Pacific Northwest NATIONAL LABORATORY

SciDAC
Scientific Discovery through Advanced Computing

Quantifying, Attributing, and Understanding Time Step Sensitivities in the E3SMv1 Atmosphere Model

Hui Wan[1], Shixuan Zhang[1], Phil Rasch[1], Vince Larson[2,1], Kai Zhang[1], Xubin Zeng[4], Huiping Yan[3], Heng Xiao[1], Balwinder Singh[1]

[1]Pacific Northwest National Laboratory, Richland, WA, USA
[2]University of Wisconsin - Milwaukee, Milwaukee, WI, USA
[3]Nanjing University of Information Science and Technology, Jiangsu, China
[4]University of Arizona, Tucson, AZ, USA

U.S. DEPARTMENT OF ENERGY BATTELLE

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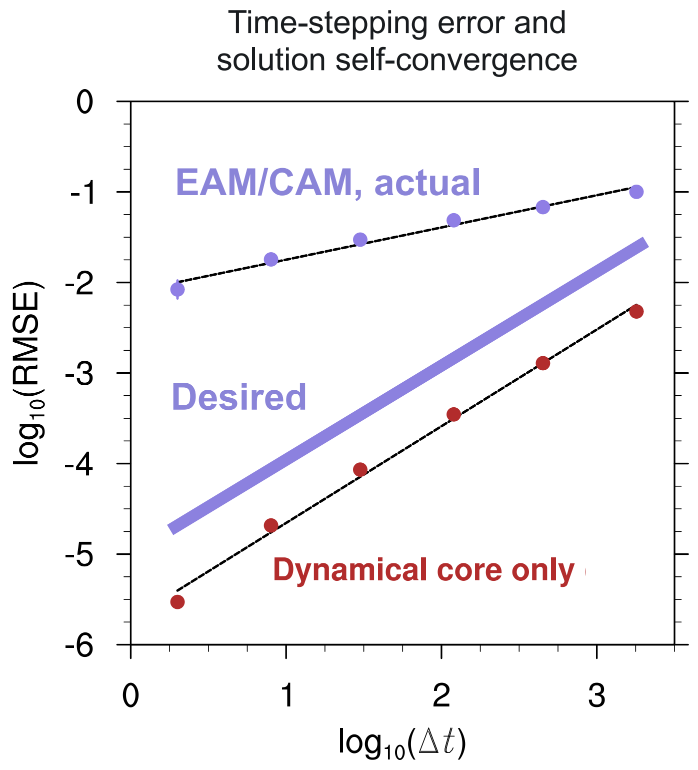
E3SM All-hands Presentation, January 21, 2021

Background and motivation

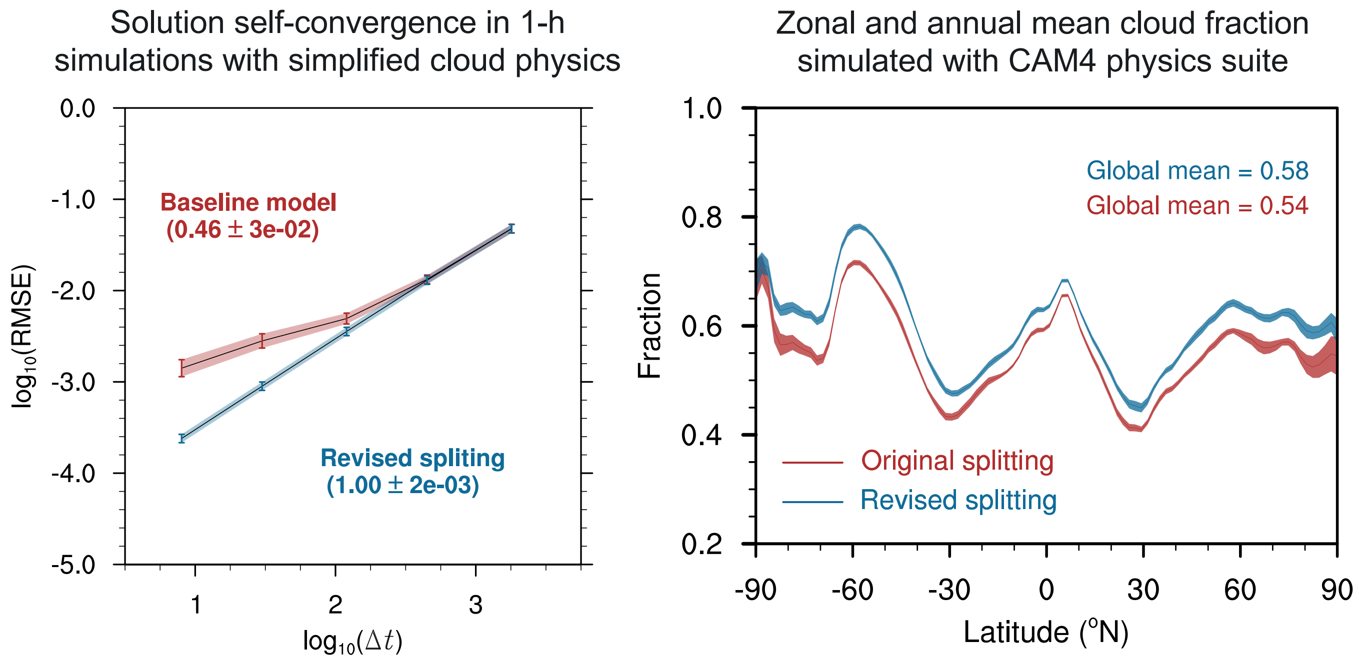
Various significant, undesirable numerical artifacts noticed in E3SM and similar models, both global and regional, at traditional and much higher resolutions

SciDAC project aiming at reducing time-stepping error and in atmospheric physics parameterizations in E3SM

- Investigations using simplified models demonstrated the feasibility and benefits of addressing time-step convergence issues
- From proofs of concept to the “real EAM”
  - **Priorities?**
  - **Relevance to day-to-day development focused on reducing model biases?**



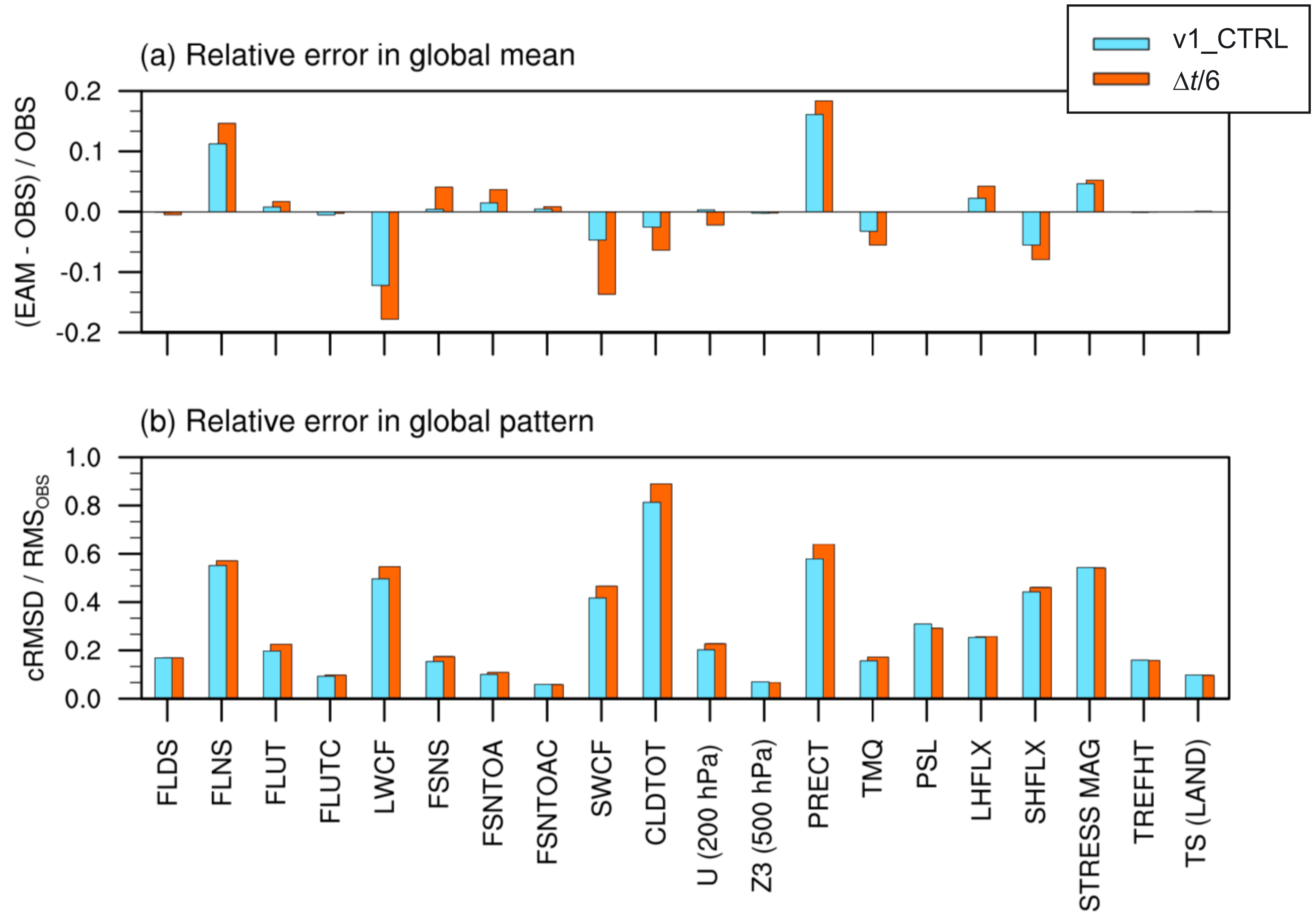
See also Wan et al. (2015, JAMES)



Wan et al. (2020, JAMES), see also Vogl et al. (2020, JAMES)

Shortening EAMv1's time steps to 1/6 of the default causes a systematic increase in model biases

