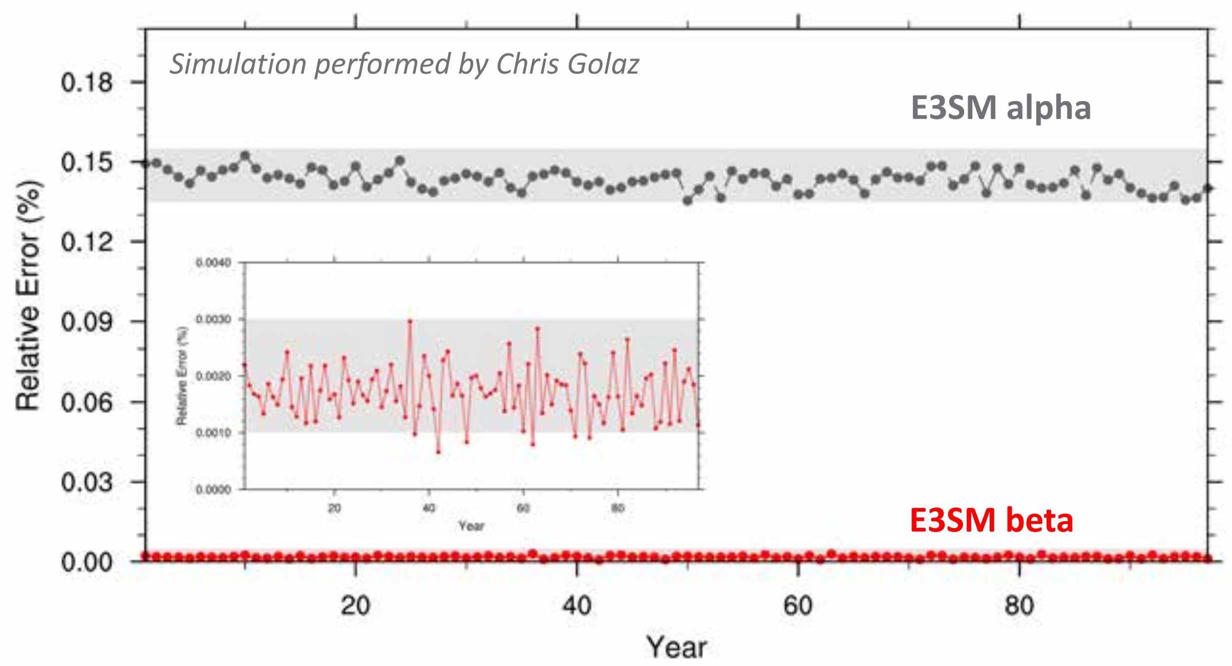

Relative error reduced by about a factor of 80

Implied sea level rise due to remaining water conservation error in 100 years: ~ 2 mm

Remaining conservation errors:

- ***QNEG4: QFLX adjustment to avoid negative concentration of Q near surface***
- ***QNEG3: clipping of negative tracers***
- ***Internal conservation errors in ZM, CLUBB, and MG2.***

Summary

- Large water conservation errors existed in E3SM alpha
- Numerical choices in physics-dynamics coupling and model physics have large impact on the conservation error in EAM.
- EAM V1 (beta onwards) conserves water much better than before, but still can be further improved (2mm per century → negligible).
- Reducing the process coupling error is important (e.g. errors related to PDC and QNEG4), and this calls for smaller time steps or better numerics.
- A consistent treatment of water and energy conservation in each parameterization is the last step for a perfect conservation.

See more details in

Zhang, K., Rasch, P. J., Taylor, M. A., Wan, H., Leung, L.-Y. R., Ma, P.-L., Golaz, J.-C., Wolfe, J., Lin, W., Singh, B., Burrows, S., Yoon, J.-H., Wang, H., Qian, Y., Tang, Q., Caldwell, P., and Xie, S.: Impact of numerical choices on water conservation in the E3SM Atmosphere Model Version 1 (EAM V1), Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2017-293, in revision, 2017.

What's Next

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- Maintain good conservation properties in highly complex physical parameterizations and the coupling between them in EAM
  - CLUBB: SciDAC convergence project
  - MAM: Coupling of aerosol emission, dry deposition, and vertical diffusion
  - P3 cloud microphysics development in EAM: CMDV-MCS project
- Energy conservation and the consistency between water and energy conservation across different model components.

