E3SM
Energy Exascale Earth System Model

Exploring the Full Potential of the E3SM Atmosphere Model (EAM) V1 in Simulating Clouds, Precipitation, and Feedbacks

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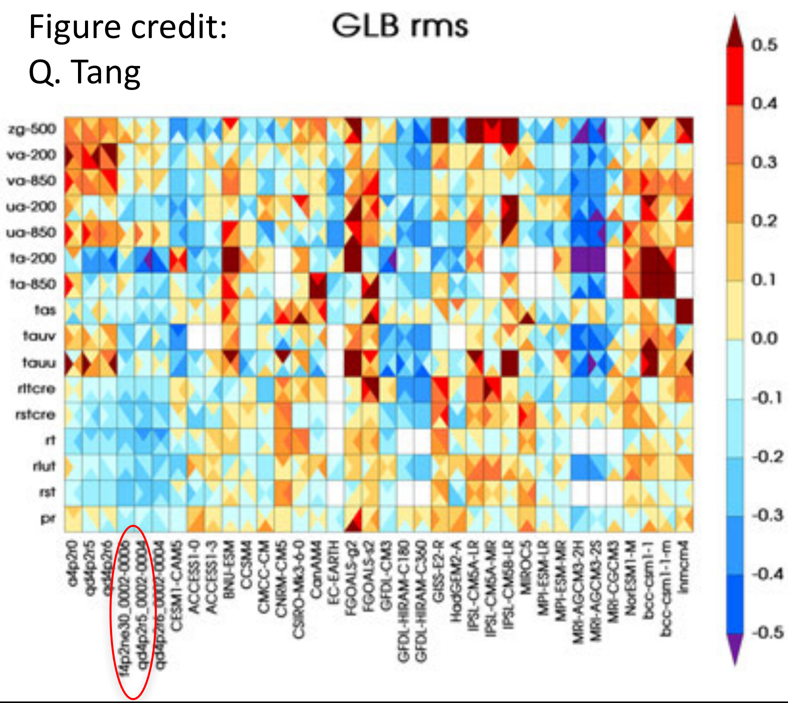
Just a reminder: EAM V1 is a very good model!

Figure credit:
Q. Tang



- Compared to CAM5:
  - Overall improved simulation of cloud, radiation, and precipitation
  - Slightly worse in large-scale circulation
- Better than most of the CMIP5 Models

Slide credit: P. Rasch

Evolution of EAM V1 Configurations

250 simulations | 400 simulations

Main Track (master)

Feb, 2016 — **AV1C-01**

known issues
- Aerosol
- Cloud
- Precipitation

Apr, 2016 — **AV1C-02**
- Cloud
- TOA energy balance difference

May, 2016 — **AV1C-03**
- AIE
- Cloud
- Aerosol
- Wind stress

Jul, 2016 — **AV1C-04**

Nov, 2016 — **AV1C-04P2**
- Cloud (stratocumulus, tropics, Arctic)
- Precipitation (TWP, Andes, Amazon)
- TOA energy balance diff.

update branch

update master

Research Track (PMA branch)

- Deep convection
- Cloud macrophysics

- Energy balance at 1850

- Auto-conversion
- Ice nucleation
- Deep convection
- SOA
- GWD

Motivation:
- Research and publish, and my desire to further improve the model
- Identify development needs and opportunities for V2 and beyond

E3SM Energy Exascale Earth System Model

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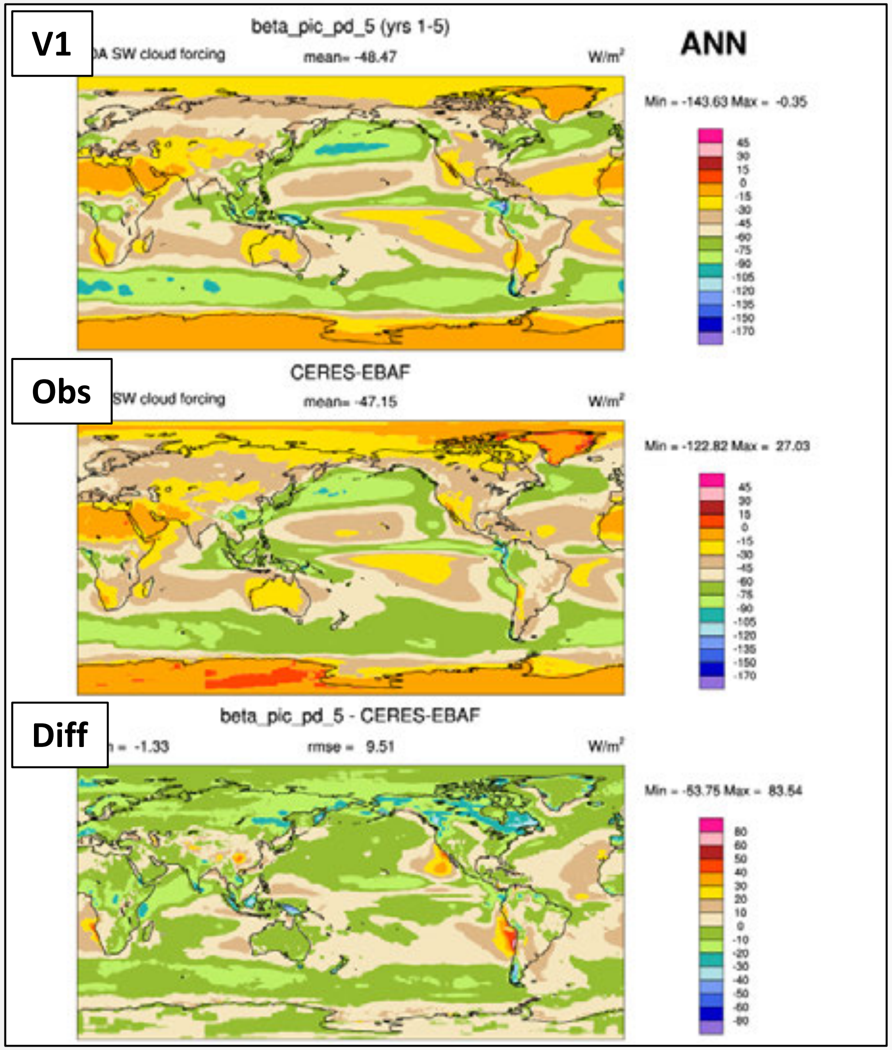
Cloud