Model biases in 10-year mean present-day climate



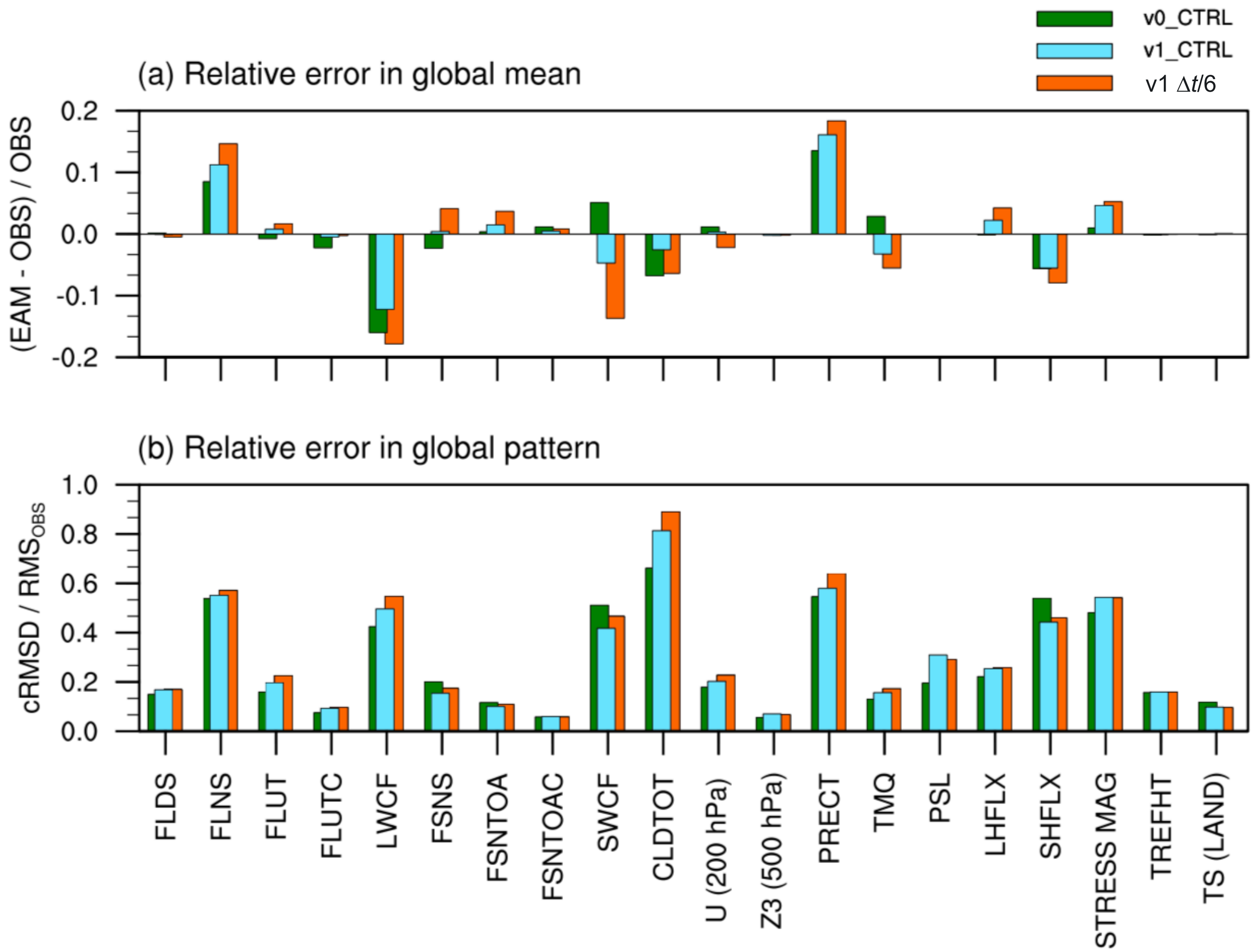
Simulation setup

- F_2000 compset
- ne30_ne30 (1-degree)

Source of obs. data:
AMWG diagnostics

The degradation in model fidelity is comparable in magnitude to the improvement from v0 to v1

Model biases in 10-year mean present-day climate



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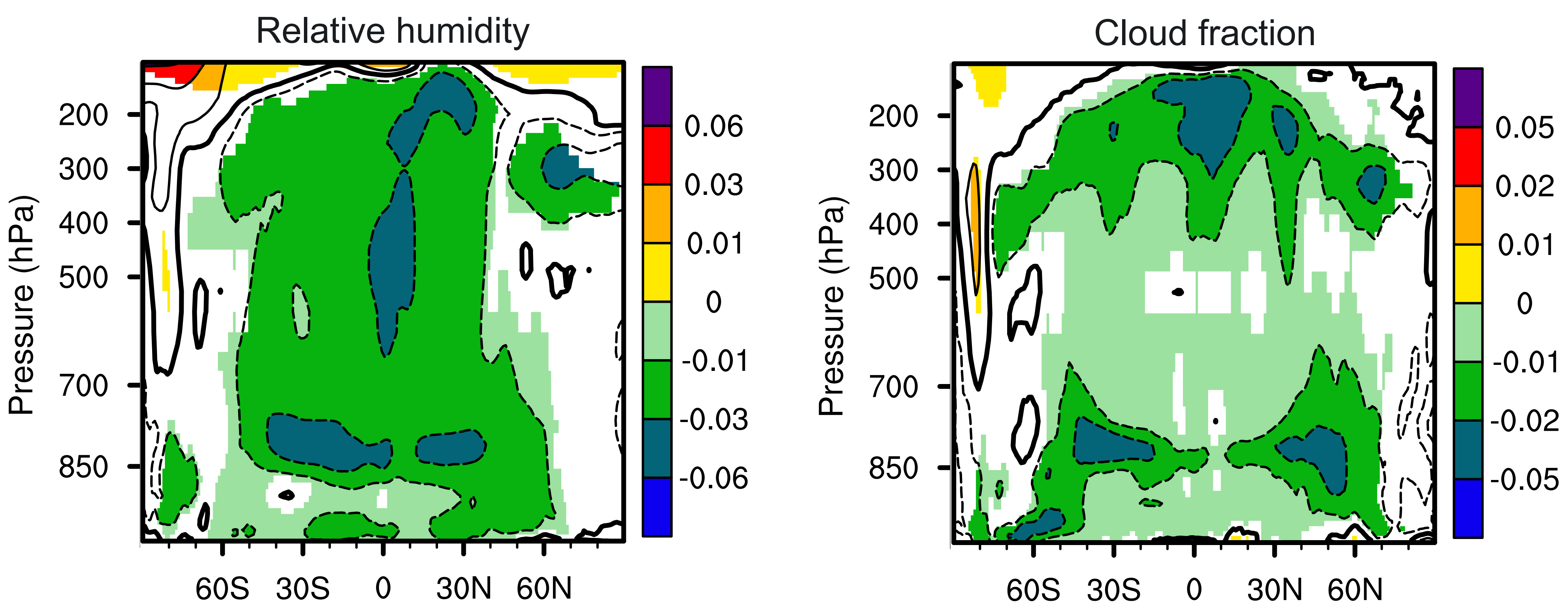
- F_2000 compset
- ne30_ne30 (1-degree)

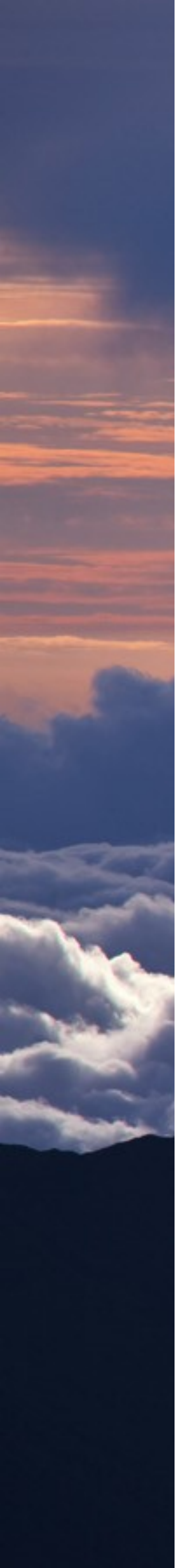
Source of obs. data:
AMWG diagnostics

Wan et al. (2020, GMD Discussion, doi: 10.5194/gmd-2020-330)

Key signatures of sensitivity include systematic drying of the troposphere and decreases in cloud fraction when time steps are shortened

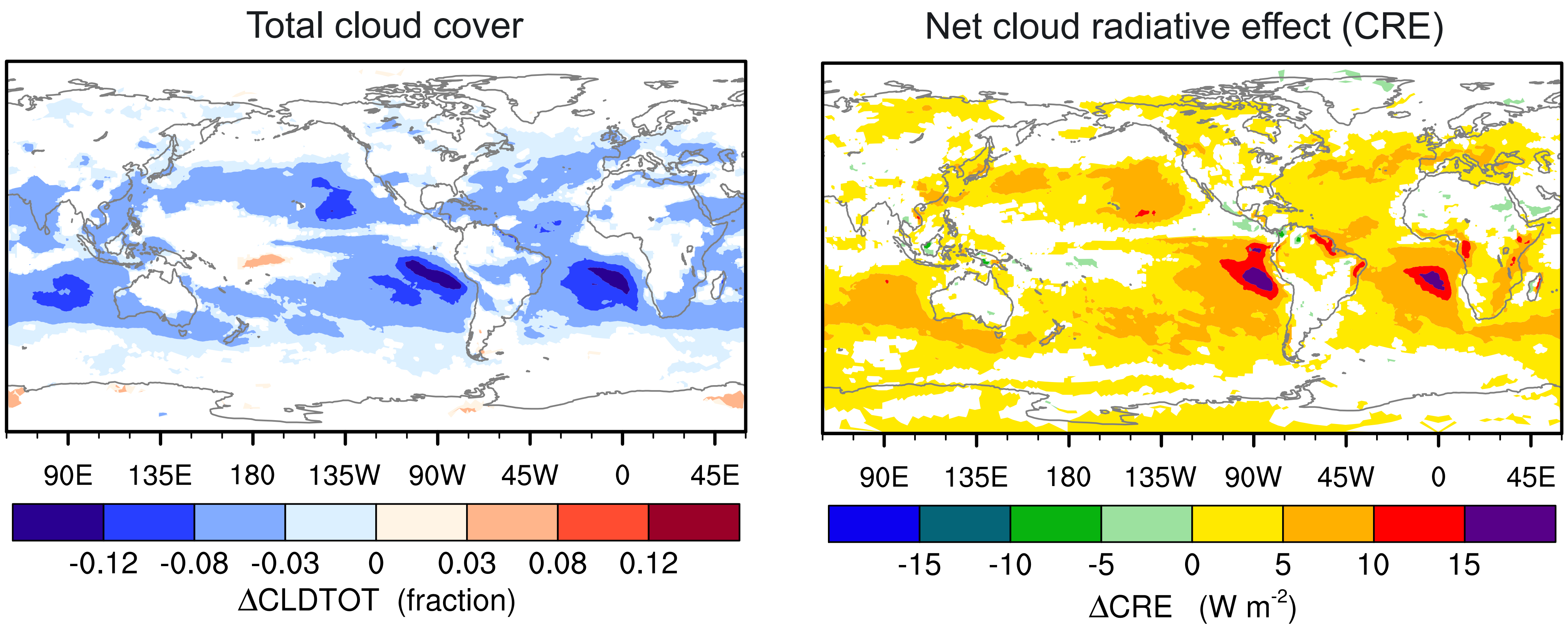
Differences in zonal mean 10-year averages, $\Delta t/6$ – v1_CTRL





Significant changes are seen in subtropical low-clouds, which has potential implications on the prediction of climate change