Backup Slides

Table 1. Water conservation error from the atmosphere model component in the coupled and atmosphere-only (Atm) simulations with E3SM V0, V1α and V1β. The relative errors are given as the ratio to the global mean precipitation rate, calculated using Eq. (5) in Section 4. The "artificial sea level rise" is defined as an equivalent sea level rise due to the artificial source of water substances in the atmosphere model, calculated using Eq. (6) in Section 4. The results are slightly different if a different length (number of years) is chosen, but they are very similar to the numbers shown in the table.

Simulation	Simulation Length (year)	Relative Water Conservation Error (%)	Equivalent Sea Level Rise (cm/century)
V0 Atm	4	0.052	5.71
V0 Coupled	28	0.051	5.48
V1α Atm	9	0.102	11.4
V1α Coupled	99	0.139	15.8
V1β Atm	9	0.00148	0.166
V1β Coupled	253	0.00171	0.188
V1γ Atm	5	<2.0 e-7	< 0.002

Table 2. Comparison of different atmosphere model configurations discussed in this paper. Abbreviations: Spec. element – spectral-element dynamical of Dennis et al. (2012) and Taylor and Fournier (2010); PB2009 – shallow convection and turbulence parameterization of Park and Bretherton (2009); PBR2014 – cloud macrophysics parameterization of Park et al. (2014); MG1 – stratiform cloud microphysics parameterization of Morrison and Gettelman (2008); MG2 – stratiform cloud microphysics parameterization of Gettelman and Morrison (2015); CLUBB – unified turbulence, shallow convection, and cloud macrophysics parameterization of Golaz et al. (2002) and Larson et al. (2002). L72 – vertical grid with 72 layers. (This is the vertical grid used in the V1 models, while the V0 model uses a 30-layer grid.) Further details of the model configurations can be found in Section 2. The sources of water conservation error are explained in Section 3.

Model version	V0	V0_L72	V0_CLUBB_MG2	V1α	V1β	V1γ
Vertical levels	30 layers	72 layers	30 layers	72 layers	72 layers	72 layers
Resolved dynamics	Spec. element	Spec. element	Spec. element	Spec. element	Spec. element	Spec. element
Parameterized physics						
Turbulence	PB2009	PB2009	CLUBB	CLUBB	CLUBB	CLUBB
Cloud macrophysics	PBR2014	PBR2014	CLUBB	CLUBB	CLUBB	CLUBB
Cloud microphysics	MG1	MG1	MG2	MG2	MG2	MG2
Sources of water conservation error						
PDC (Sect. 3.1)	Yes	Yes	Yes	Yes	No	No
LHFLX (Sect. 3.2)	N/A	N/A	Yes	Yes	No	No
QNEG4 (Sect. 3.3)	Yes	Yes	Yes	Yes	Yes	No
QNEG3 (Sect. 3.4)	Yes	Yes	Yes	Yes	Yes	No
INTERR (Sect. 3.5)	Yes	Yes	Yes	Yes	Yes	Yes

Table 3. Water conservation error in the 5-day atmosphere-only simulations with EAM V0 and V1 model configurations. The equivalent sea level change is calculated using Eq. (6). The Normalized conservation error is calculated using Eq. (5).

Model version	V0	V0_L72	V0_CLUBB_MG2	V1α	V1β	V1γ
Equivalent sea level change per century	6.99 cm	7.90 cm	13.5 cm	12.8 cm	0.127 cm	negligible
Normalized conservation error δW	0.0606%	0.0776%	0.120%	0.128%	1.26E-3%	negligible
Relative contribution of error from different sources						
PDC	100%	99.7%	77.1%	74.0%	negligible	(Not calculated)
LHFLX	N/A	N/A	22.8%	24.7%	N/A	(Not calculated)
QNEG4	0.00%	0.282%	0.00%	1.24%	99.8%	(Not calculated)
QNEG3+INTERR	0.00%	0.029%	0.0875%	0.001%	0.2%	(Not calculated)