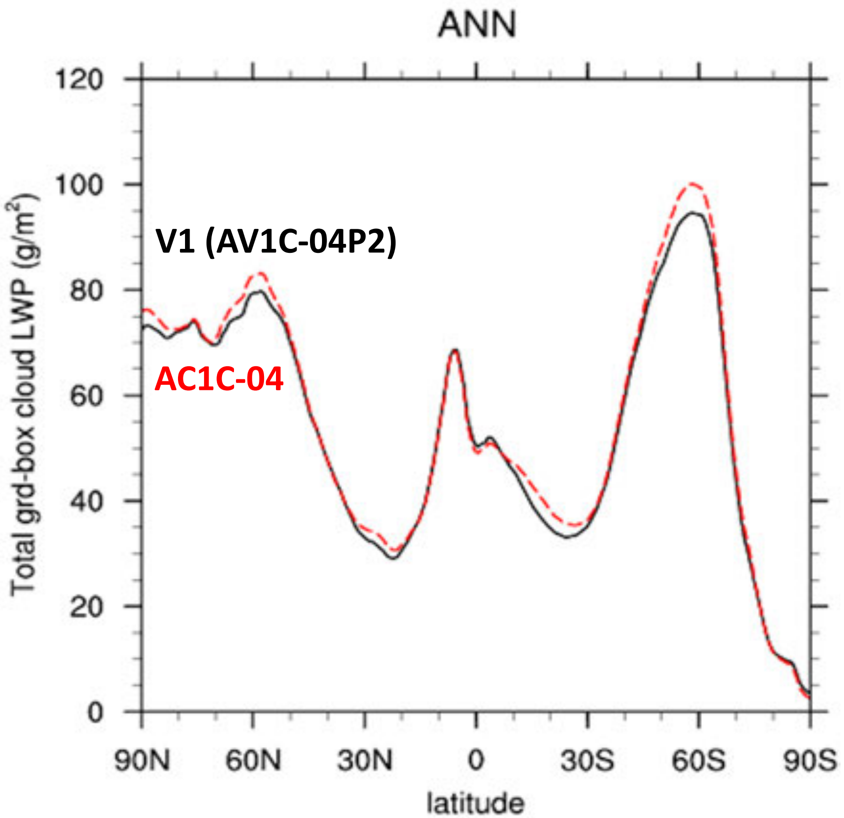
- **List of issues**
  - Lack of coastal stratocumulus
  - Lack of clouds in TWP
  - LWP in high latitudes seems too high.

- **What I have done** (inspired by or consulted with)**:**
  - Turbulence, skewness, and entrainment tuning (Xiao, Larson, Golaz)
  - Skewness-based tuning of turbulent mixing and PDF (Xiao, Larson, Golaz)
  - Retune microphysics: subgrid condensate variance, accretion, sedimentation, Droplet nucleation, ice nucleation, phase (Gettelman, Morrison, M. Wang, Larson, Chepfer, Z. Zhang, Suzuki, Liu, H. Wang, K. Zhang)
  - Retune deep convection: entrainment, evaporation, trigger level, autoconversion, detrained condensate size (Diagnostics from Coupled Simulation Team, Rasch, Gryspeerdt, Quaas)
  - Gustiness over ocean (Harrop et al, in review)

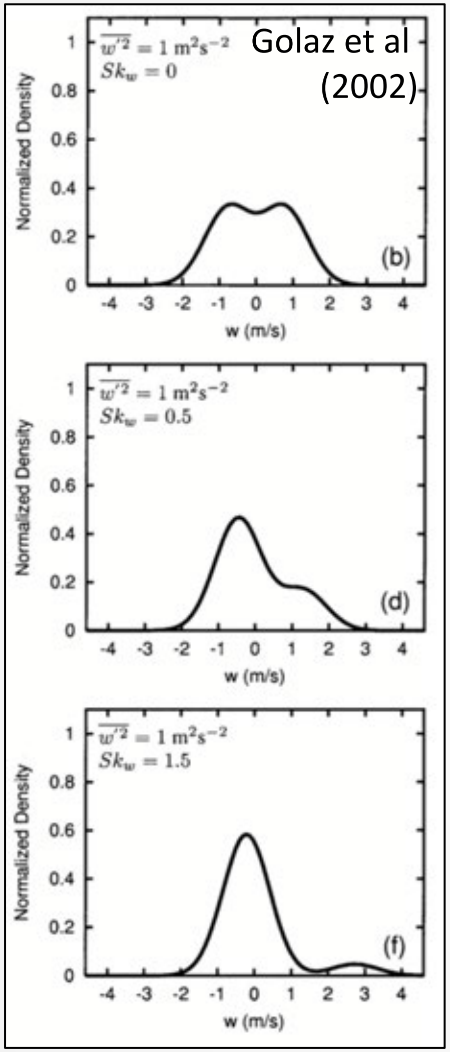
Lack of coastal stratocumulus
High-latitude LWP seems too high



- Coastal Sc SWCF bias: 40W/m² (VOCALS)
- LWP in high latitudes seems too high, despite the observational uncertainty.

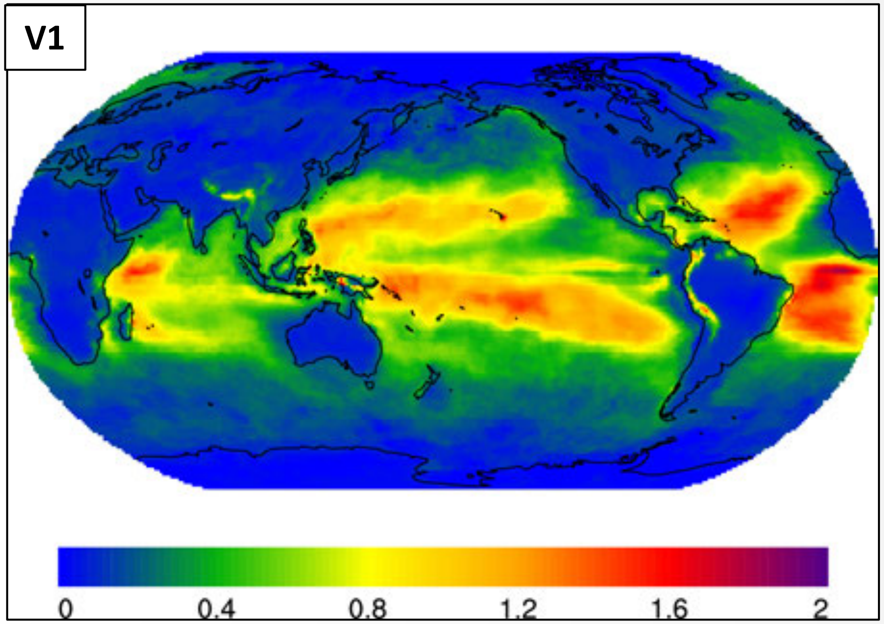


Skewness $Sk_w = (\overline{w'^3})/(\overline{w'^2}^{1.5})$



Low skewness
Symmetric
Stratocumulus

High skewness
Strong updrafts
Shallow Cu



- EAM V1 has a reasonable skewness distribution: high skewness in the shallow convective regime and low skewness in stratocumulus regime, except the Sc region is too narrow and the annual mean skewness is probably too high.

