Towards Better Numerical Coupling of Cloud Processes in the E3SM Atmosphere Model (EAM)

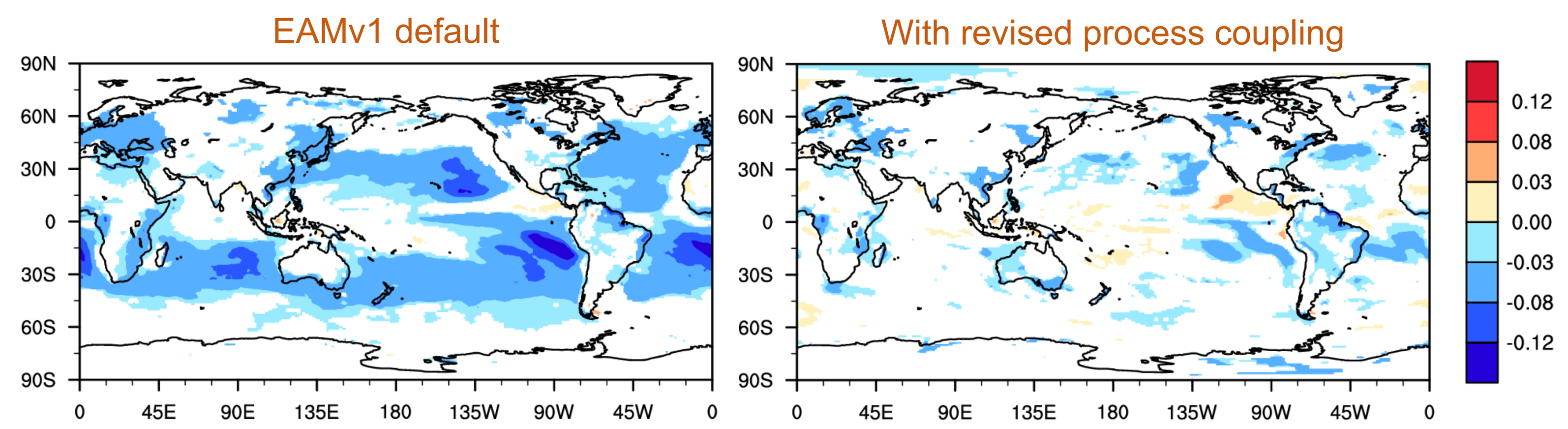
Hui Wan[1] (Hui.Wan@pnnl.gov), Shixuan Zhang[1], Philip J. Rasch[1], Vincent E. Larson[1,2], Xubin Zeng[3], Christopher J. Vogl[4], Carol S. Woodward[4], Quan M. Bui[4], Kai Zhang[1], Ross D. Dixon[5], Huiping Yan[6]

MOTIVATION AND CHALLENGE

Strong time-step sensitivities in the simulate long-term climate suggest that EAM's time integration and process coupling algorithms have large errors. These errors must be substantially reduced to avoid numerical artifacts overwhelming physical responses in EAM's simulations.

Due to complex and nonlinear interactions among atmospheric processes, it is often challenging to pinpoint error sources and distinguish between causes and effects.

Figure 1. *Changes in the 10-year mean low-cloud fraction (ΔCLDLOW) caused by a factor-of-6 time-step reduction in EAMv1 before and after revising the numerical schemes of process coupling.*



