E3SM
Energy Exascale
Earth System Model

High cloud responses to aerosols and surface warming in two versions of E3SM with different cloud and convection tunings

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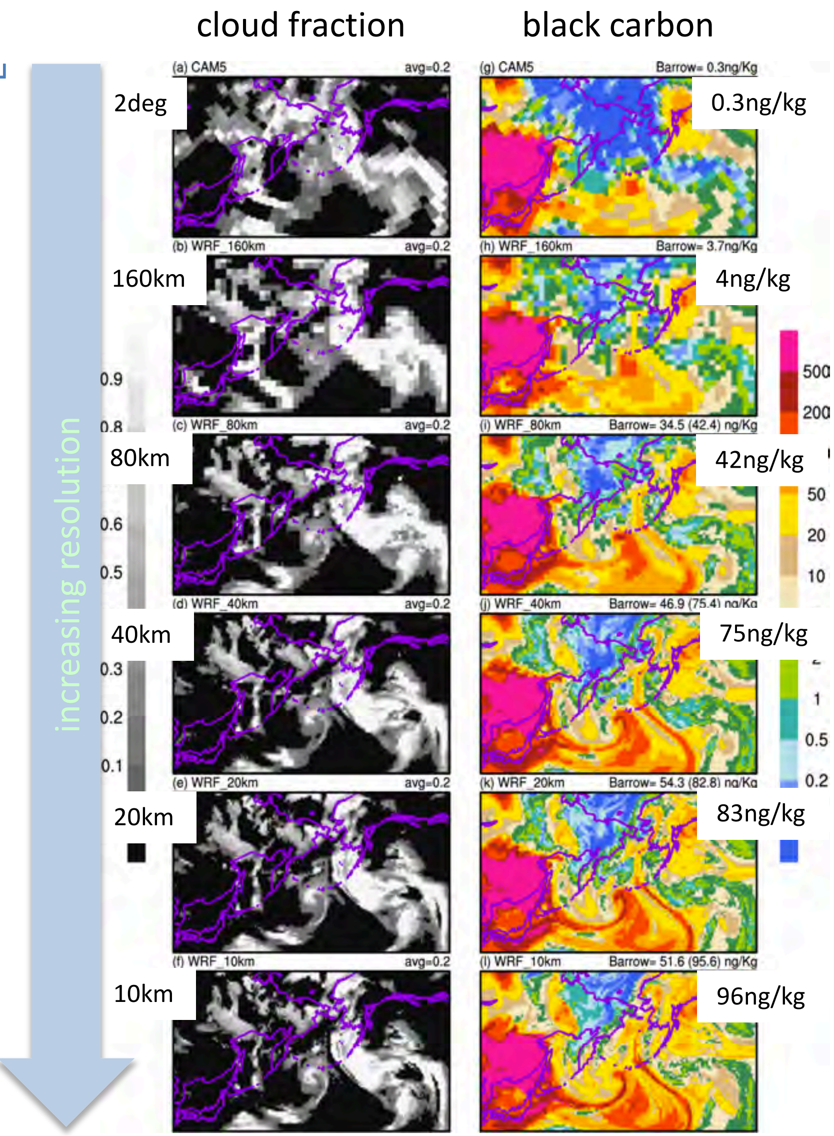