Tune and then use skewness

- A subset of CLUBB equations from Bogenschutz et al (2013):

$$\frac{\partial\overline{w'^2}}{\partial t} = -\overline{w}\frac{\partial\overline{w'^2}}{\partial z} - \frac{\partial\overline{w'^3}}{\partial z} - 2\overline{w'^2}\frac{\partial\overline{w}}{\partial z} + \frac{2g}{\theta_0}\overline{w'\theta_v'} - C_5\left(-2\overline{w'^2}\frac{\partial\overline{w}}{\partial z} + \frac{2g}{\theta_0}\overline{w'\theta_v'}\right) + \frac{2}{3}C_5\left(\frac{g}{\theta_0}\overline{w'\theta_v'} - \overline{u'w'}\frac{\partial\overline{u}}{\partial z} - \overline{u'w'}\frac{\partial\overline{v}}{\partial z}\right) + \frac{C_1}{\tau}\overline{w'^2} + \nu_1\nabla_z^2\overline{w'^2},$$

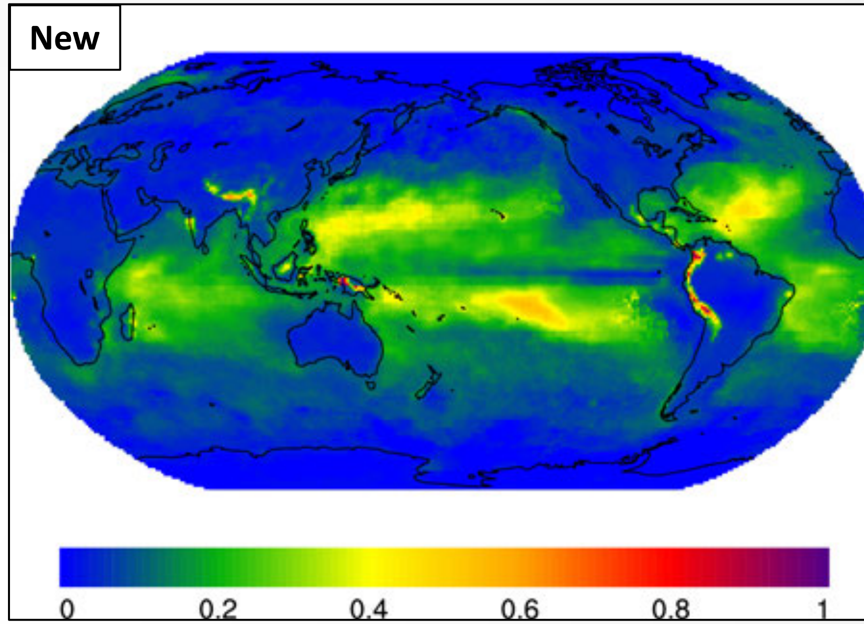
This should be a – sign

$$\frac{\partial\overline{w'^3}}{\partial t} = -\overline{w}\frac{\partial\overline{w'^3}}{\partial z} - \frac{\partial\overline{w'^4}}{\partial z} + 3\overline{w'^2}\frac{\partial\overline{w'^2}}{\partial z} - 3\overline{w'^3}\frac{\partial\overline{w}}{\partial z} + \frac{3g}{\theta_0}\overline{w'^2\theta_v'} - \frac{C_8}{\tau}(C_{8b}Sk_w^4 + 1)\overline{w'^3} - C_{11}\left(-3\overline{w'^3}\frac{\partial\overline{w}}{\partial z} + \frac{3g}{\theta_0}\overline{w'^2\theta_v'}\right) + (K_w + \nu_8)\nabla_z^2\overline{w'^3}$$

$$\frac{\partial\overline{q_t'\theta_l'}}{\partial t} = -\overline{w}\frac{\partial\overline{q_t'\theta_l'}}{\partial z} - \frac{\partial\overline{w'q_t'\theta_l'}}{\partial z} - \overline{w'\theta_l'}\frac{\partial\overline{q_t}}{\partial z} - \overline{w'q_t'}\frac{\partial\overline{\theta_l}}{\partial z} - \frac{C_2}{\tau}\overline{q_t'\theta_l'} + \nu_2\nabla_z^2\overline{q_t'\theta_l'}, \quad \text{(B8)}$$

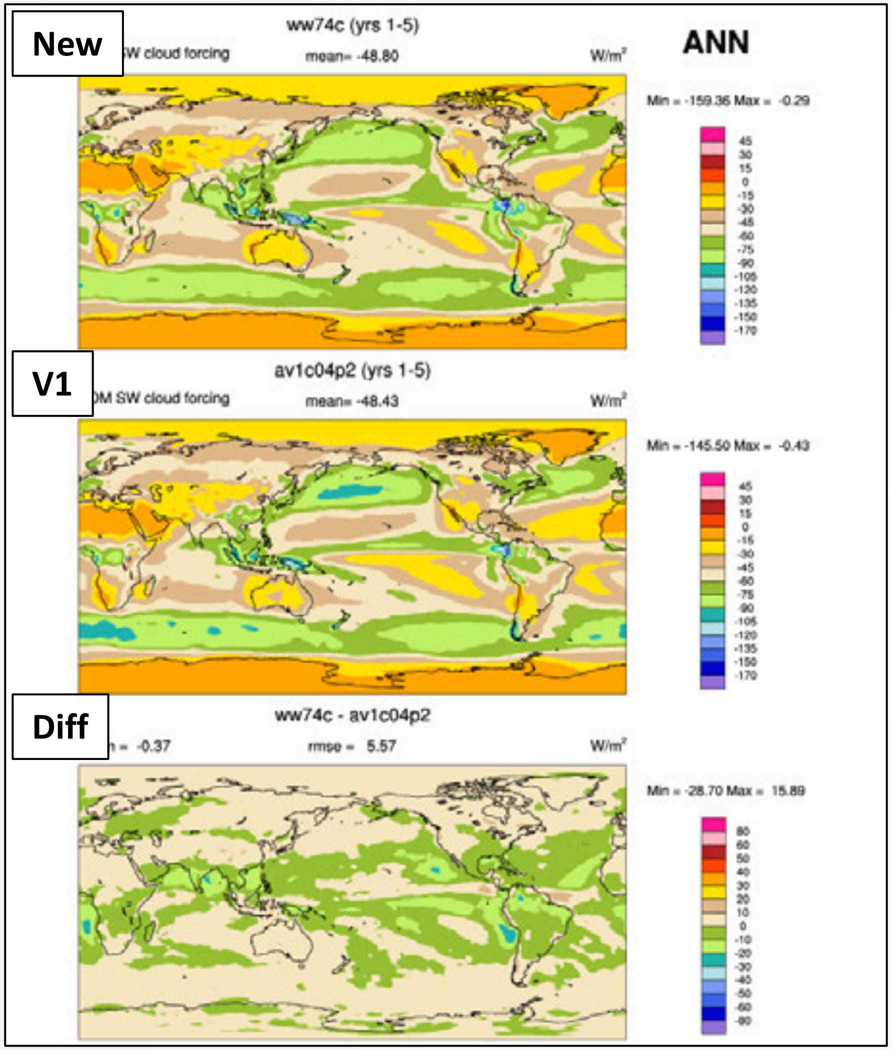
$$\frac{\partial\overline{w'q_t'}}{\partial t} = -\overline{w}\frac{\partial\overline{w'q_t'}}{\partial z} - \frac{\partial\overline{w'^2q_t'}}{\partial z} - \overline{w'^2}\frac{\partial\overline{q_t}}{\partial z} - \overline{w'q_t'}\frac{\partial\overline{w}}{\partial z} + \frac{g}{\theta_0}\overline{q_t'\theta_v'} - \frac{C_6}{\tau}\overline{w'q_t'} + C_7\left(-\overline{w'q_t'}\frac{\partial\overline{w}}{\partial z} + \frac{g}{\theta_0}\overline{q_t'\theta_v'}\right) + \nu_6\nabla_z^2\overline{w'q_t'}, \quad \text{(B9)}$$