Differences in 10-year averages, Δ*t*/6 – v1_CTRL



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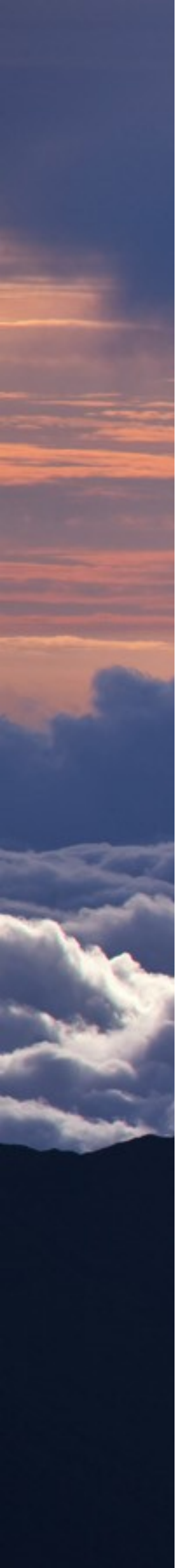
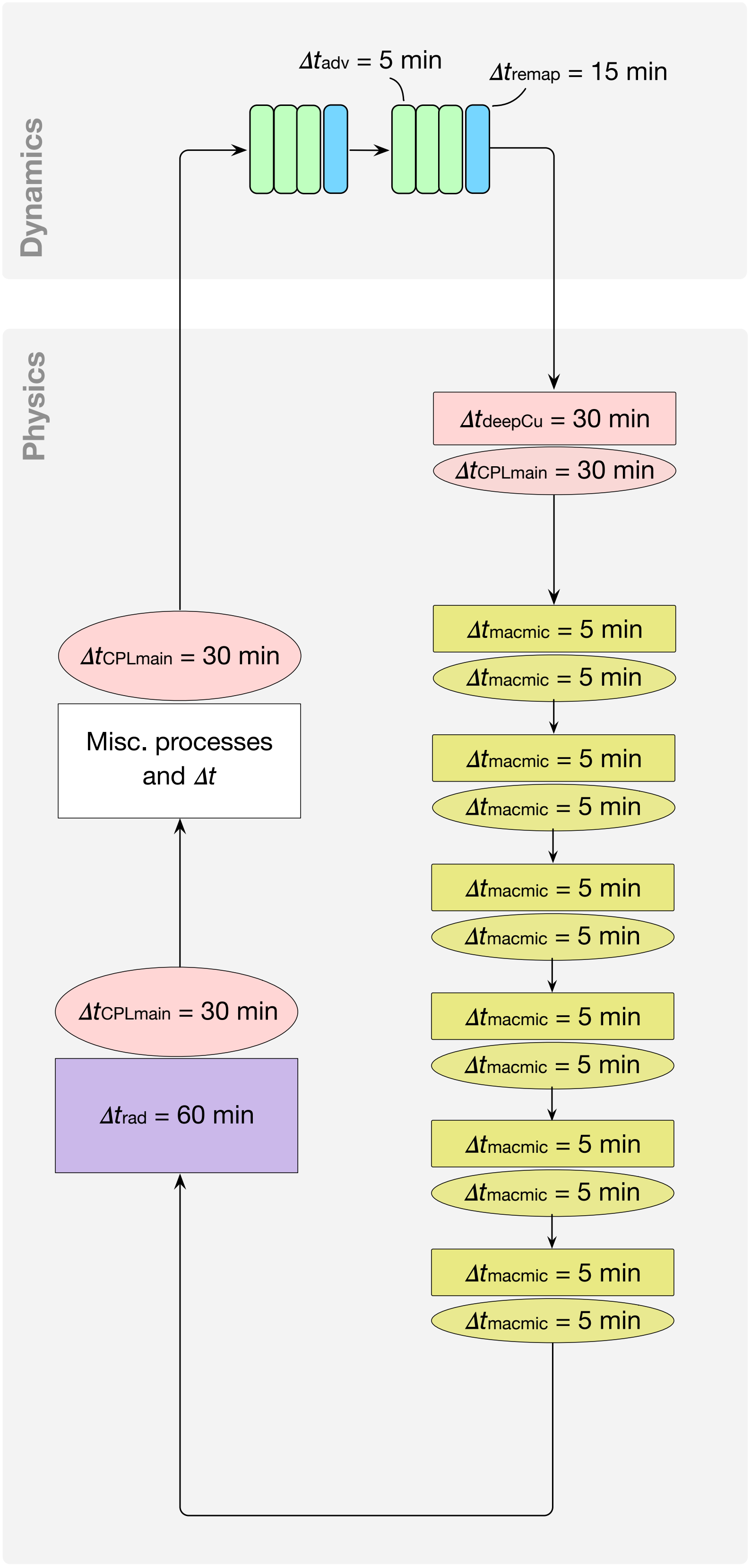


"Perhaps unsurprisingly to those familiar with model development, the largest deviations can be attributed to the parametrizations of clouds and moist convection. ***Perhaps less predictable is how and where these deviations are…"*** *— anonymous reviewer*

- "How and where"
- "By what and why"

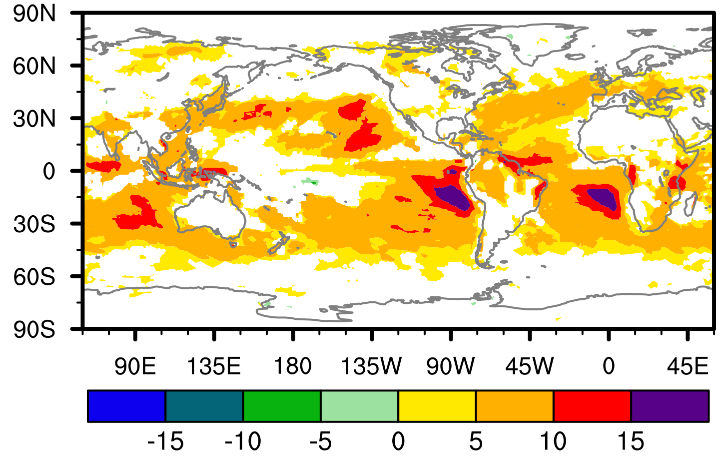
Our experiments: time step sizes in various components of EAMv1 are varied separately or in combination to attribute time step sensitivities



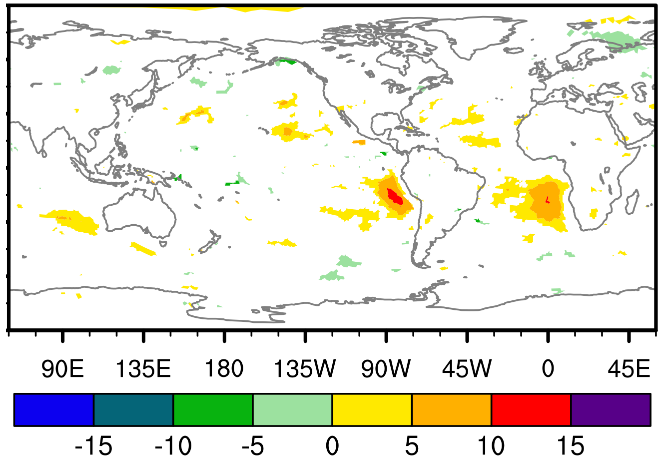
These simulations reveal key impactors in different cloud regimes

Differences in 10-year averages of shortwave cloud radiative effect

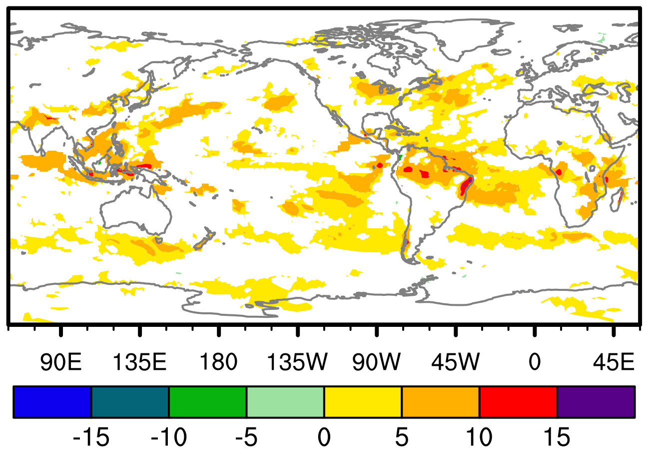
All major processes



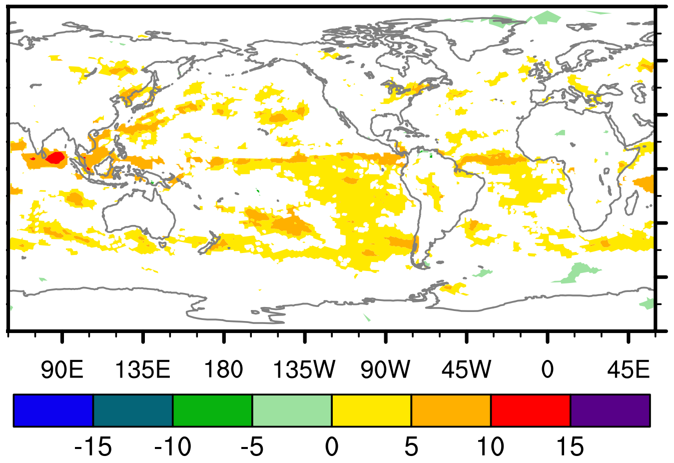
Coupling between cloud macro-/microphysics and rest of model

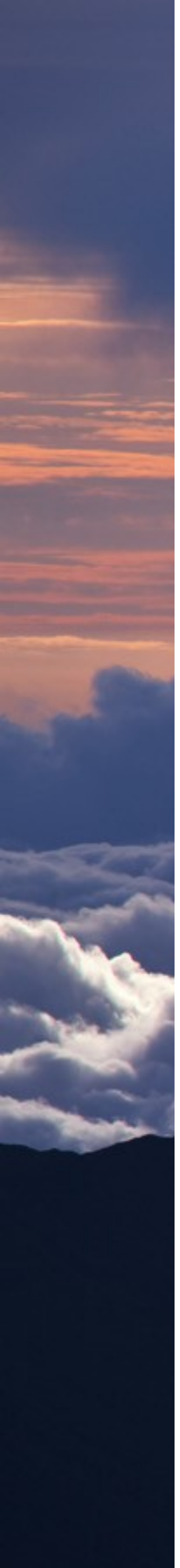


Shallow cumulus and stratiform cloud macro/microphysics



Deep convection and its interaction with dynamics etc.