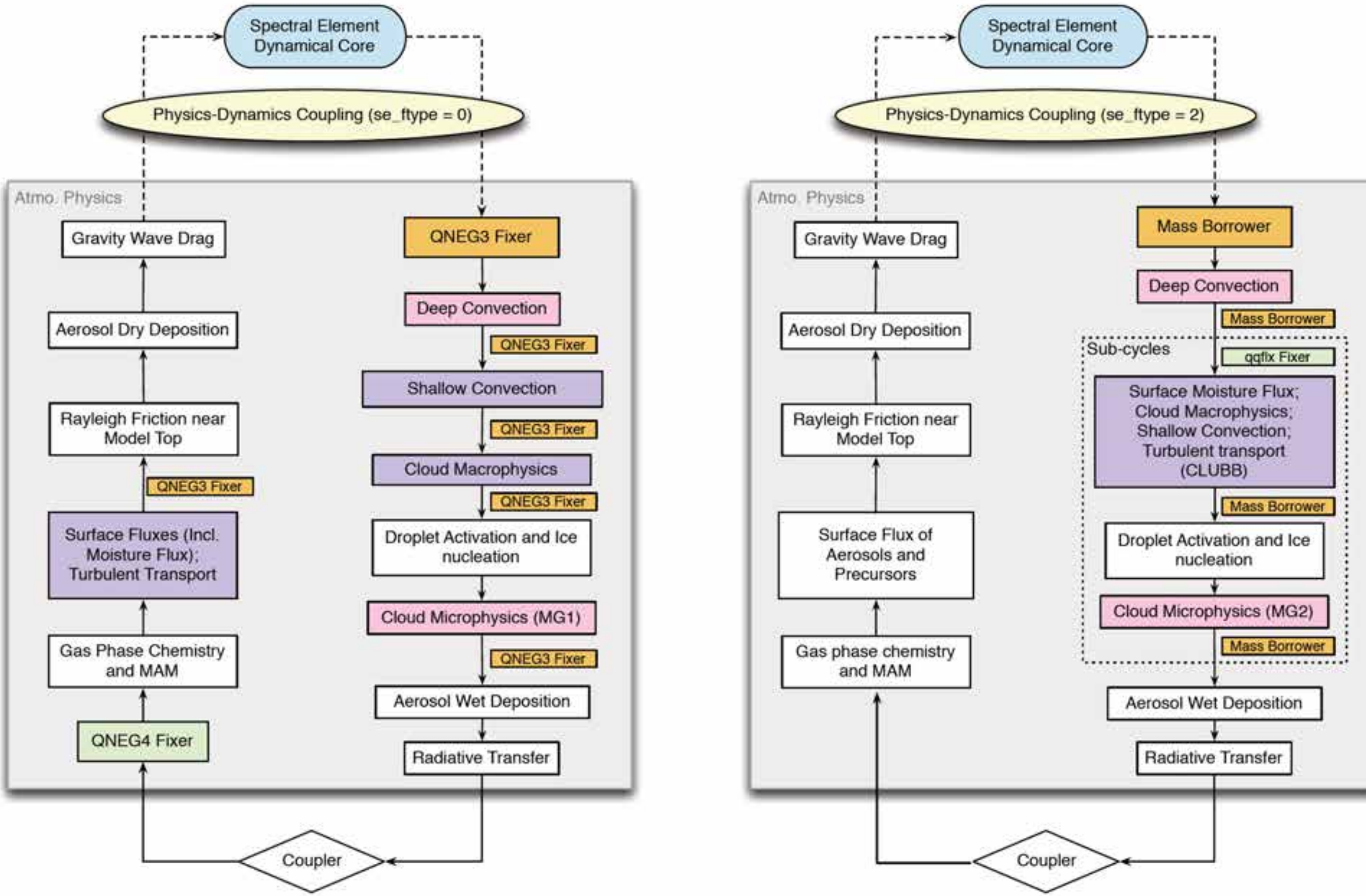
Table 4. Default model configuration parameters for EAM V1α at various spatial resolutions. All configurations use a radiation time step of 1h.