$$\frac{\partial\overline{w'\theta_l'}}{\partial t} = -\overline{w}\frac{\partial\overline{w'\theta_l'}}{\partial z} - \frac{\partial\overline{w'^2\theta_l'}}{\partial z} - \overline{w'^2}\frac{\partial\overline{\theta_l}}{\partial z} - \overline{w'\theta_l'}\frac{\partial\overline{w}}{\partial z} + \frac{g}{\theta_0}\overline{\theta_l'\theta_v'} - \frac{C_6}{\tau}\overline{w'\theta_l'} + C_7\left(-\overline{w'\theta_l'}\frac{\partial\overline{w}}{\partial z} + \frac{g}{\theta_0}\overline{\theta_l'\theta_v'}\right) + \nu_6\nabla_z^2\overline{w'\theta_l'}, \quad \text{(B10)}$$

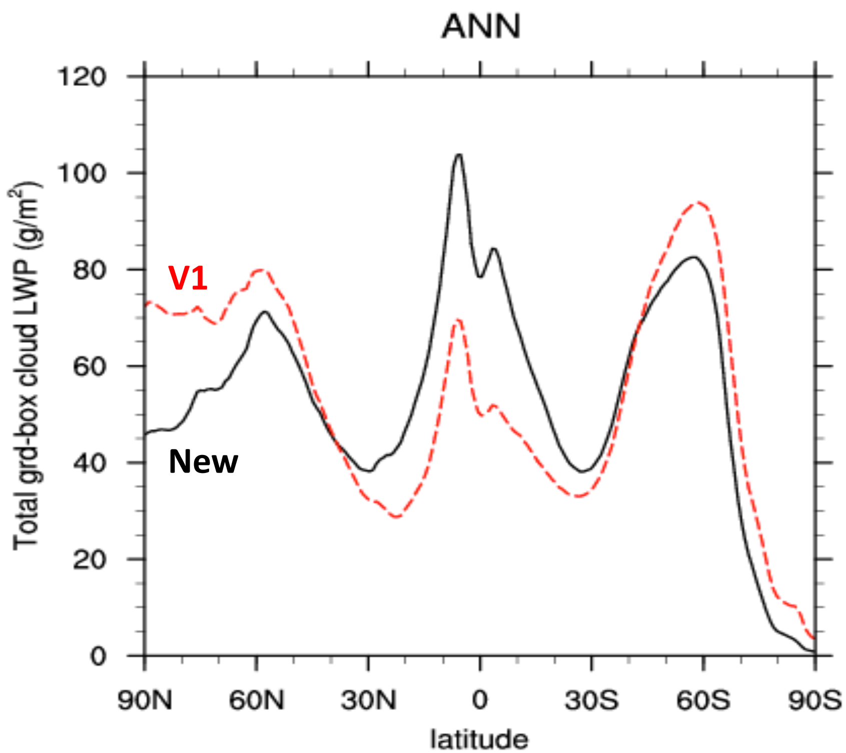


- Enhance turbulence
- Reduce skewness, especially in the coastal Sc regions to increase the areal extent of low skewness
- Use the tuned skewness for mixing and PDF tuning

Improvements



- **Costal stratocumulus** is improved significantly.
- **Meridional distribution** of LWP is realistic now.



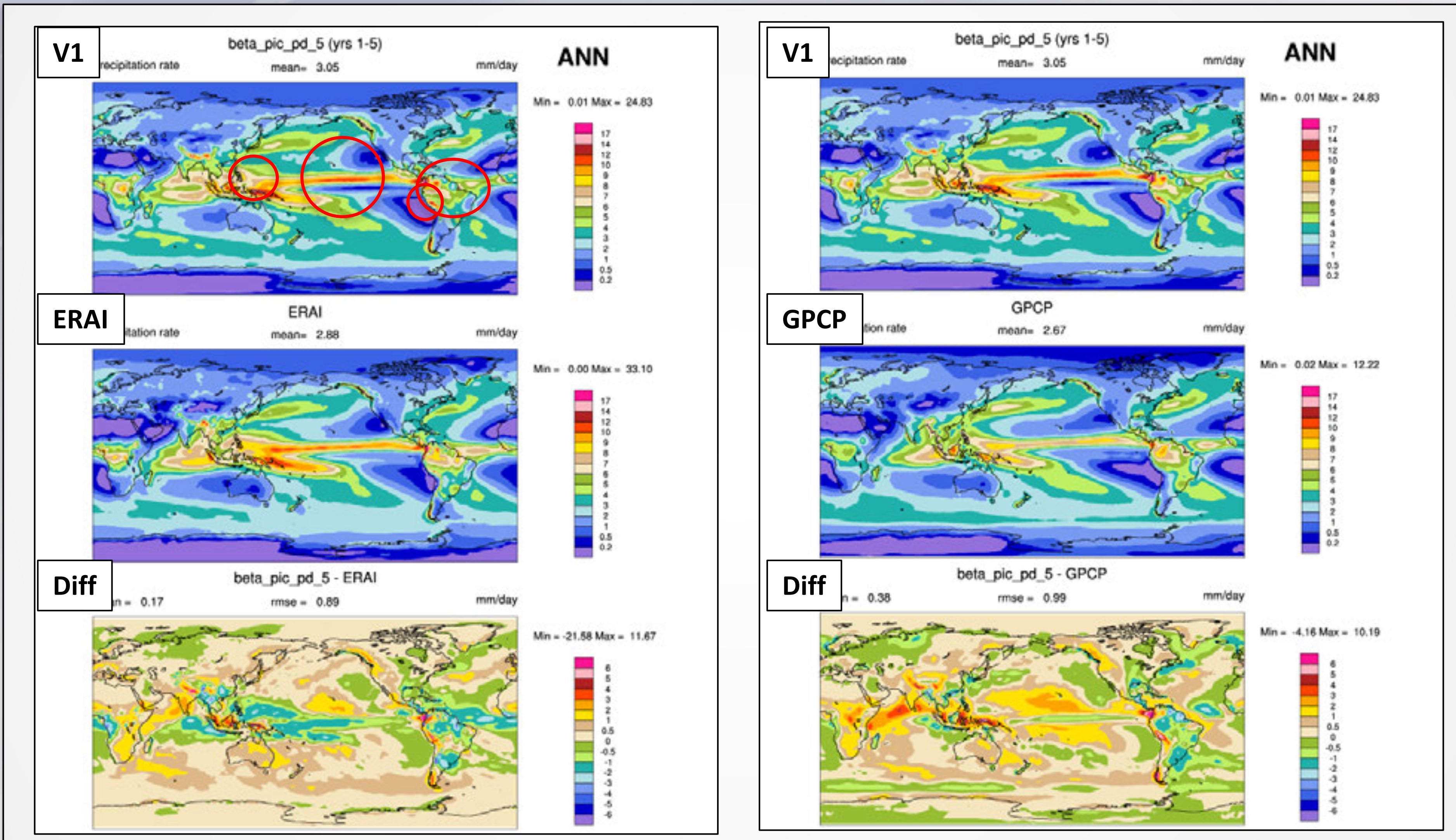
- New challenge: Stratocumulus clouds are highly susceptible to aerosols, so **increasing Sc greatly enhances AIF** (from -1.1 to -1.6 W/m²).