PROGRESS AND NEXT STEPS

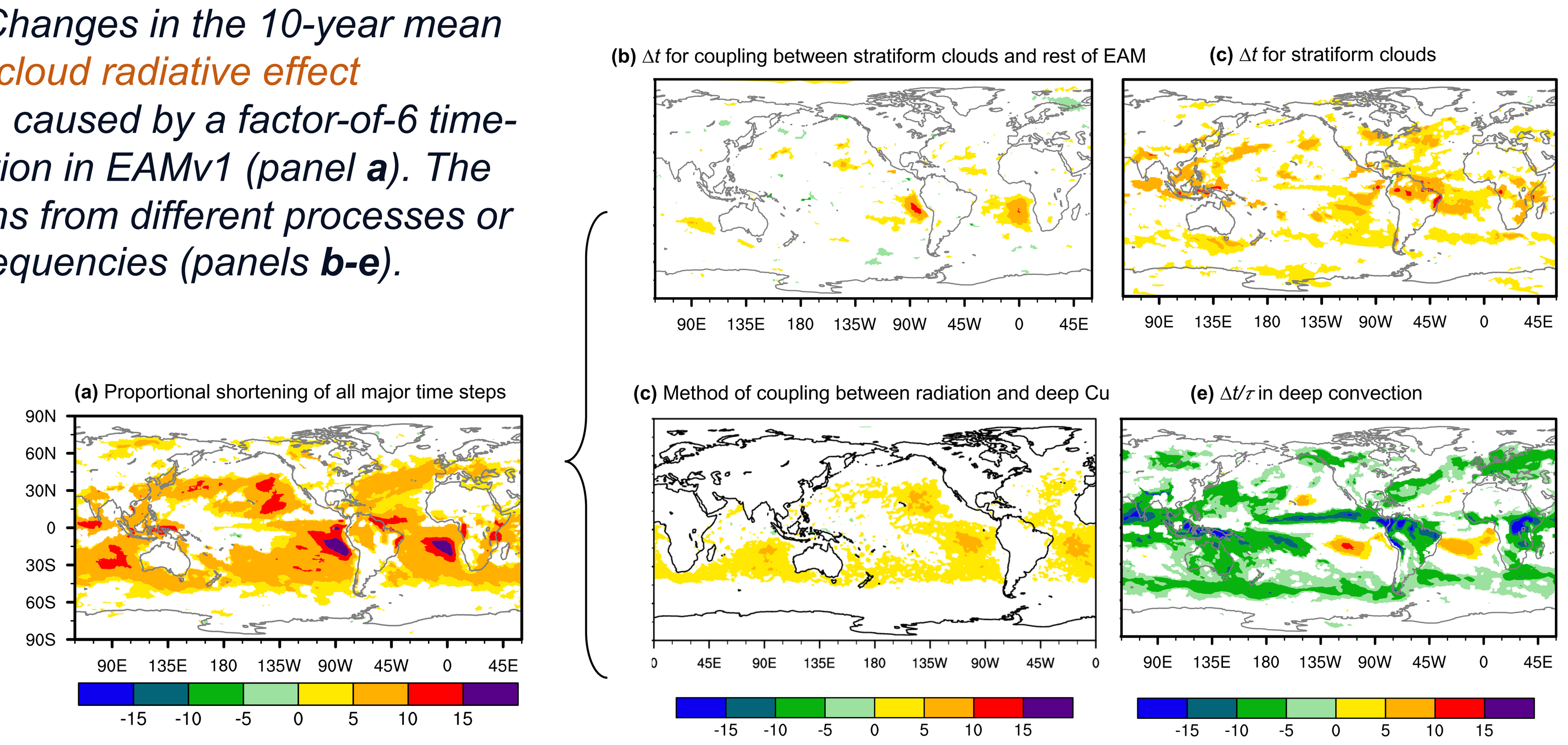
Using the methods and tools described below, we have substantially reduced time-step sensitivities in the subtropical low clouds in EAMv1 (Figure 1).

The next foci are deep convection and high clouds. We also started to quantify and reduce resolution sensitivities in the simulated aerosol life cycles.

ERROR QUANTIFICATION AND ATTRIBUTION

EAM uses sub-stepping for many processes or groups of processes. The code and data structures are flexible and hence can support different ordering and coupling methods. These code features are exploited to identify the sources of time-step sensitivities in different cloud regimes (Wan et al, 2021, GMD; see also Santos et al., 2021, JAMES).