Parameters	Description	ne11 (2.8°)	ne16 (1.9°)	ne30 (1°)	ne120 (1/4°)
ne_sphere	Number of spectral elements on the sphere	726	1536	5400	86400
ncol	Number of physics columns	6536	13826	48602	777602
dx (km)	Approximate grid box size	280	190	100	25
se_ftype	Physics-dynamics coupling options	0	0	0	0
Δt	Time step size for physics-dynamics coupling and most physical processes	7200s	1800s	1800s	900s
se_nsplit (time step)	Number of sub-cycles for dynamics (including vertical remapping of the semi-Lagrangian vertical coordinate)	4 (1800s)	1 (1800s)	2 (900s)	4 (225s)
se_rsplit (time step)	Number of sub-cycles for tracer advection in each dynamics sub-cycle	2 (900s)	3 (600s)	3 (300s)	3 (75s)
cld_macmic_num_steps	Number of sub-cycles for macro-/micro- physics in Δt	6	6	6	6

Table 5. Water conservation error in 5-day atmosphere-only simulations conducted with the default E3SM V1α model at different horizontal resolutions. The model configurations, including the time step sizes for various parts of the model, are summarized in Table 4. The equivalent sea level change is calculated using Eq. (6). The Normalized conservation error is calculated using Eq. (5).

Model version	V1α_ne11	V1α_ne16	V1α_ne30	V1α_ne120
Equivalent sea level change per century (ΔH)	61.5 cm	4.56 cm	12.8 cm	32.7 cm
Normalized conservation error δW	0.660%	0.0467%	0.128%	0.292%
Contribution to ΔH from different sources				
PDC	31.2 cm	0.00 cm	9.47 cm	28.3 cm
LHFLX	2.04 cm	4.53 cm	3.16 cm	4.45 cm
QNEG4	28.3 cm	0.0291 cm	0.159 cm	0.019 cm
QNEG3+INTERR	0.00 cm	0.0093 cm	0.00 cm	0.01 cm

(a) EAM V0 (b) EAM V1γ



Problems Identified and Fixed Also in Other Model Components

- Coupler (CIME): *remapping*
- River routing model (MOSART): too high *storage* capacity
- Land surface model (ALM): *missing perched drainage and ponding*
- Ocean (MPAS): *Grid inconsistency between MPAS, MOSART and ALM*

Water conservation in each model component should be carefully checked in the coupled system!

Source: Hongyi Li, Jingyun Tang, Jon Wolfe, and ACME Coupled team telecon notes

Conservation Errors inside Individual Processes (ZM-deep, CLUBB, and MG2)

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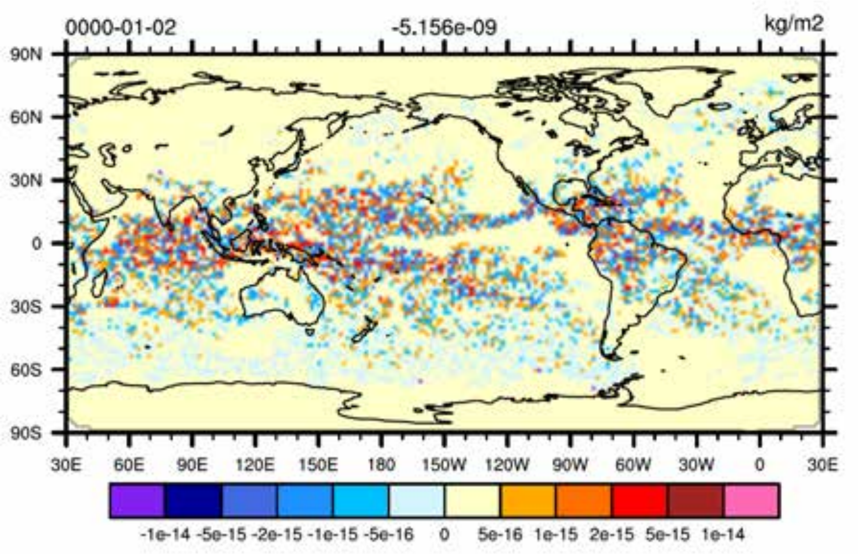
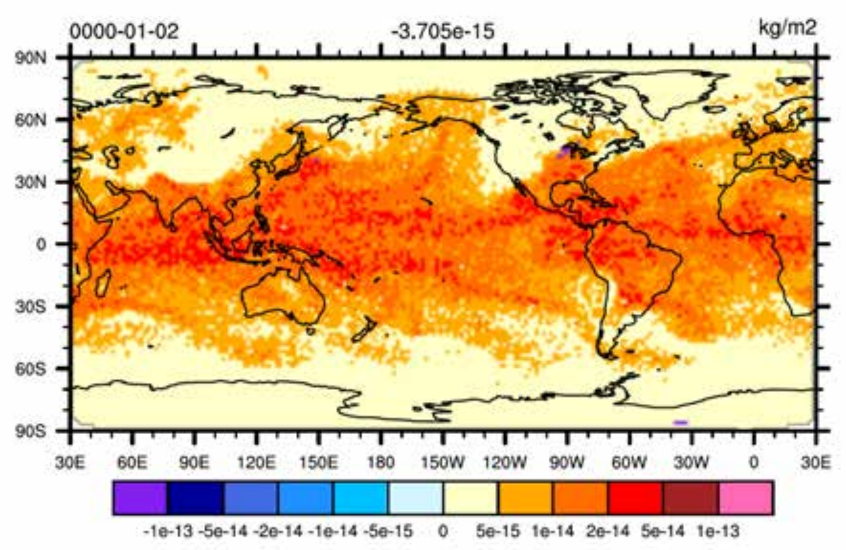
Daily Mean