Precipitation

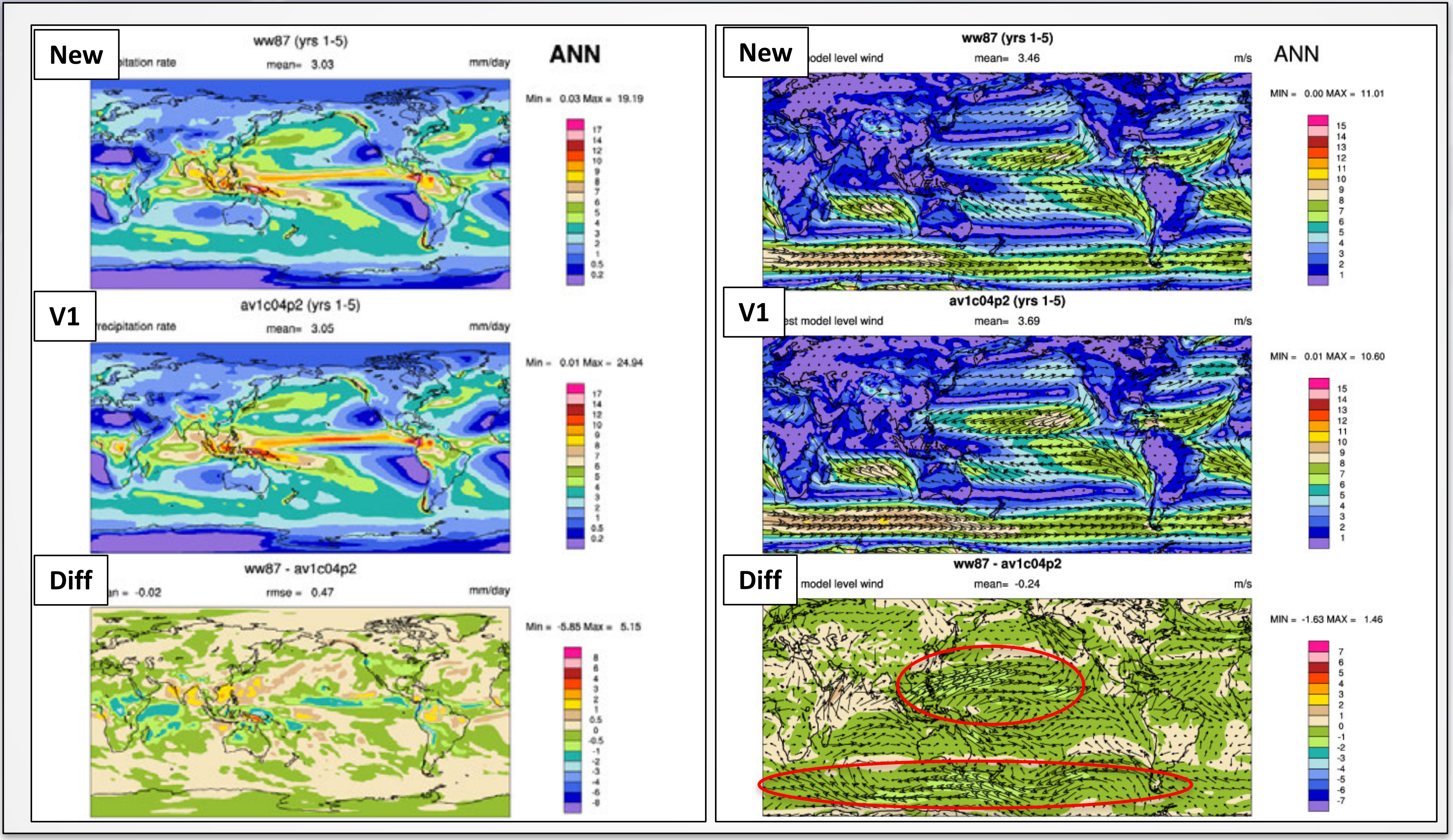
- **List of issues**
  - Biased low in TWP(related to ENSO)
  - Biased high in central Pacific (related to ENSO)
  - Biased high at high elevation (e.g., Andes)
  - Biased low over Amazon

- **What I have done** (inspired by or consulted with)**:**
  - Retune deep convection: entrainment, evaporation, trigger level, autoconversion, detrained condensate size (Diagnostics from Coupled Simulation Team, Rasch, Gryspeerdt, Quaas)
  - Gustiness over ocean and land (Harrop, Leung, Rasch, Zeng, Bisht, Riley)
  - Retune microphysics: subgrid condensate variance, accretion, sedimentation, Droplet nucleation, ice nucleation, phase (Gettelman, Morrison, M. Wang, Larson, Chepfer, Z. Zhang, Suzuki, Liu, H. Wang, K. Zhang)

Precipitation bias over TWP, Central Pacific, Amazon, high elevation (e.g., Andes)



Gustiness (subgrid wind) and new tunings improve precipitation and surface wind in the tropics (affects cold tongue and ENSO) and over SO