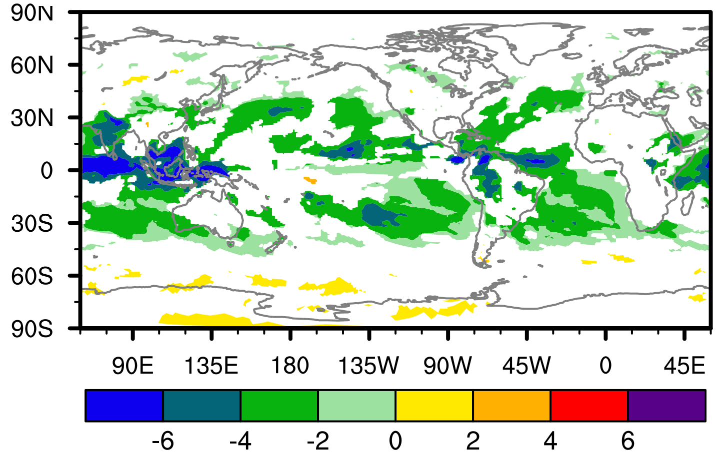




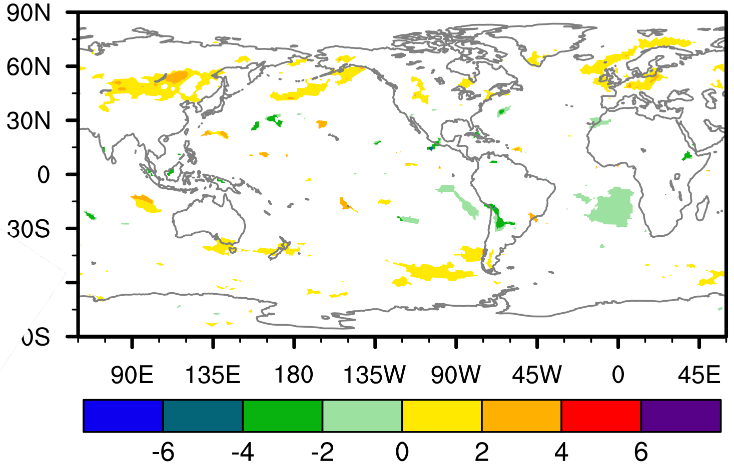
These simulations reveal key impactors in different cloud regimes (cont'd)

Differences in 10-year averages of longwave cloud radiative effect

All major processes



Coupling between cloud macro-/microphysics and rest of model



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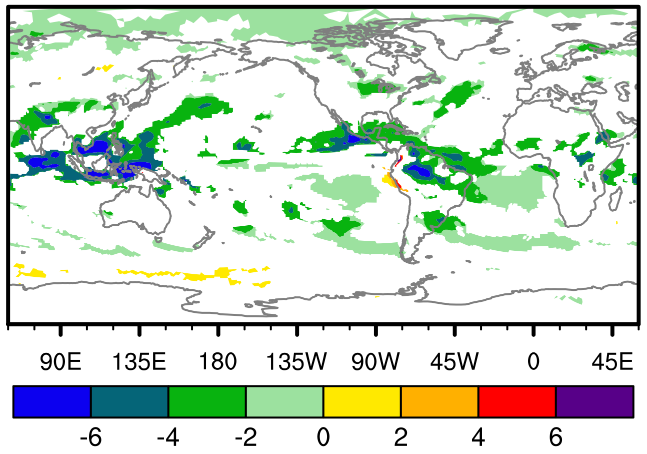
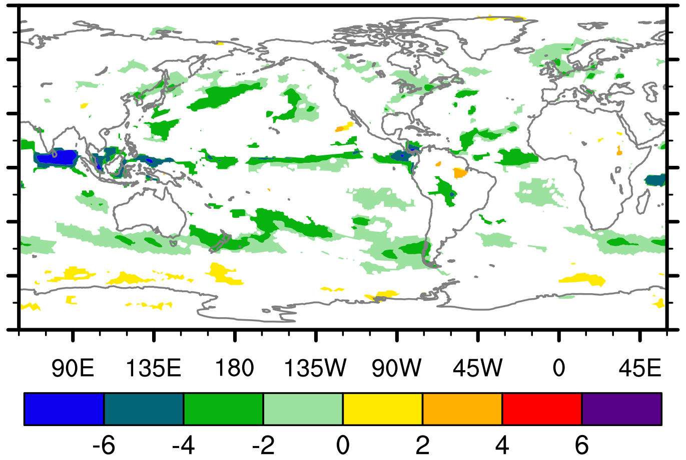


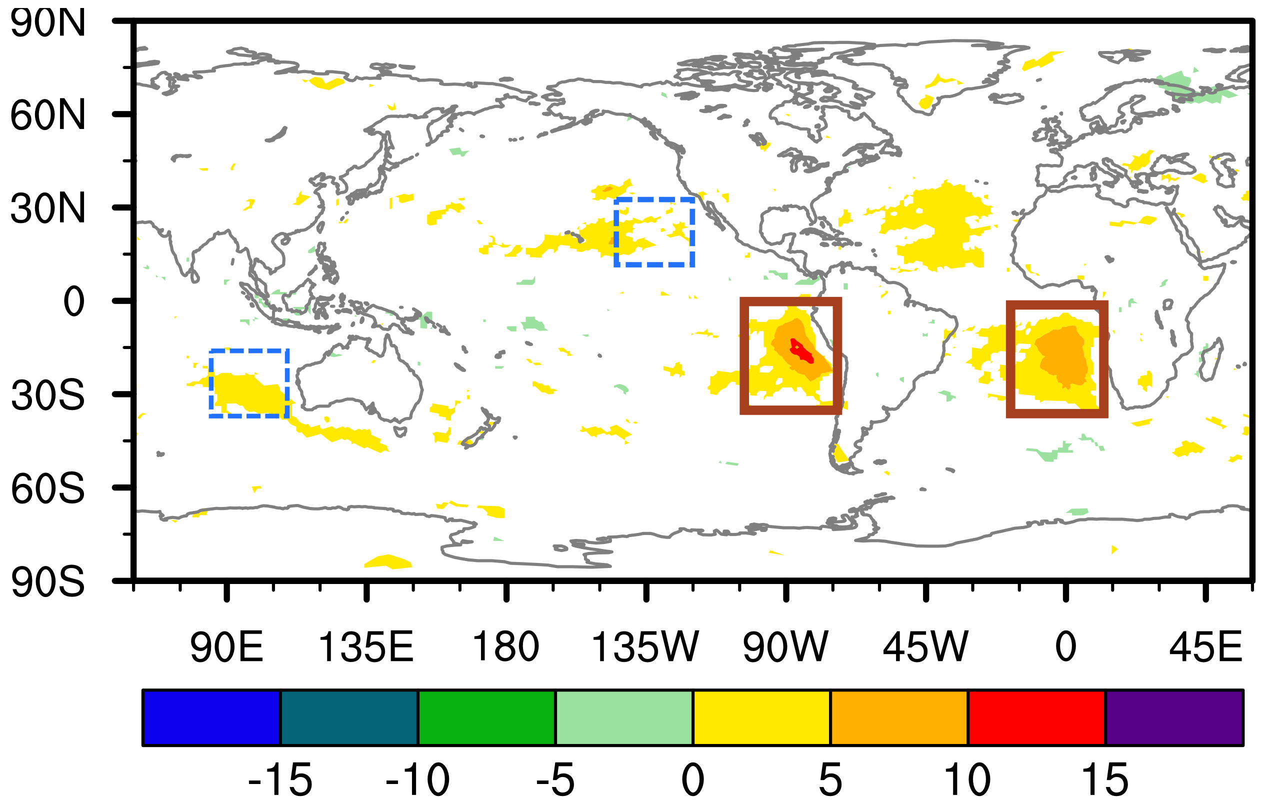
Deep convection and its interaction with dynamics etc.



Going beyond attribution — understanding and addressing the root causes

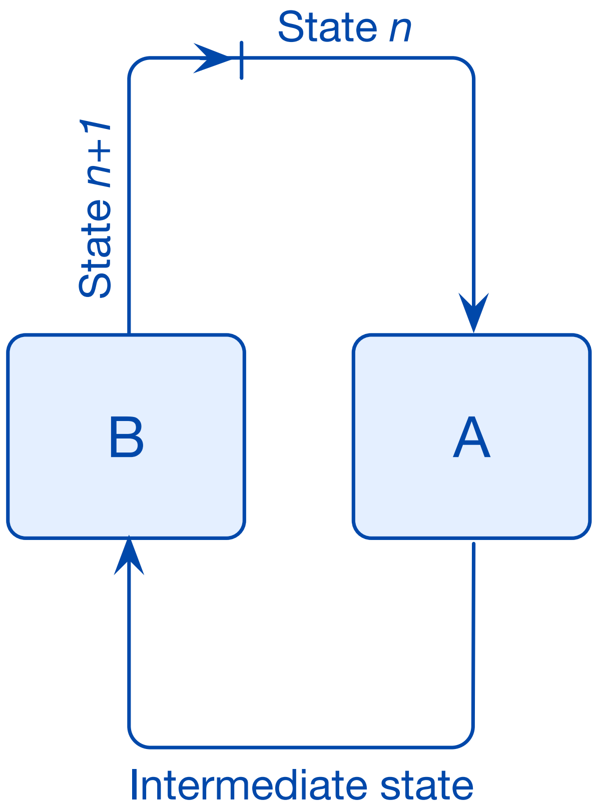
This presentation: discussing process coupling as an example

10-year mean total CRE differences caused by more frequent coupling between cloud macro/microphysics and rest of model