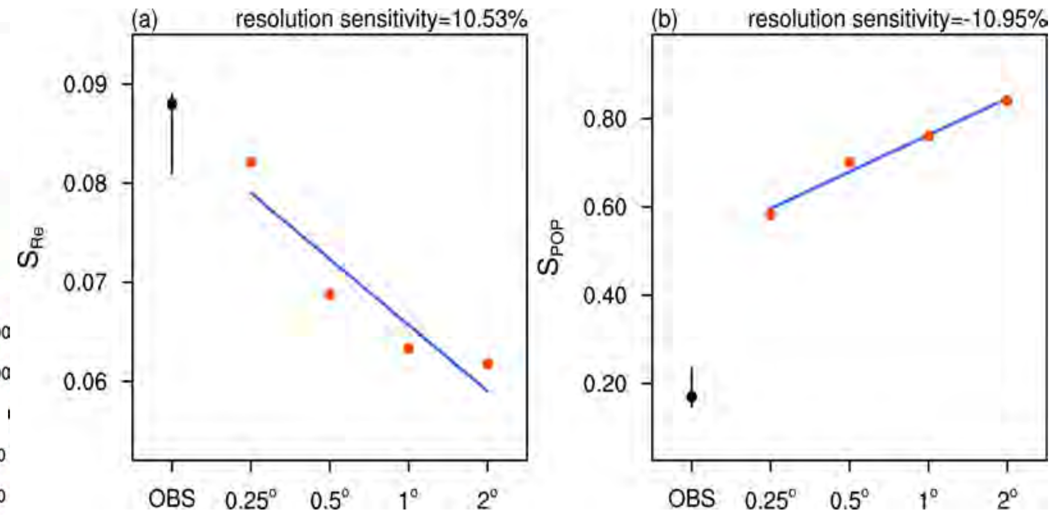
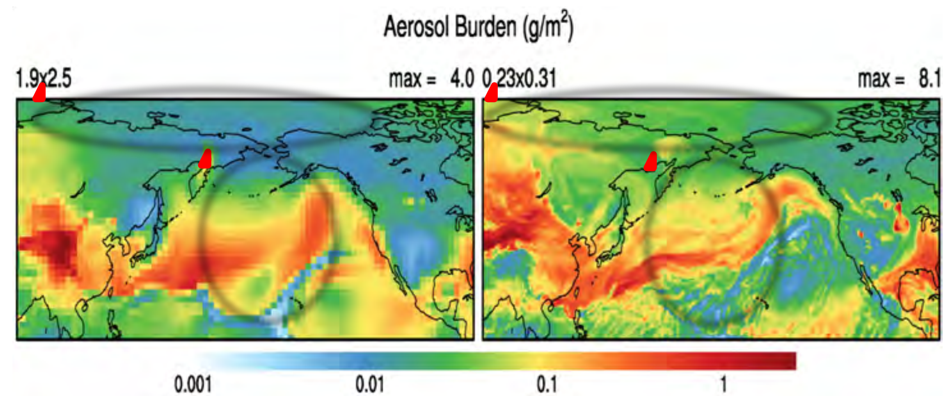
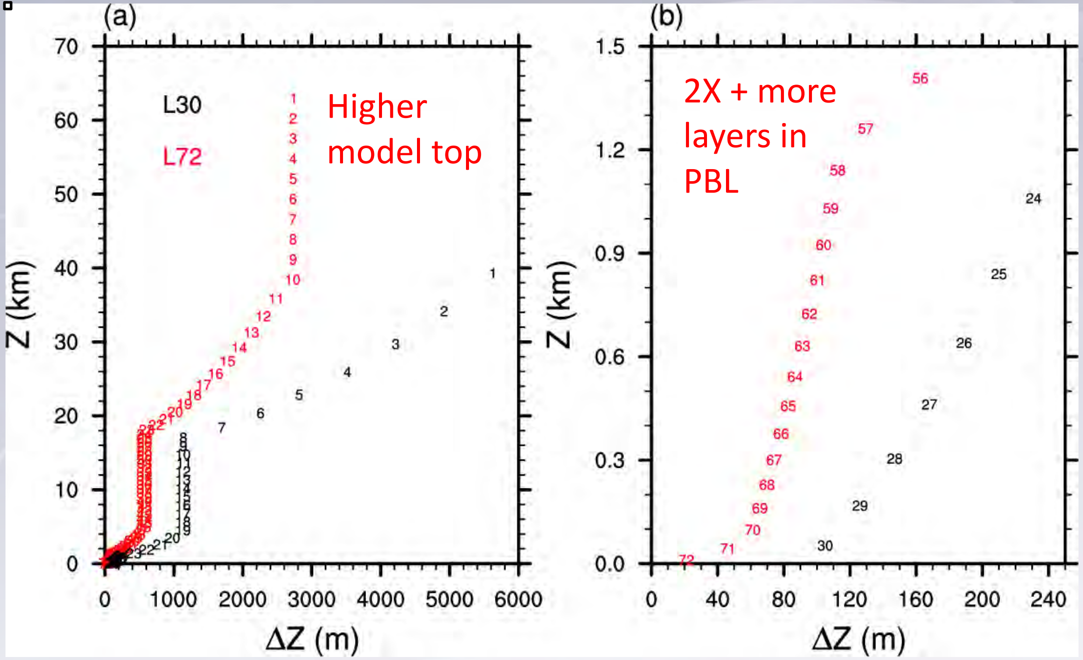
Increasing horizontal resolution improves aerosol transport, aerosol-cloud interactions, etc