Deep Convection



5-day absolute field maximum : O(e-3)

CLUBB



5-day absolute field maximum : O(e-6)

- ***Global Averaged Vertical Integrated Conservation Errors inside ZM-deep, CLUBB, and MG2 are small***
- ***However, it could be much larger at certain locations and time steps***

Impact of Using Different QFLX input

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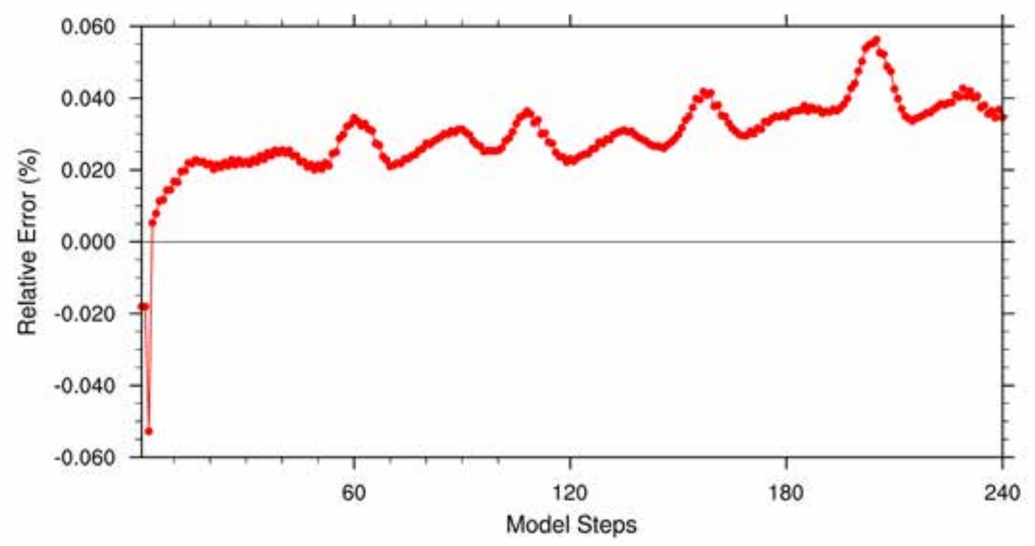
- In the original CLUBB, the surface moisture flux passed to the vertical diffusion/turbulence calculation is LHFLX / Lv, rather than QFLX.



Only ~ 20% of the total relative error (0.15%)

Physics and Dynamics Coupling (I)