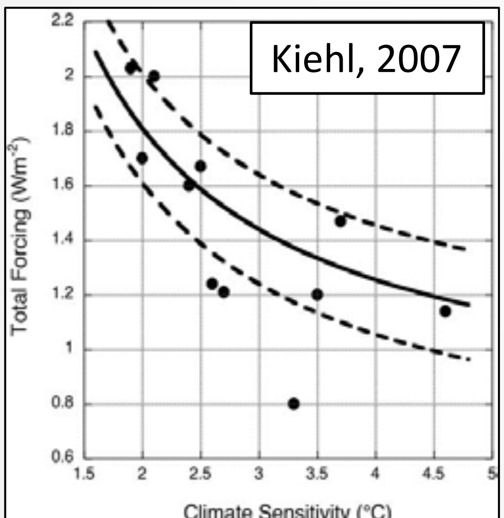
System feedback and response

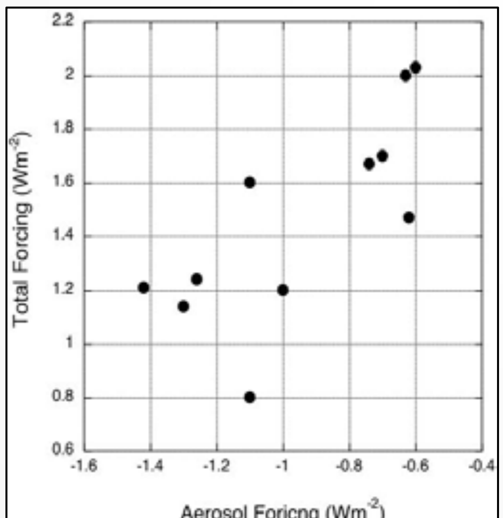
- **List of issues**
  - ΔRESTOM (PD-PI TOA energy balance difference) might be low
  - Cloud feedback might be weak
  - AIF might be high.

- **What I have done** (inspired by or consulted with)**:**
  - Sensitivity tests to find out parameters/processes affecting AIF and CF (Gryspeerdt, Quaas, Gettelman, Klein, Chepfer)
  - Retune the model based on the sensitivity study.

System response to aerosol and temperature perturbations in EAM V1

	AIF (-0.3 to -1.0)	ΔRESTOM (+0.8)	AF (1.3 ± 0.6)
AV1C-01	-1.82	-0.11	-
	-1.1	-0.29	
AV1C-02	-2.92	-0.4	-
	-0.3	-0.1	
AV1C-03	-2.95	-0.5	-
	+1.85	+0.52	
AV1C-04	**-1.25**	**0.02**	**1.18**
	+0.15	+0.47	
AV1C-04P2	**-1.10**	**0.49**	**1.27**



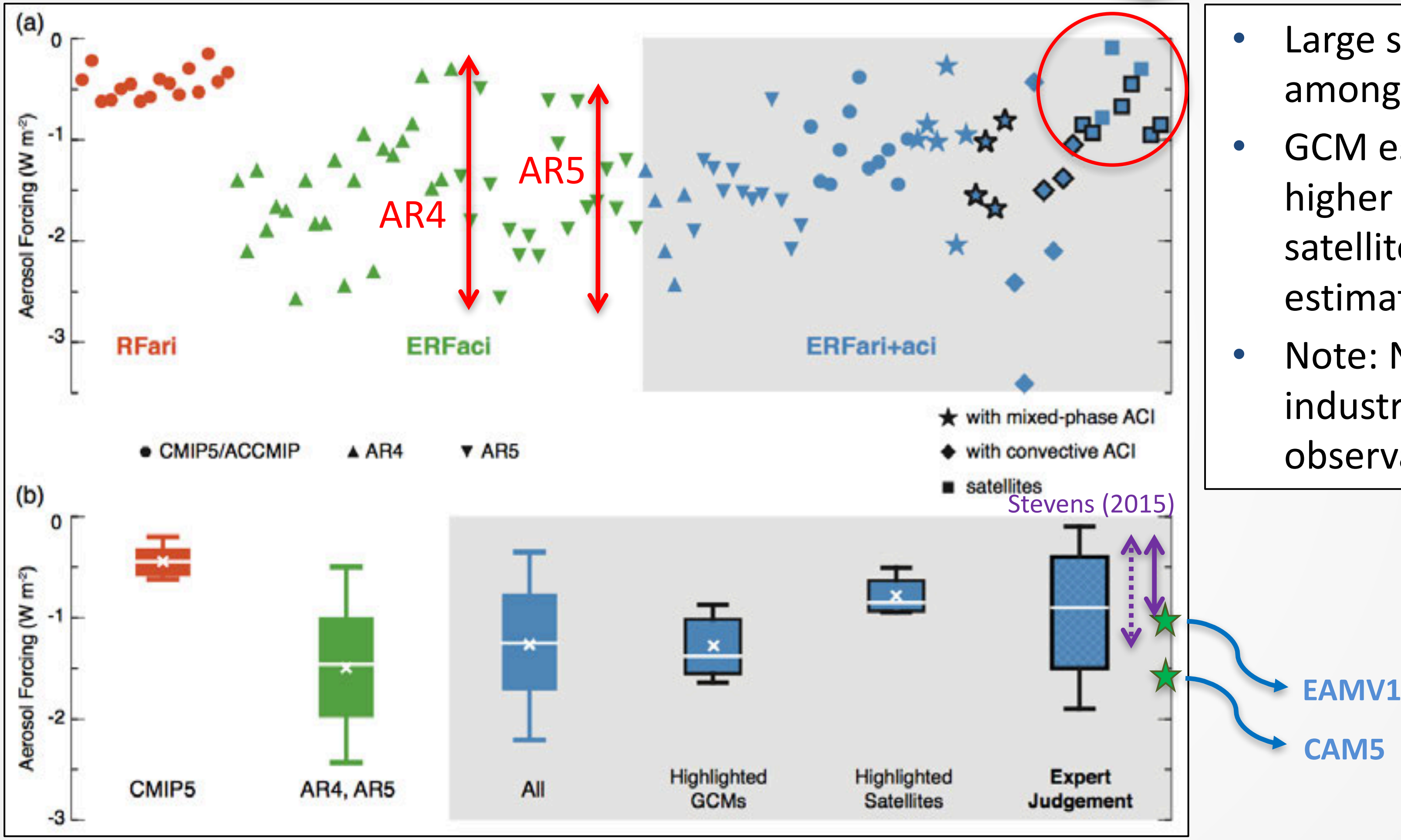


- EAM V1's **ΔRESTOM** (0.5W/m^2) is low.
- AIF is high.
- AF is on the low side.
- **CF** is low (0.25 W/m^2/K) compared with AR5 (0.6; from -0.2 to 2.0)
- GFDL-AM3 with 2 different **cloud tunings** have different **AIF** (Golaz et al 2011) and **CS** (Golaz et al 2013).
- **PD cloud state** is insufficient to constrain historical climate (Suzuki et al 2013).
- Kiehl 2007: **Aerosol forcing** regulates climate sensitivity; Forster et al 2013: **Cloud feedbacks** are important.
- CS depends on **base state and cloud feedback** (Gettelman et al 2012, 2016; Klein and Hall 2015; Bony et al 2006; Webb et al 2006; Zelinka et al 2012, etc).
- **Aerosols mediate CF** in CESM (Gettelman et al 2016) and HadAM3 (Gryspeerdt).