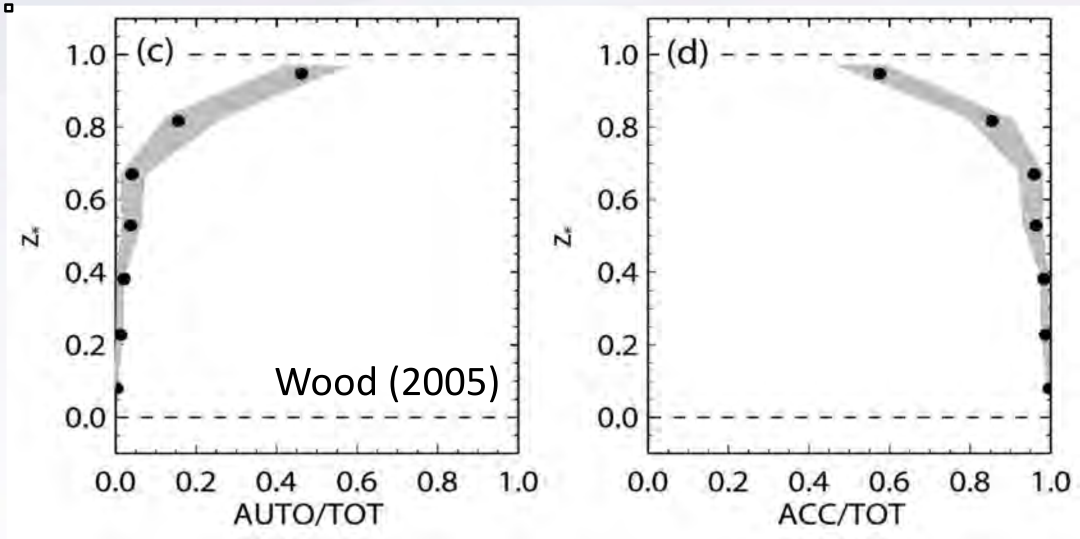






Ma et al., 2014, 2015; Liu, Ma, et al 2016





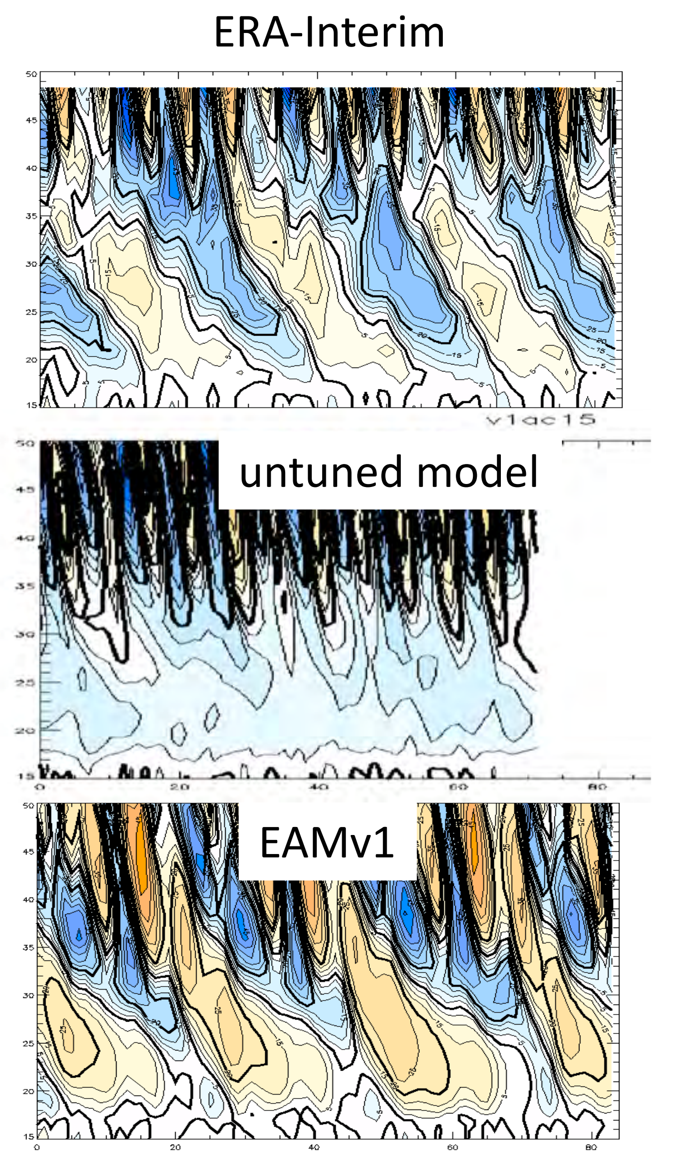


Figure produced by Julio Bacmeister

Overview of the EAMv1

Rasch et al., in prep.