Figure 2. *Changes in the 10-year mean shortwave cloud radiative effect (ΔSWCRE) caused by a factor-of-6 time-step reduction in EAMv1 (panel **a**). The contributions from different processes or coupling frequencies (panels **b-e**).*



THEORETICAL ERROR ANALYSIS

Applied mathematicians on our team developed a theoretical error analysis technique to distinguish process coupling error from time integration errors of individual processes. For example, for a generic two-process problem $dy/dt = A + B$, the local truncation errors resulting from sequential and parallel splitting are

$$\mathcal{E}_{\text{sequential}} = \frac{\Delta t^2}{2}\left(-\frac{dA}{dy}B + \frac{dB}{dy}A\right) + \mathcal{O}(\Delta t^3)$$

$$\mathcal{E}_{\text{parallel}} = \frac{\Delta t^2}{2}\left(-\frac{dA}{dy}B - \frac{dB}{dy}A\right) + \mathcal{O}(\Delta t^3)$$

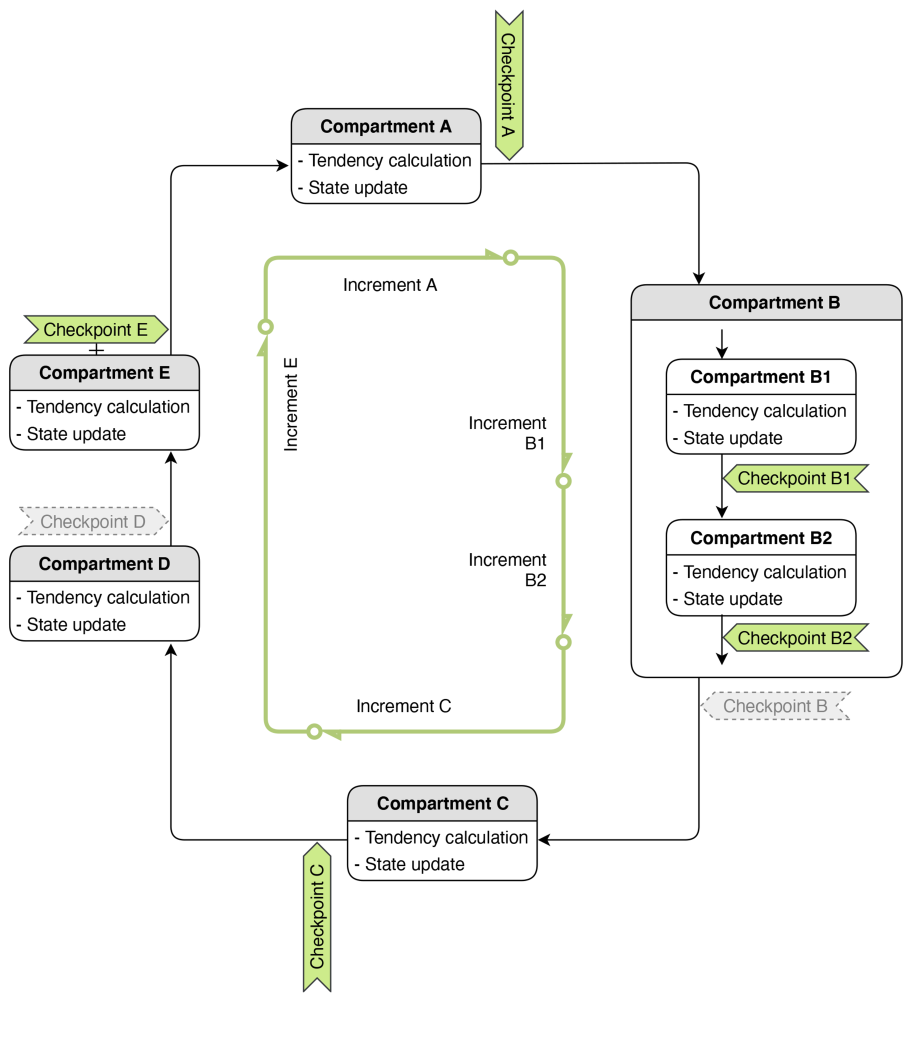
These expressions, combined with budget analysis results from EAM, can be used to estimate the coupling error of different coupling schemes. The method has been used to help explain results shown in Figure 2.

RELATIONSHIP CHARACTERIZATION

Strongly interacting processes often cause large numerical errors. Budget analysis can help identify such processes and subsequently guide the design of accurate coupling schemes.