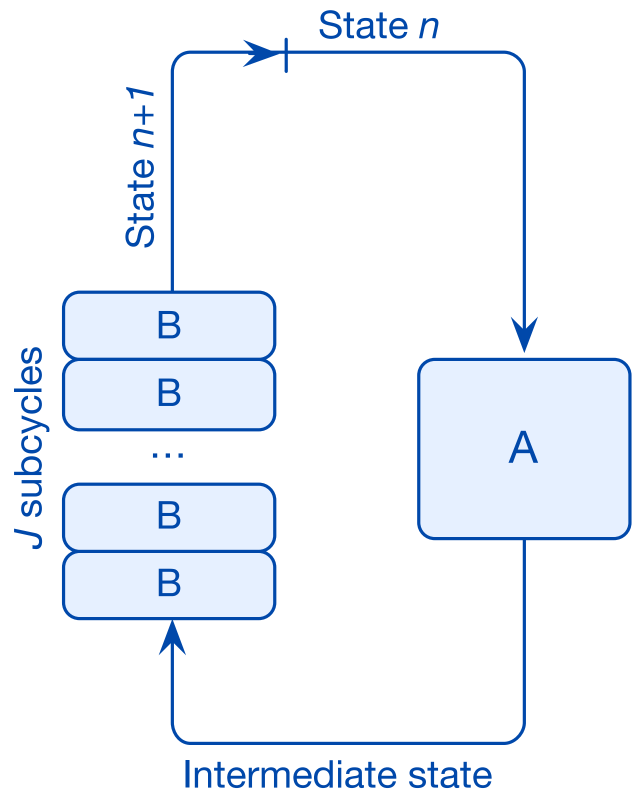


Sequential splitting is the primary process coupling method used in EAM

Without substepping

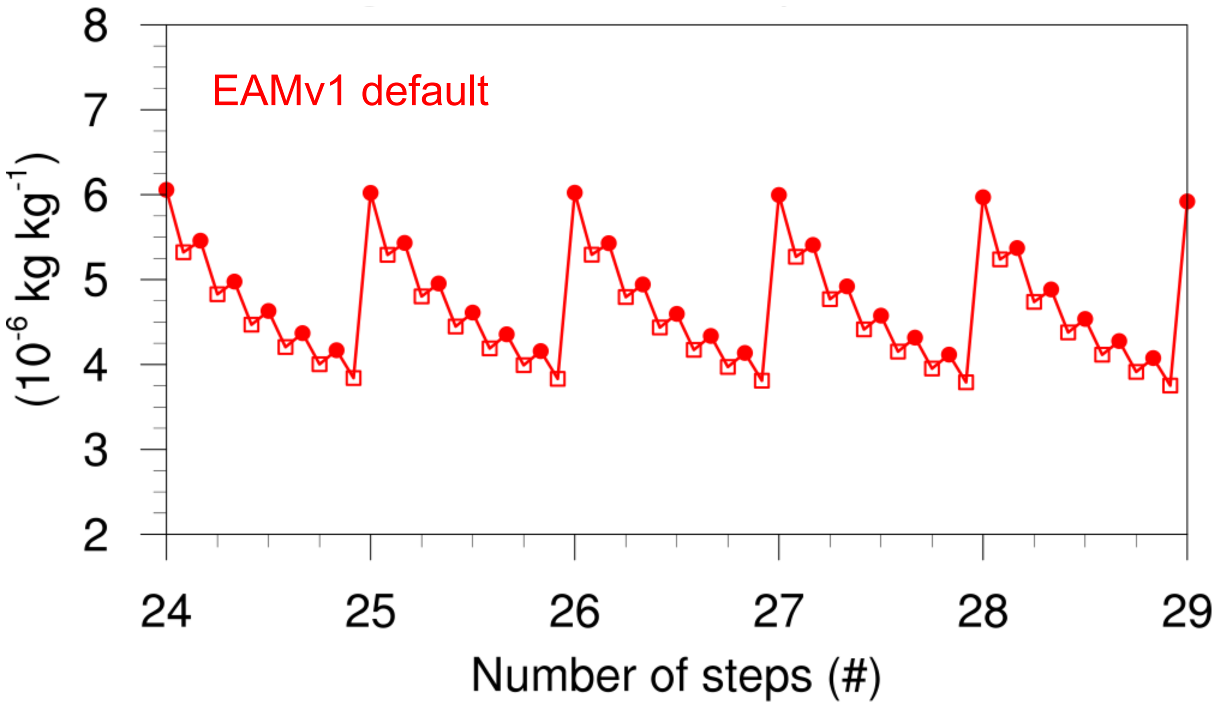


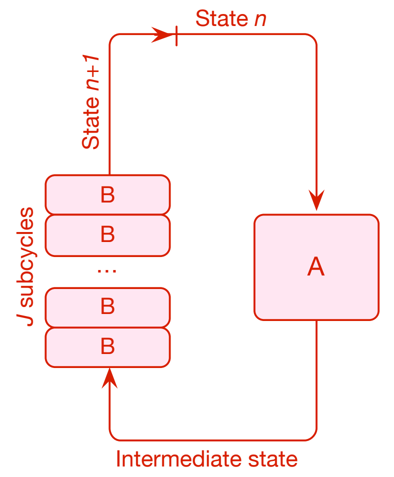
With substepping



Sequential splitting can cause strong oscillation of atmospheric state within each time step

Global mean concentration of stratiform cloud liquid (CLDLIQ) over 5 time steps (30 subcycles)

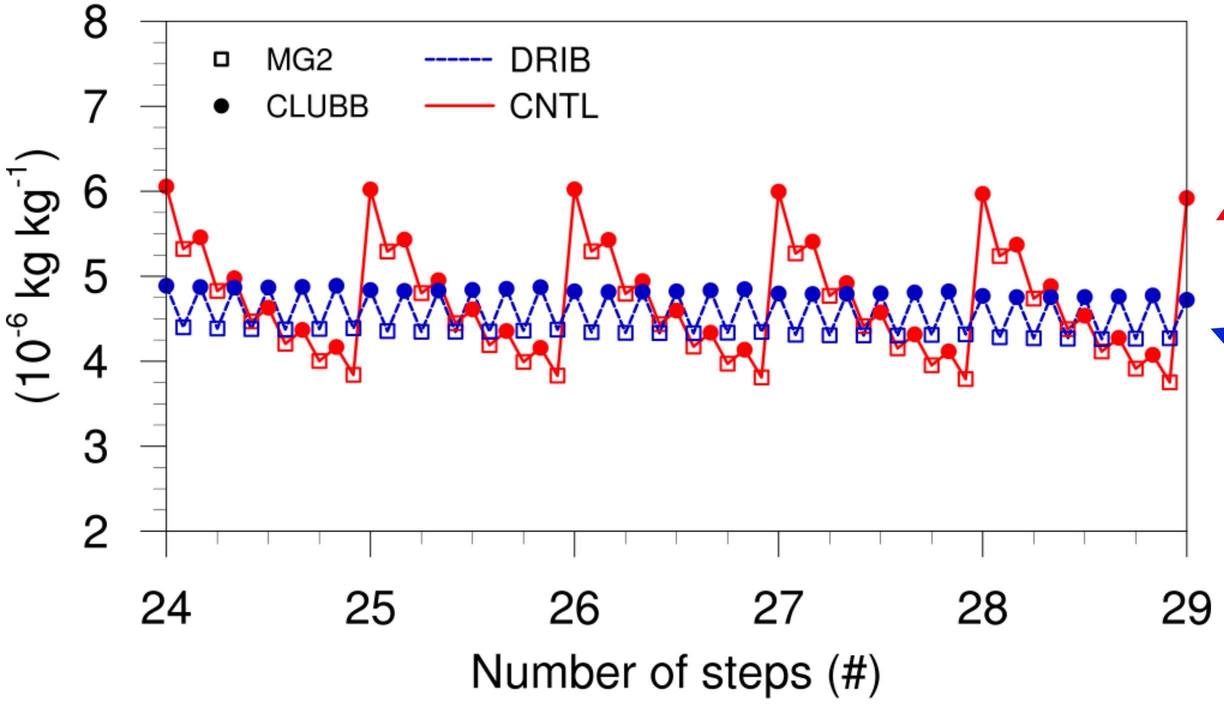


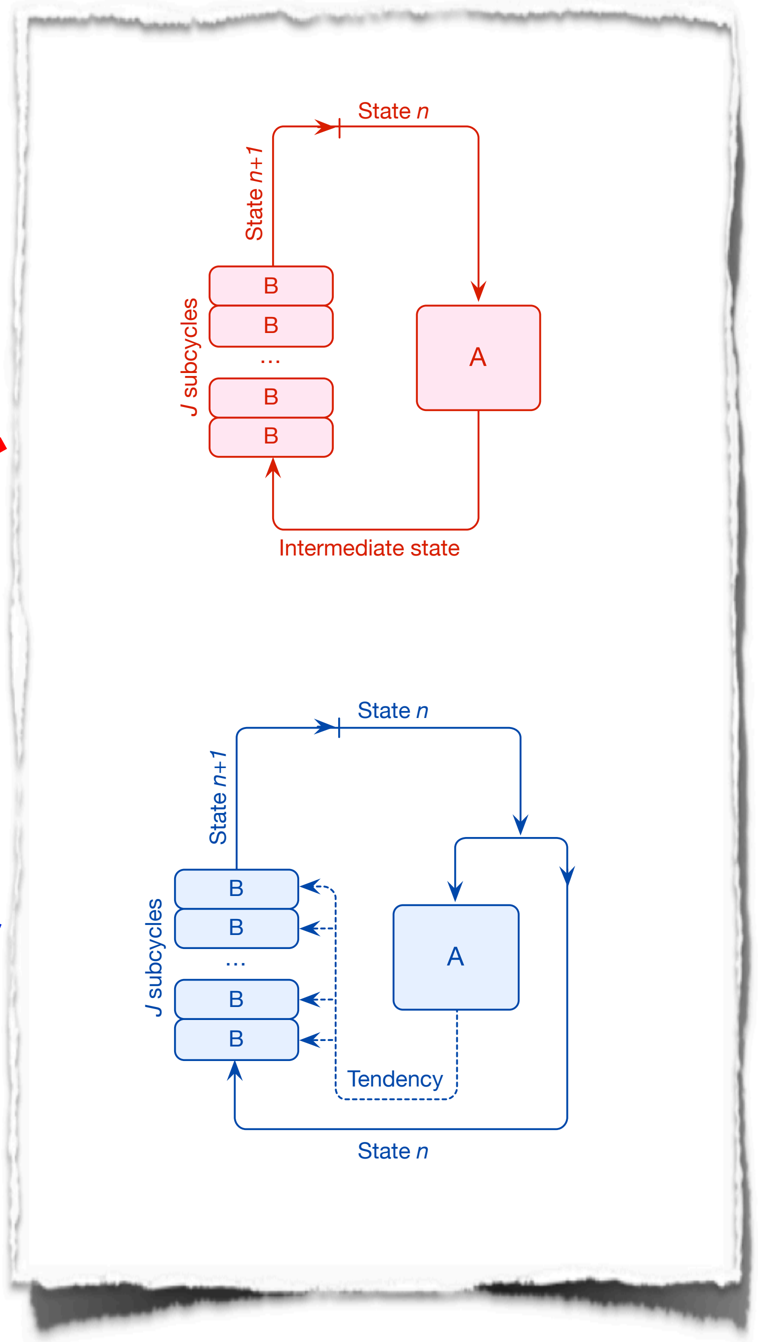


B = CLUBB + MG2
A = all other processes (grid resolved *and* unresolved)

Tighter coupling can help alleviate the problem

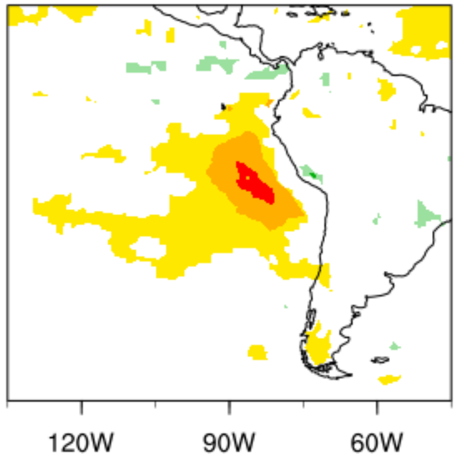
Global mean concentration of stratiform cloud liquid (CLDLIQ) over 5 time steps (30 subcycles)