Aerosol Indirect Forcing

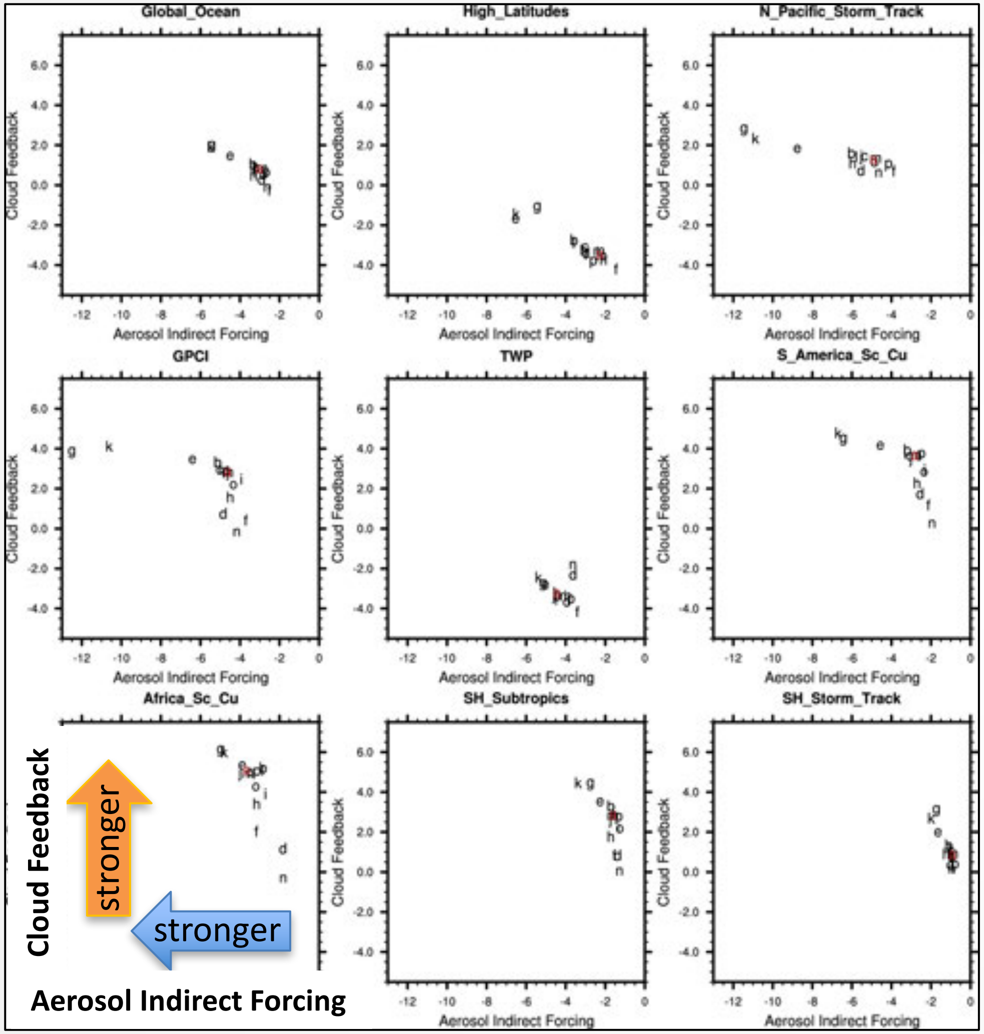
IPCC AR5 Chapter 7, 2014

Note: Limitation of satellite methods (Ma et al)



- Large spread among GCMs
- GCM estimates higher than satellite estimates
- Note: No pre-industrial satellite observations

Processes regulating cloud response to aerosols also regulate cloud response to temperature perturbation

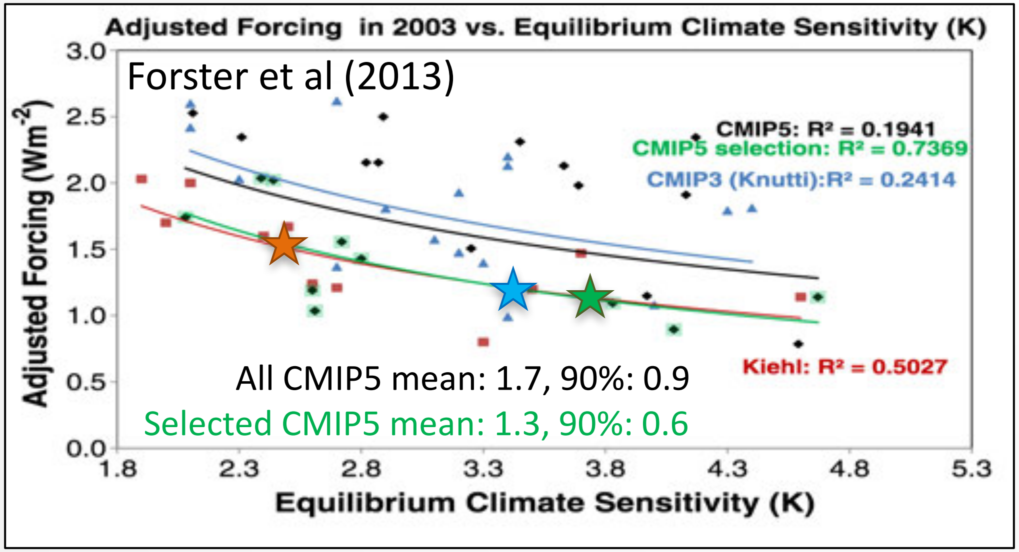


- EAMV1 CF is weak (0.25 $W/m^2/K$), compared to AR5 models (multi-model mean = 0.6, ranging from -0.2 and 2.0 $W/m^2/K$).
- Processes that control AIF usually also control CF, but a large regional variability exists.
- **Nucleation** affects AIF.
- **Precipitation efficiency** effects depend on processes: **Autoconversion** (and **subgrid var**) affects AIF and CF; **Accretion** affects only CF.
- **Convective precipitation efficiency** affects CF.
- **Cloud phase** affects AIF greatly, except in SO where it affects CF greatly (Tan et al 2016).
- **PDF width** affects AIF and CF
- **Turbulence** tuning affects AIF and CF
- **Skewness** tuning affects AIF and CF (increase Sc).
- **Sedimentation** affects AIF (Ackerman et al 2004, 2009; Bretherton et al 2007; Guo et al 2011)
- **Entrainment** for DpCu changes CS in HadAM3 (Knight et al 2007; Sanderson et al 2007; Rougier et al 2009) and GFDL AM4 (Zhao 2014; Zhao et al 2016); no effect in EAM.