We developed a new online diagnostics tool in EAM (Figure 3) that makes conditional sampling and budget analysis runtime configurable. This avoids tedious coding and large amount of model output that are often required by process-level analysis (Wan et al, 2022, GMD).

Figure 3. *A new online diagnostics tool in EAM.*

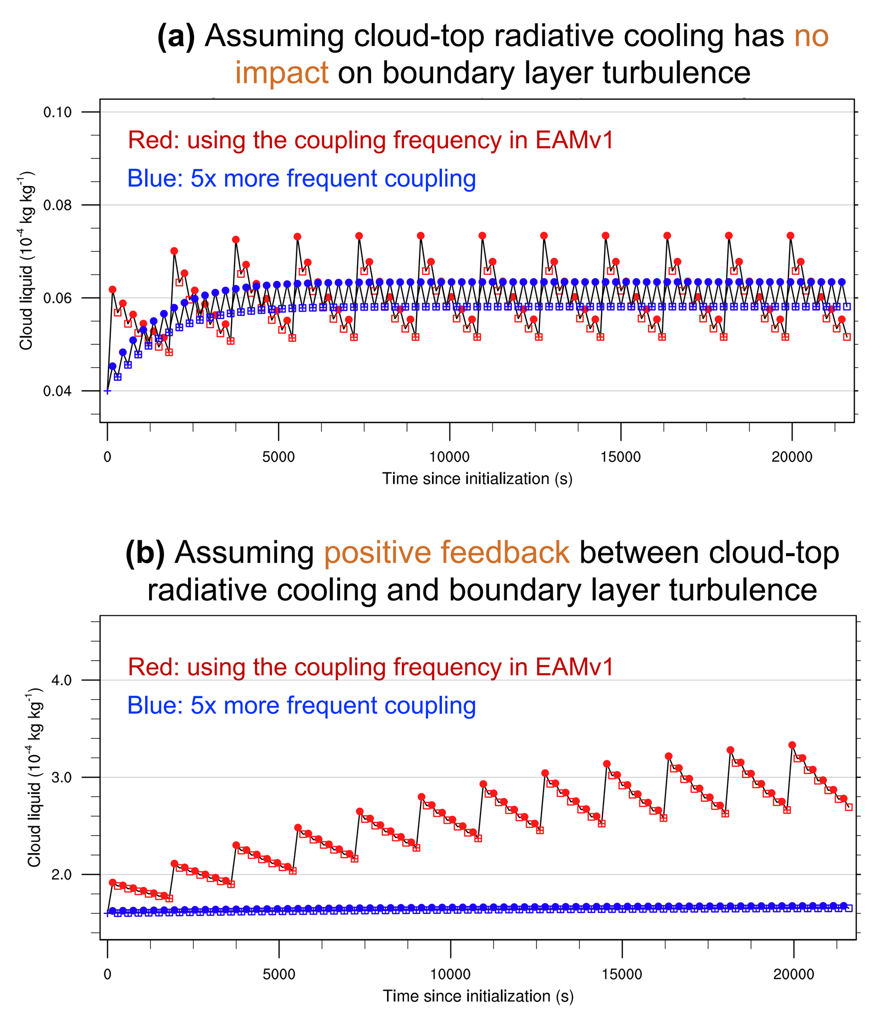


IDEALIZED MODELS

Inspired by EAM simulations and budget analysis results, we developed idealized models (toy models) to help investigate the interplay between numerical errors and model physics.

Figure 4 is an example in which a different coupling frequency leads to a drift of the mean state when nonlinear positive feedback is present in the equation system. This explains the time-step sensitivities shown in Figure 2b.

Figure 4. *Toy model simulations showing the sensitivity of stratiform cloud liquid concentration to the frequency of coupling between the cloud physics parameterizations and other atmospheric processes (e.g., dynamics, radiation).*



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Author affiliations:
1. Pacific Northwest National Laboratory, 2. University of Wisconsin – Milwaukee, 3. University of Arizona, 4. Lawrence Livermore National Laboratory, 5. University of Nebraska – Lincoln, 6. Nanjing University of Information Science and Technology