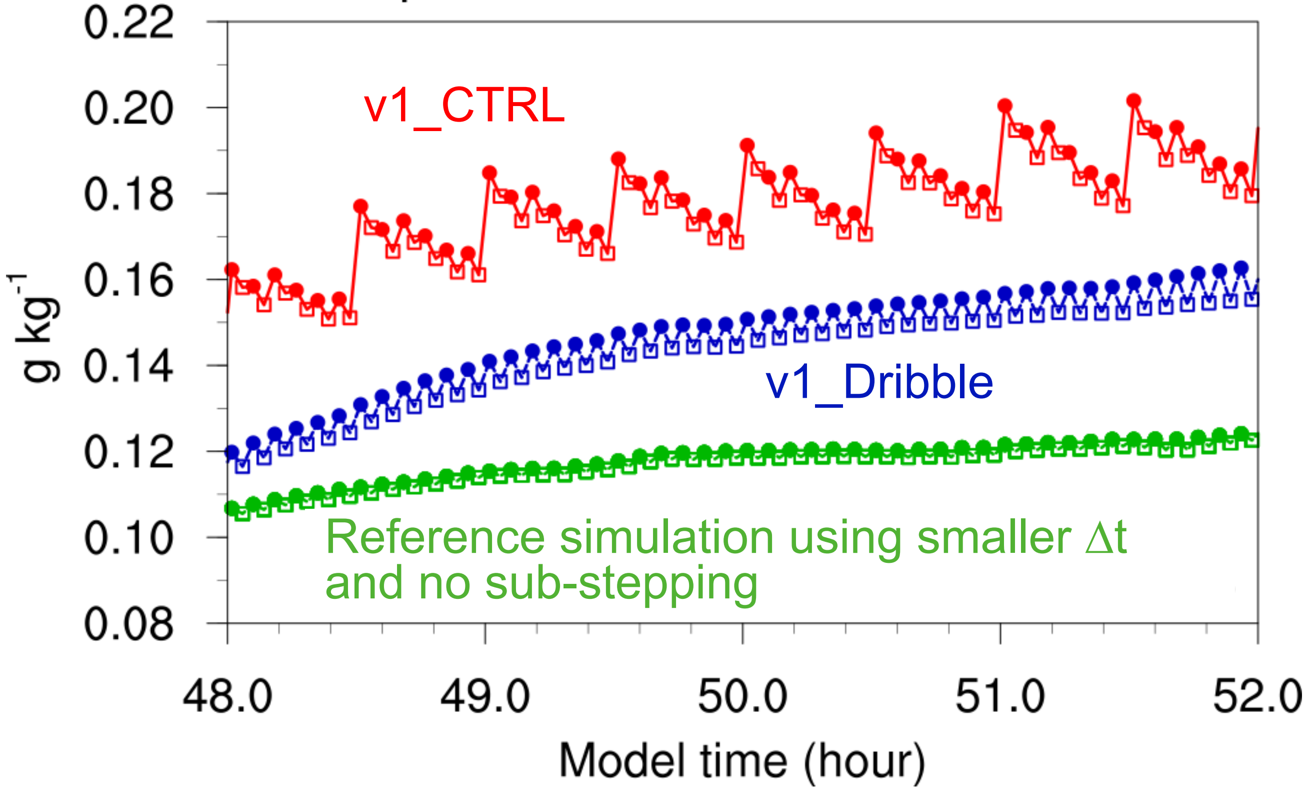


Change in coupling frequency can lead a shift of the mean state

ΔCRE, v1_Dribble – v1_CTRL



Peruvian stratocumulus region,
4-hour time series of CLDLIQ (700-1000 hPa)



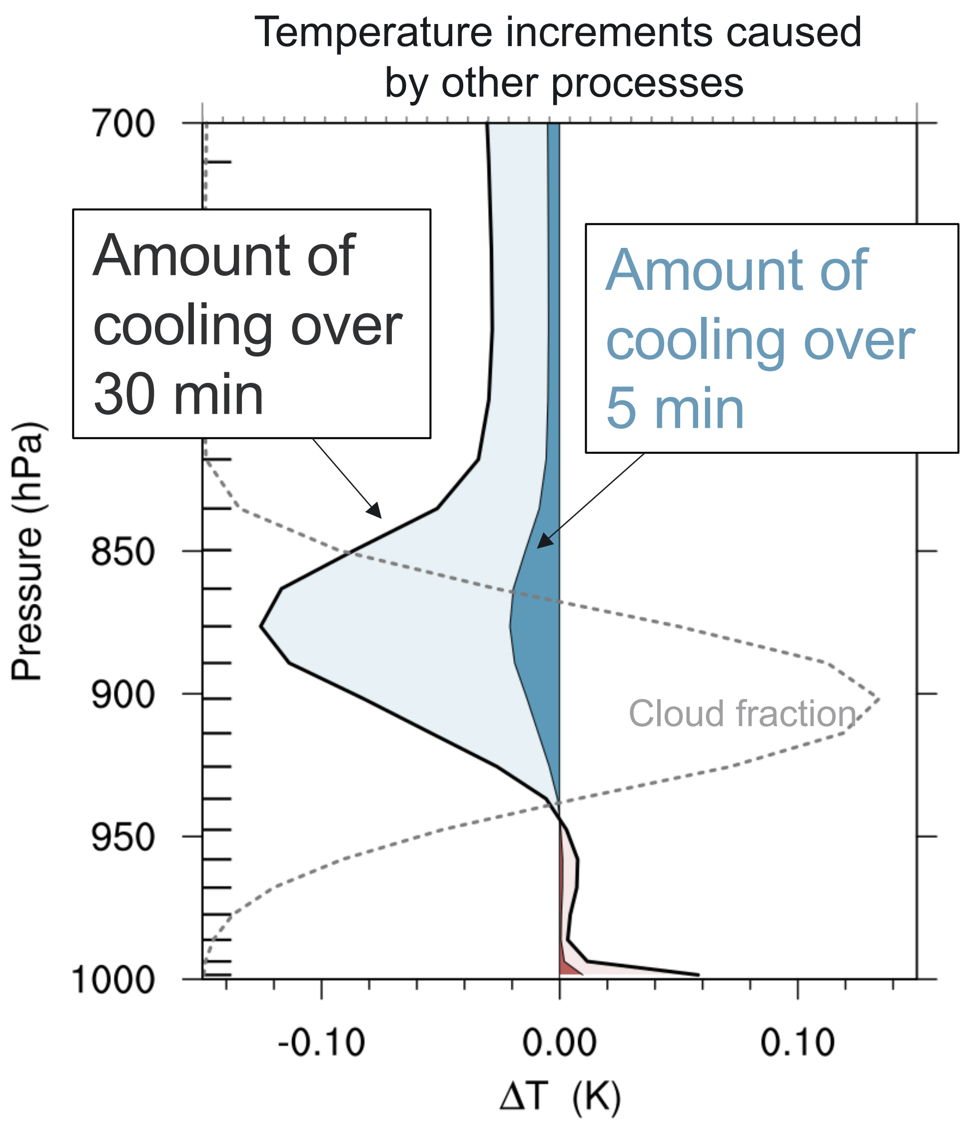
Why decreases in stratocumulus?

Sequential splitting results in a direct impact of coupling step size on the atmospheric state seen by CLUBB

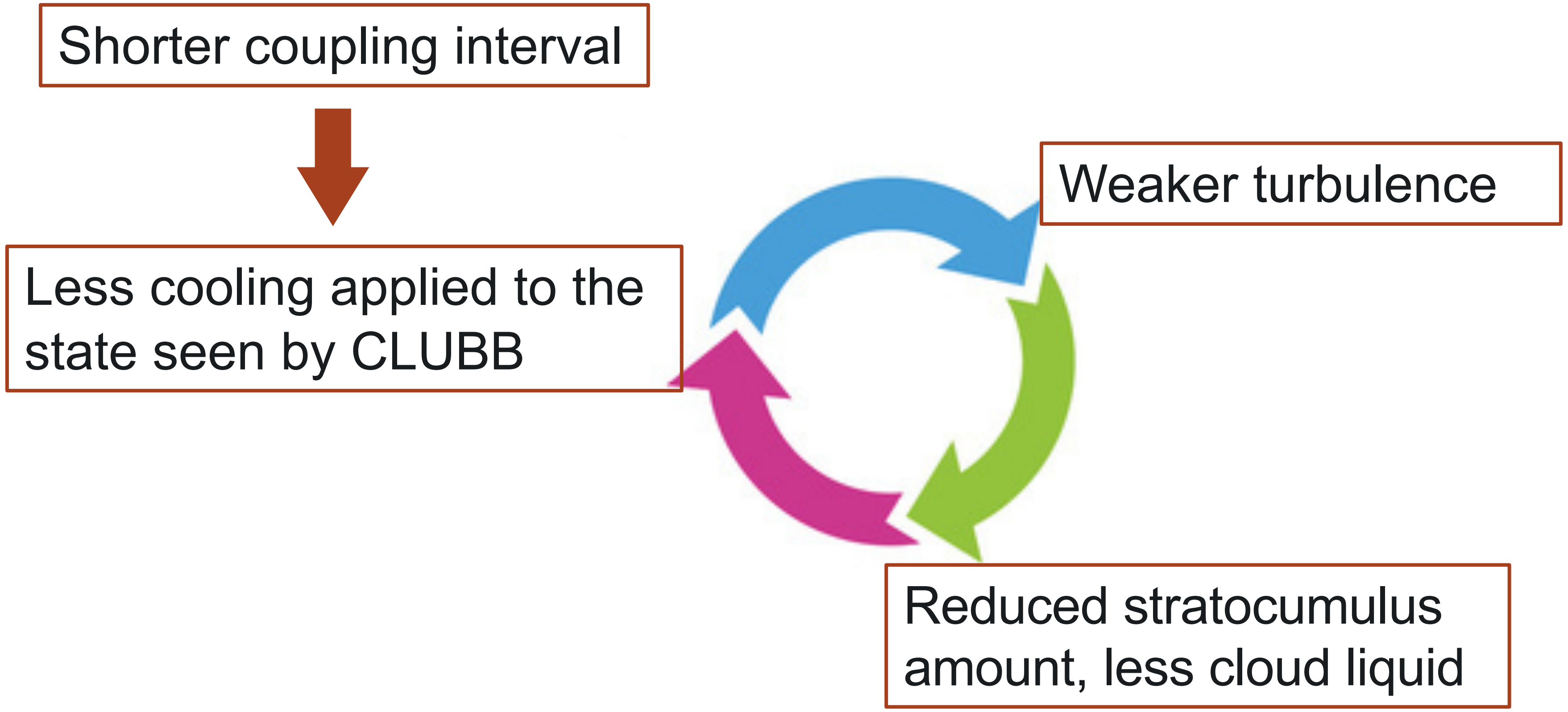
Shorter coupling interval

↓

Less cooling applied to the state seen by CLUBB

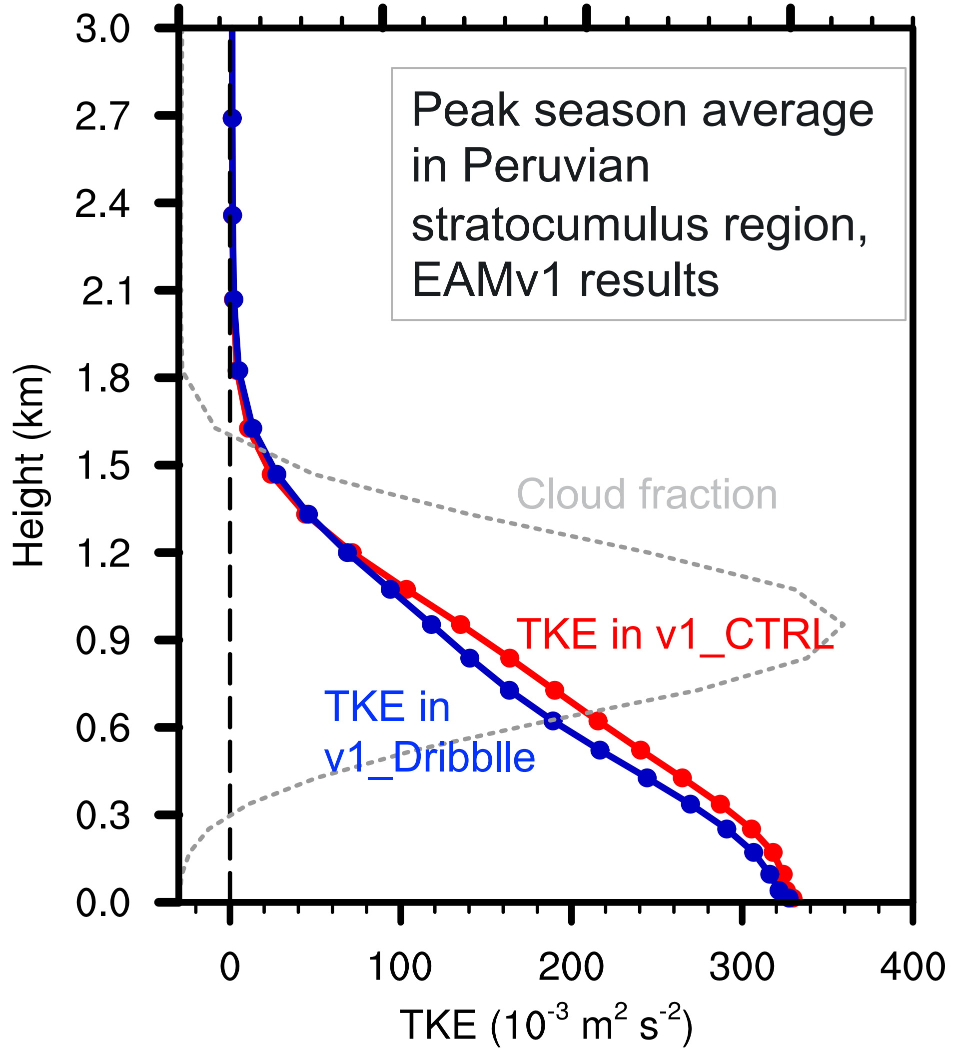


Positive feedback between cloud-top cooling and stratocumulus amount enhances the model’s response to coupling frequency