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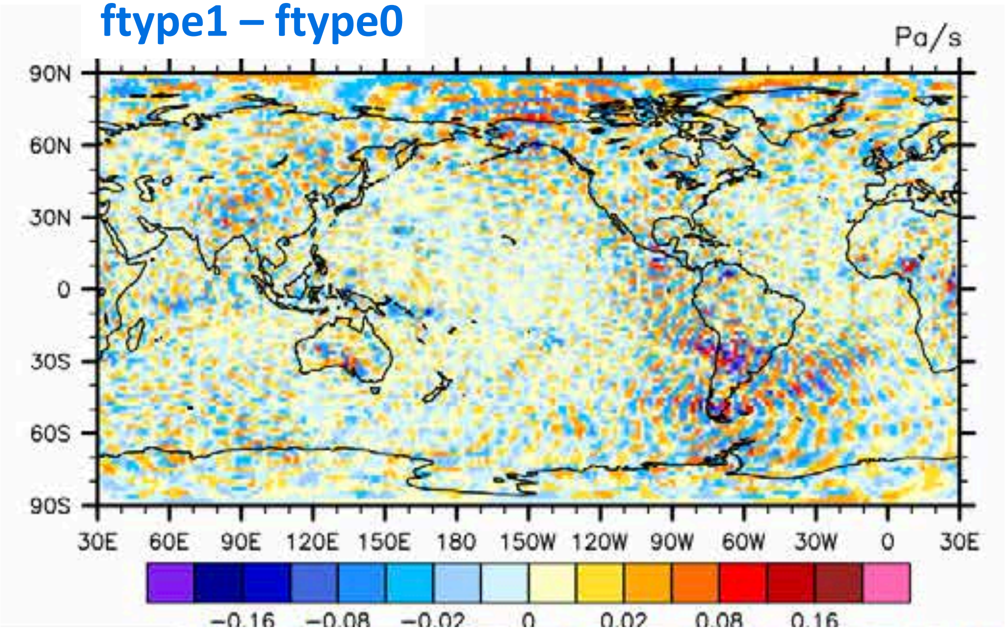
The previous version of SE dycore added the physical tendency only once before the dycore sub-cycle starts (so called hard adjustment, **ftype=1**).

With a **30min** time step for physics, it was found the simulated OMEGA field had spurious numerical noise.

Changes in OMEGA at 500 hPa



Physics and Dynamics Coupling (II)

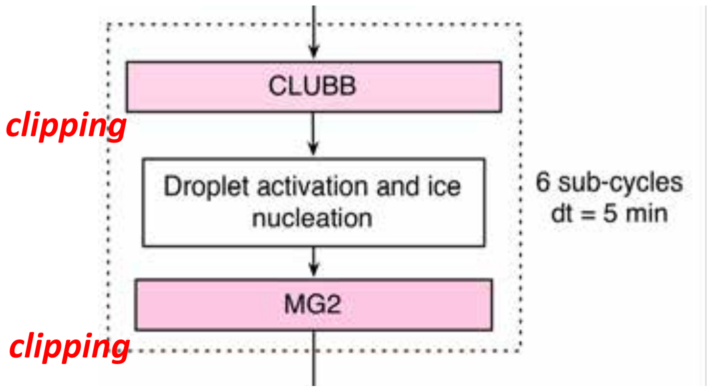
A new dynamics-physics coupling treatment (incrementally add the physical tendency inside the dycore sub-cycle, ftype=0) was recommended by *Thatcher and Jablonowski (2016)* and this was the standard setup for ACME alpha-version simulations.

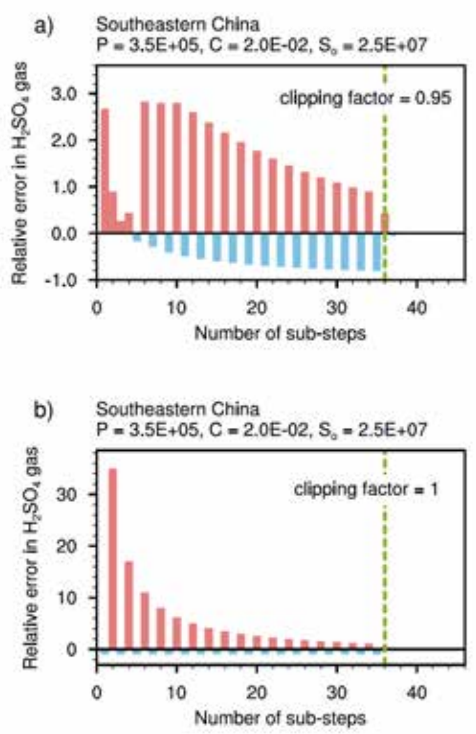
We found that this coupling method causes water conservation problem and we proposed a new solution. (We learned from Peter Laurizen that he also found this problem, PDC workshop, Sept 20, 2016).

The proposed solution utilizes a **hybrid physics-dynamics coupling** treatment (Hui and Mark). For winds and temperature, the model still incrementally adds the physical tendency inside the dycore sub-cycle, so that the dynamical fields are smooth. For water substances and other tracers, the model uses hard adjustments.