More analyses are needed to understand why!

Improvement on system response

	AIF (-0.3 to -1.0)	ΔRESTOM (+0.8)	AF (1.3 ± 0.6)
AV1C-01	-1.82	-0.11	-
AV1C-02	-2.92	-0.40	-
AV1C-03	-2.95	-0.50	-
AV1C-04	**-1.25**	**+0.02**	**1.18**
AV1C-04P2	**-1.10**	**+0.49**	**1.27**
New$_{Dec\ 11}$	**-0.80**	**+0.74**	**1.51**



- All energy balance metrics are improved and in good agreement with state-of-the-art estimates.
- AIF decreases, and ΔRESTOM and CF increase, producing higher AF and implying lower ECS (inferred from Forster et al 2013).
- Most aspects of the mean state climate are improved.
- EAM with different cloud tunings can produce atmospheric simulations that are different, or indistinguishable from each other but produce different climate projections.
- More research is required to constrain/reduce this uncertainty.

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Summary: Process calibration improves system characteristics without introducing new uncertainty

- **Improved cloud (through subgrid winds, skewness, subgrid clouds, microphysics):**
  - improved deep convective clouds, shallow convective clouds, coastal stratocumulus cloud, high-latitude clouds
  - found new ways to improve cloud features in the present day climate (i.e., through changing turbulence, skewness, PDF, and microphysical processes).
- **Improved precipitation (through subgrid winds, ice physics, deep convection):**
  - improved the tropical precipitation and surface wind stress over tropics. These features are important to ENSO, so the new configuration might improve ENSO.
  - improved precipitation over Amazon (expected) and Andes (unexpected). This demonstrates the importance of subgrid variability of surface winds (associated with convections) in surface flux calculation over land.
- **Improved system response to aerosol and temperature perturbation (through calibration at process level):**
  - improved AIF and ΔRESTOM which produced higher AF, implying lower ECS (inferred from Forster et al 2013)
  - recognized observations and LES results in various cloud/meteorological regimes are essential to constrain the uncertainty of subgrid physics, in order to simulate system feedbacks and responses correctly.

Big (exascale) model, big data, big effort

- Mar-Aug 2017: Slow progress on Research Track (**1 SYPW**).
- Aug-Dec 2017: Anvil and cori-knl have become very useful (**10 SYPD**). Special thanks to Rasch, Xie, Taylor, Jacob for continuous help in identifying available resources. Special thanks to the SE and Performance teams to make the model run faster on various platforms.
- About **450 simulations** (1-mo, 1-yr, and 5-yr runs) and **600 standard climatology diagnostics** have been produced and assessed.
- High-frequency, instantaneous output for process-level diagnostics takes about **400 TB** disk space. Performing process-level analyses is challenging (requires **parallel computing**).

List of all new, science-guided modifications (inspired by or consulted with great minds)

- Gustiness over ocean and land (Harrop, Leung, Rasch, Zeng, Bisht, Riley)
- Turbulence, skewness, and entrainment tuning (Xiao, Larson, Golaz)
- Skewness-based tuning of turbulent mixing and PDF (Xiao, Larson, Golaz)
- Subgrid condensate variance, accretion, sedimentation, Droplet nucleation, ice nucleation, phase (Gettelman, Morrison, M. Wang, Chepfer, Z. Zhang, Suzuki, Liu, H. Wang, K. Zhang)
- Deep convection: entrainment, evaporation, trigger level, autoconversion, detrained condensate size (Rasch, diagnostics from Coupled Simulation Team, Gryspeerdt, Quaas)
- Test shorter timestep (Taylor)
- Use ΔRESTOM, AIF, and CF as constraints
- A lot of new in-situ diagnostics
- Retune for answer-changing bug fixes
- Process observational data to guide model calibration

Green font indicates code modification

On-going work, remaining issues, etc.

- **Constrain subgrid properties/assumptions such as wp2, wp3, skewness, condensate distribution, etc. in various cloud and meteorological regimes**: Collaboration with Berg and Fast (PNNL/ICLASS), Chepfer (UPMC/LMD), Gijs (CU), Gryspeerdt (Imperial College), Gustafson (PNNL/LASSO), Larson (UWM), Quaas and Muelmenstaedt (Leipzig), Suzuki (Tokyo), Winker (NASA/LARC), Wood (UW), Zhang (UMBC).
- Better **coupling between convection, macro-, and micro- physics** (e.g., CMDV-MCS) might be helpful for constraining the uncertainty in subgrid physics (before cloud-resolving resolution is achieved). This does not mean cloud microphysics is perfect.
- **SH stratocumulus** can be further improved.
- **Shallow-to-deep** convection transition needs to be studied further.
- **Clear-sky bias** is compensated by LWCF, as always.
- Need evaluation on **variabilities** (diurnal cycle, MJO, ENSO, QBO) and stratospheric state
- Longer timescale climate state, variability, and feedbacks require **coupled simulations**.
- A shorter **timestep** does not seem to have any benefit other than improving stability.
- Surface moisture flux in low wind regime is biased, causing biased **moisture distribution**.
- Analyzing **big data** is a challenge. Need more **in-situ diagnostics** and **diagnostics tools that support parallel processing.**

Research Track: Publish useful findings!

600 simulations | 850 simulations

Nov, 2016 — **AV1C-04P2**

Jul, 2017 — **Beta-1**

- ENSO
- High clouds (retune for bug fixes)

Aug, 2017 –

Main Track (master)

- Skewness
- Mixing & PDF
- Gustiness
- Convection
- Turbulence
- ΔRESTOM & CF
- Liquid & ice nucleation
- Precipitation
- Sedimentation
- Entrainment
- Evaporation
- Cloud phase

Research Track (PMA branch)

- **Paper 1** on processes regulating cloud response to aerosol and temperature perturbations
- **Paper 2** on improving precipitation over Amazon and Andes using gustiness (land)
- **Paper 3** on improving Sc and Sc-to- ShCu transition using skewness
- **Paper 4+** on OBS/LES constraints

Main Track: A possible future upgrade!

600 simulations

850 simulations

Main Track (master)

Nov, 2016

AV1C-04P2

Jul, 2017

Beta-1

- ENSO
- High clouds (retune for bug fixes)

Aug, 2017 –

Possible V2-01 (TBD)

- Code and tuning integration
- Code review and testing
- Further evaluation
- Documentation/Publication
- Executive Committee's approval

Yellow font indicates what I have started working on.

TBD

Research Track (PMA branch)

- Skewness
- Mixing & PDF
- Gustiness
- Convection
- Turbulence
- ΔRESTOM & CF
- Liquid & ice nucleation
- Precipitation
- Sedimentation
- Entrainment
- Evaporation
- Cloud phase

- **Paper 1** on processes regulating cloud response to aerosol and temperature perturbations
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Thank you, and Merry Christmas!