Diagnostics from inside CLUBB support our hypothesis

- Weaker turbulence and buoyancy flux in the boundary layer
- Decreased convective stability at cloud top

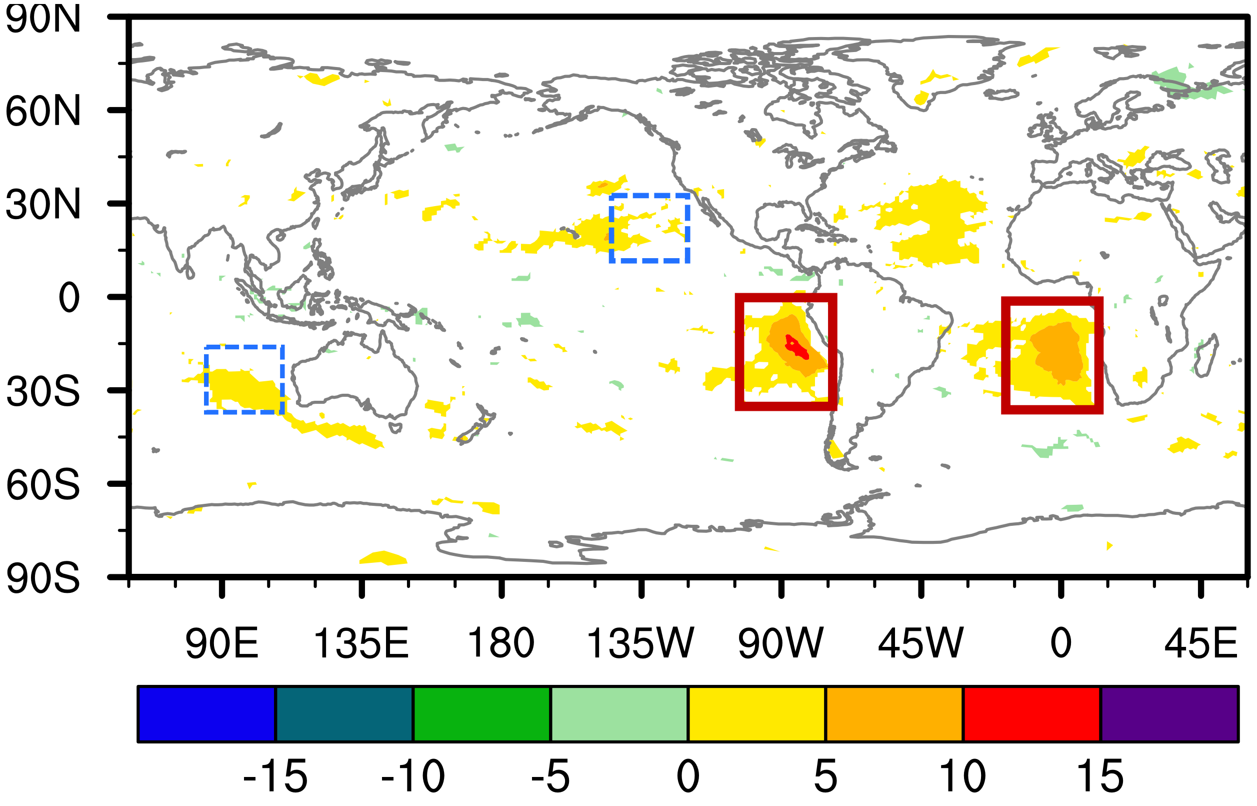


Single-column simulation further confirms the role of radiation

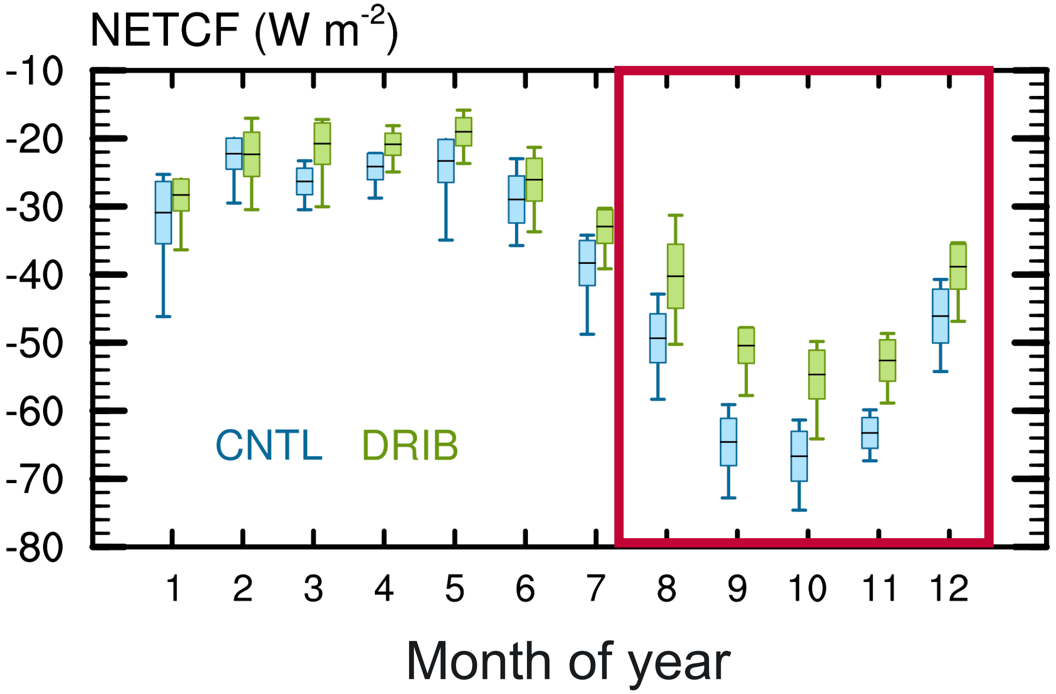
- DYCOMS-II RF01 case
- No deep convection
- No horizontal advection
- With or w/o microphysics, with or w/o shortwave radiation, model shows the same qualitative behavior

Impact of process coupling appear to be time and location dependent - why?

10-year mean ΔCRE caused by more frequent coupling between cloud macro/microphysics and rest of model