Sub-Stepping in Physics and Potential Negative Impact of Clipping

Sub-stepping together with clipping can cause large model errors





Wan et al. (GMD2013)

Overall conservation error is small, but the compensating error might be larger.

Balance between PRECT and QFLX

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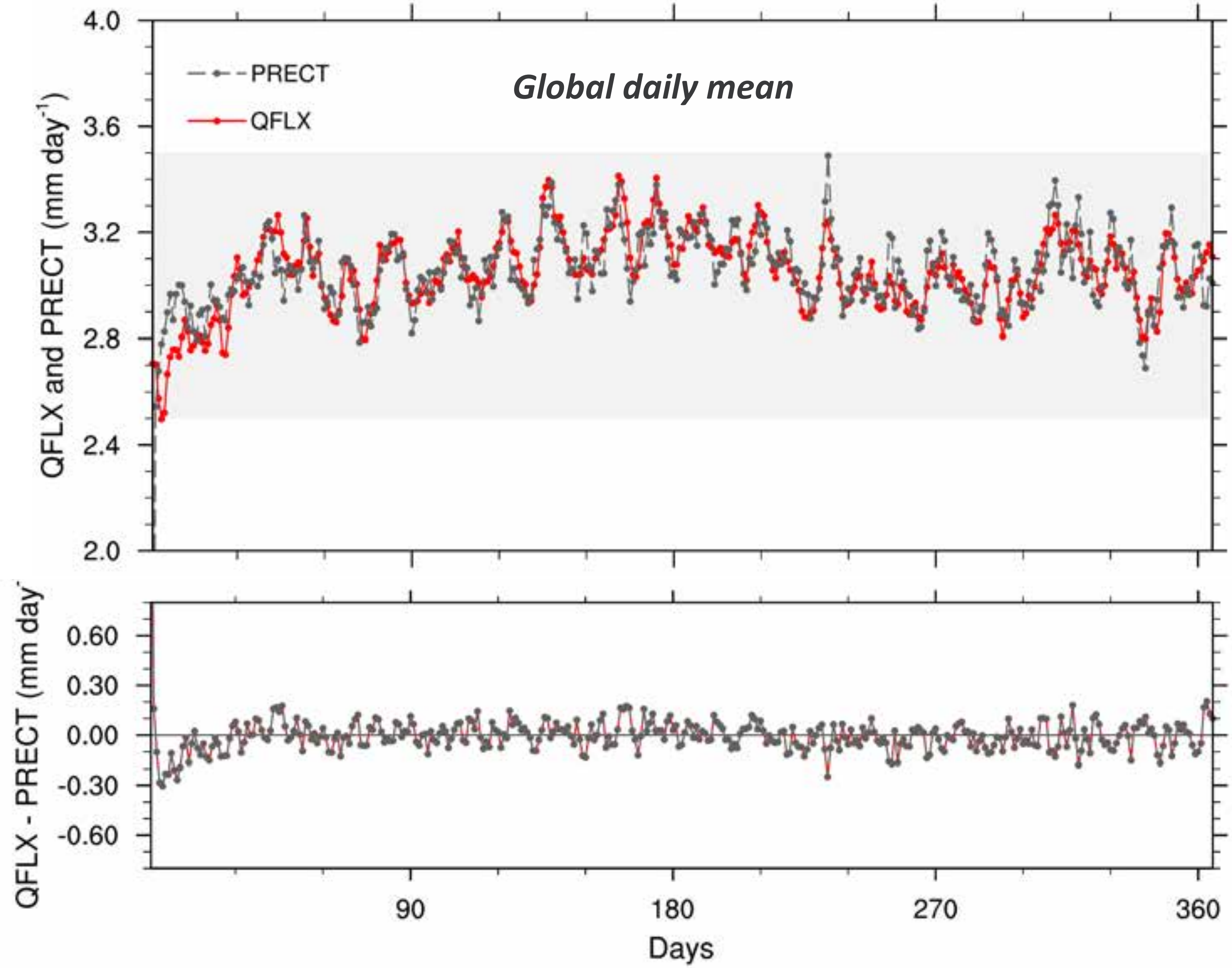

Global mean PRECT and QFLX vary like in tandem

Implied change in atmosphere water storage is relatively small