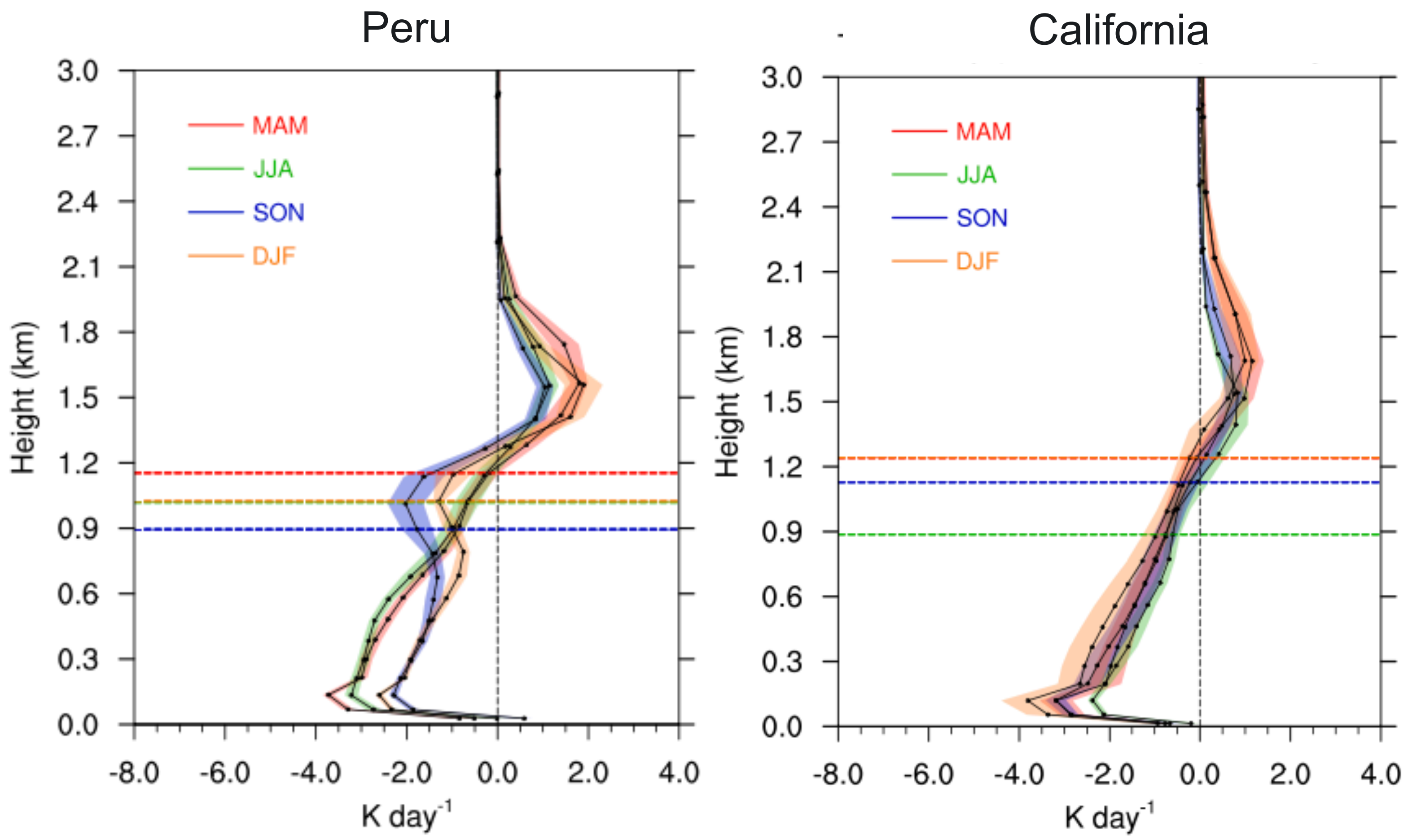


Annual cycle of CRE over the Peruvian stratocumulus region

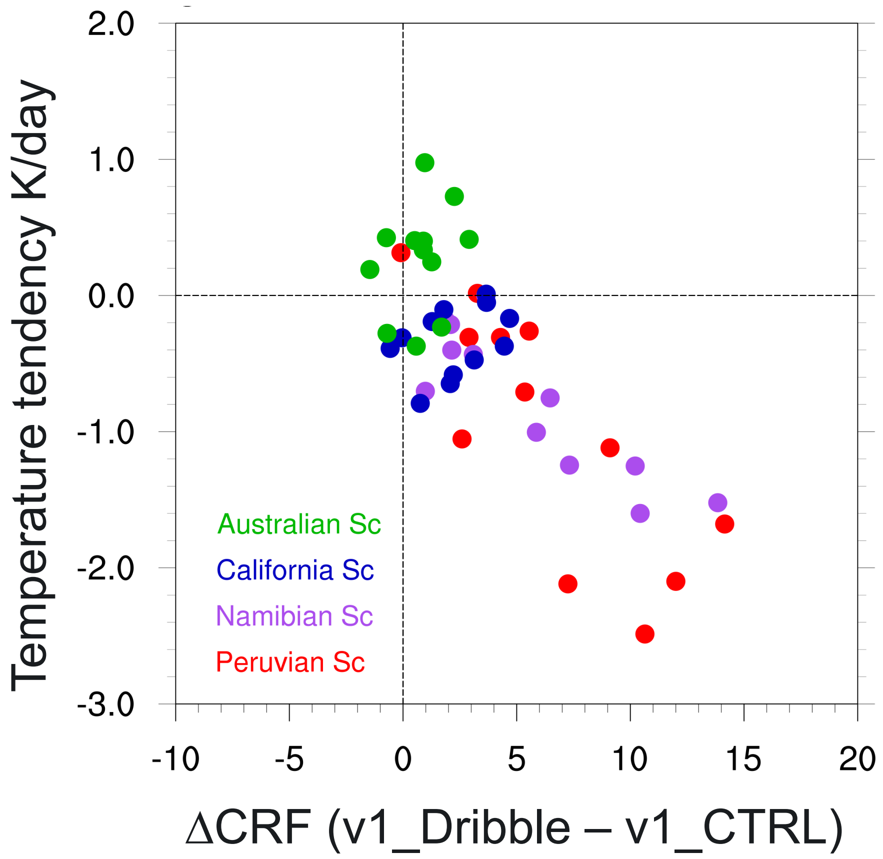


The proposed mechanism is expected to be valid only when radiative cooling is sufficiently strong to result in a negative out-of-subcycle T-tendency

Seasonal averages of out-of-subcycle T-tendency



Monthly mean out-of-subcycle T-tendency v.s. ΔCRF



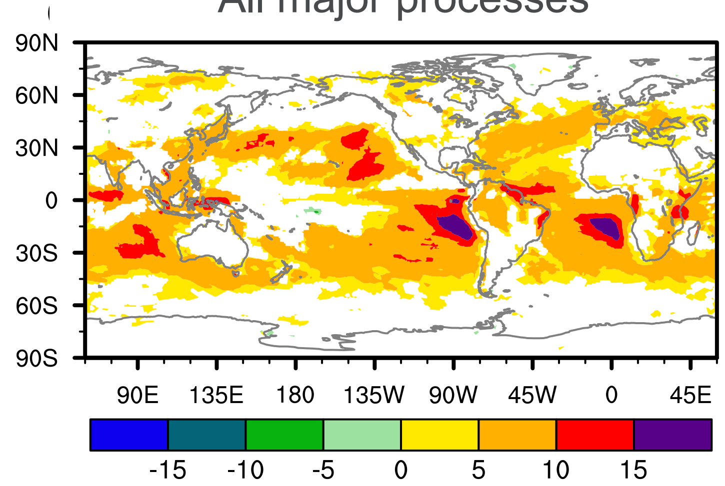
Conclusions so far

- Time step sensitivity is non-negligible in EAMv1's present-day climate simulations
  - Inconvenient for model developers focusing on model fidelity
  - Indication of significant time-stepping error needing to be addressed

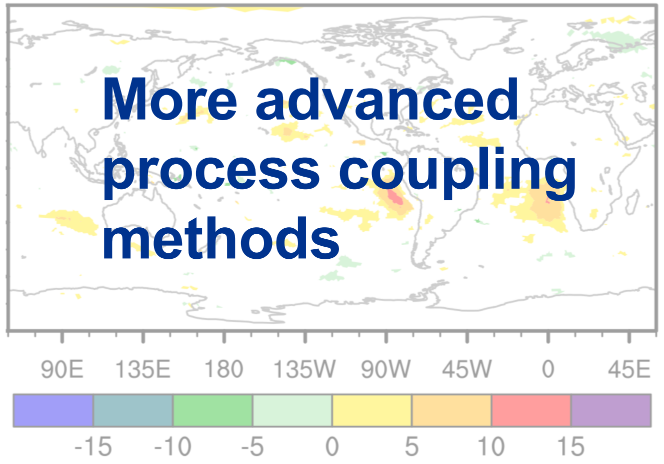
- Sources and root causes of time step sensitivity can be identified and addressed
- Process coupling is an important area to put more efforts in

On-going and future work

All major processes



Coupling between cloud macro-/microphysics and rest of model



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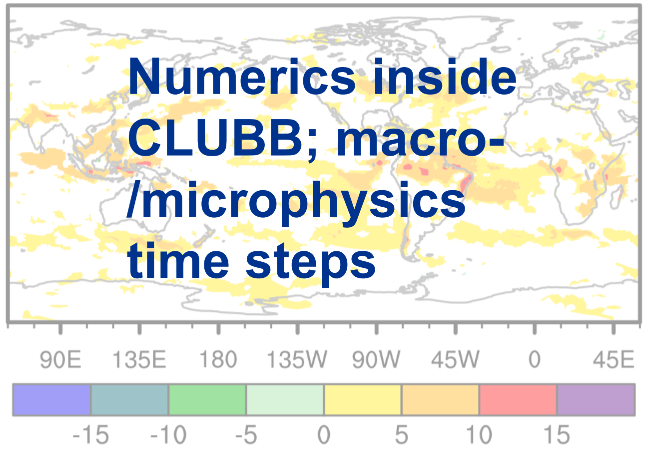
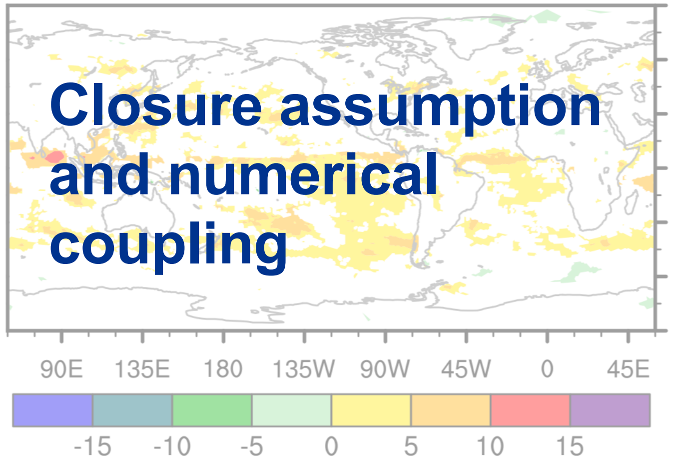
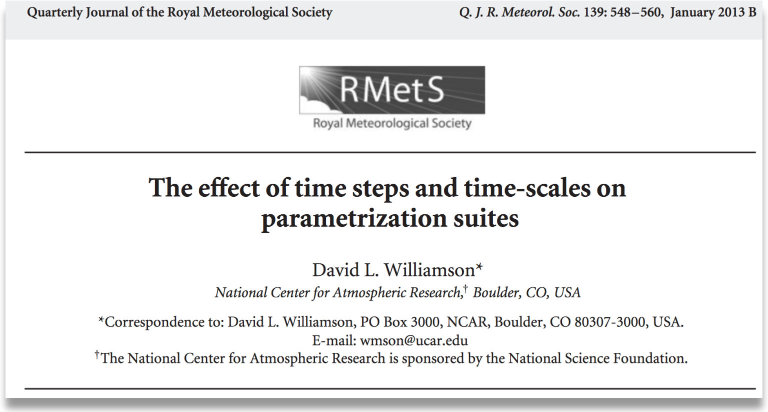


Deep convection and its interaction with dynamics etc.



Teaser slide: deep convection, time steps, and timescales



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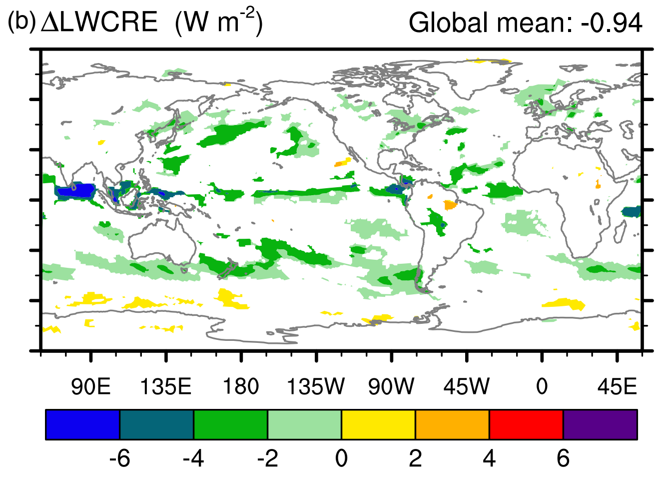
The effect of time steps and time-scales on parametrization suites

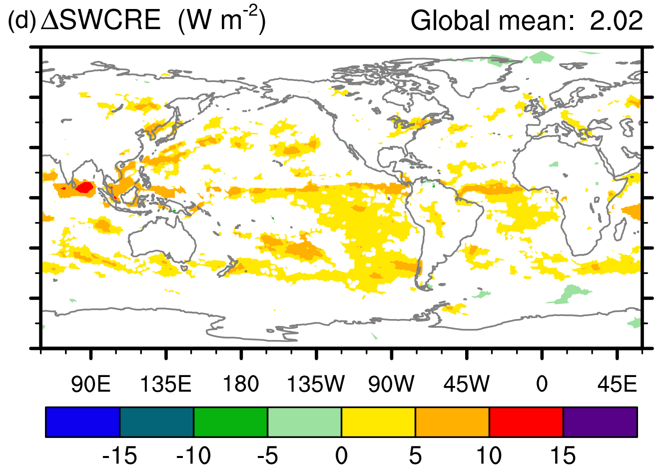
David L. Williamson*
National Center for Atmospheric Research,[†] Boulder, CO, USA
*Correspondence to: David L. Williamson, PO Box 3000, NCAR, Boulder, CO 80307-3000, USA.
E-mail: wmson@ucar.edu
[†]The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Can the $\Delta t/\tau$ ratio explain our observed time step sensitivities? Yes, but there is more to it.

10-year annual mean ΔCRE corresponding to a factor-of-6 reduction of $\Delta t/\tau$

by changing Δt





by changing τ