- **Dynamical core:** Spectral Element (SE)
- **Horizontal resolution:** Two released resolutions (1^{o} and $1/4^{o}$) and one in testing ($1/8^{o}$)
- **Vertical resolution:** 72 layers with the model top at 0.1hPa and a surface layer of 20m thickness
- **Physics innovations**
  - **Aerosols**
    - 4 mode version of Modal Aerosol Mudule (MAM4) (Liu et al., 2016)
    - Marine organic aerosol (Burrows et al., submitted)
    - Parameterized SOA emission (Shrivastava et al., 2015)
    - Convective transport/scavenging (Wang et al., 2013)
    - Resuspension (Easter et al., in preparation)
  - **Cloud microphysics**
    - MG2 (Gettelman and Morrison, 2014), recalibrated
    - Observationally based autoconversion scheme
    - Ice microphysics (K. Zhang et al., in preparation)
  - **Cloud macrophysics, turbulence, shallow convection**
    - CLUBB (Golaz et al., 2002, Xie et al., submitted), recalibrated
    - Integration between CLUBB, ZM, MG2, and MAM4
  - **Deep convection:** ZM recalibrated
  - **Ozone:** Linearized production and loss (Cameron-Smith et al., in preparation)
- **RRM capability:** CONUS RRM (Roesler et al., in preparation)
- **Satellite simulator capability** (Y. Zhang et al., in preparation)

EAMv1 produces better climatology than most CMIP5 models

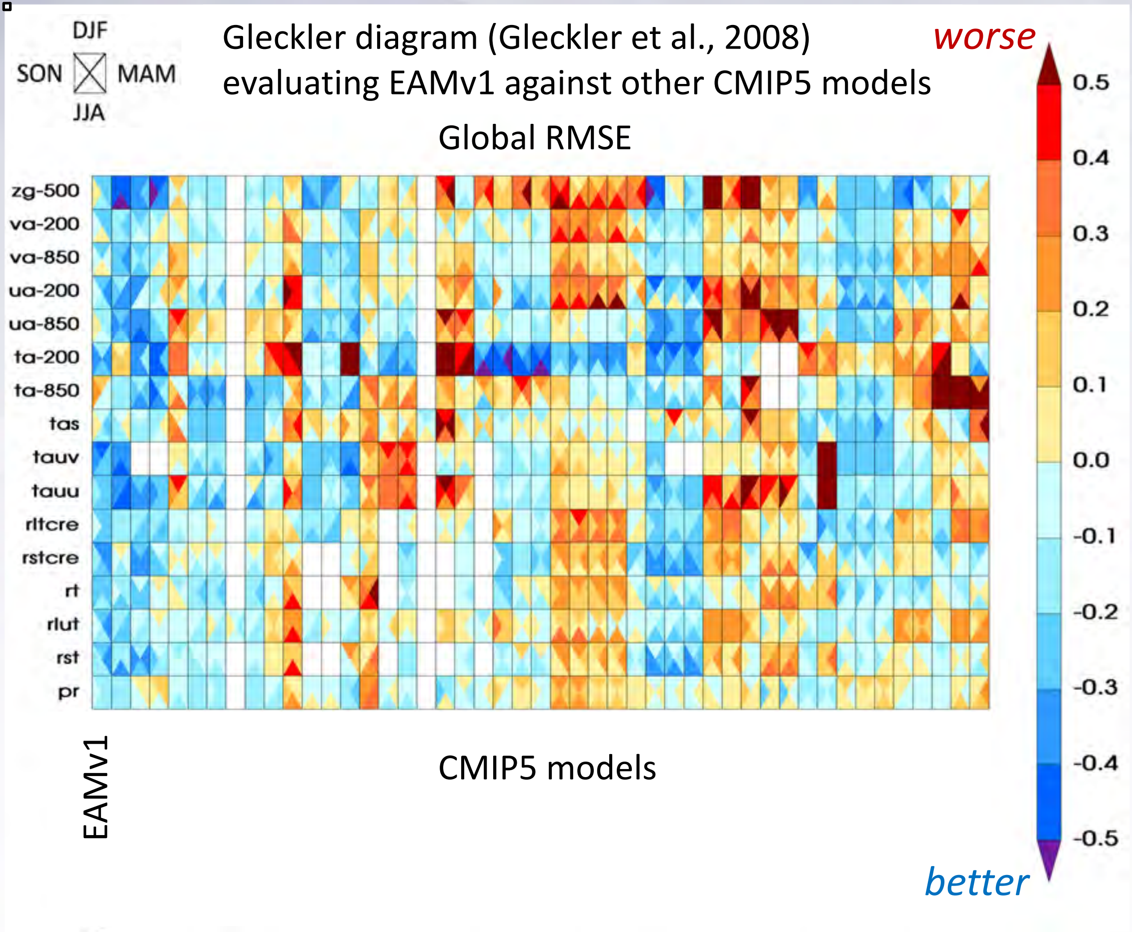


Figure produced by Qi Tang

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Issues we weren't able to address before EAMv1 was frozen

- **Clouds**
  - Lack of stratocumulus
  - Shallow cumulus too bright
  - Bright storm track
  - Cloud phase bias
  - Small TWP warm pool cloud deck and very narrow SPCZ
  - High sensitivity to aerosols (but forcing is within AR5 uncertainty range probably due to lack of high sensitivity clouds such as Sc)
  - Deep convections not deep enough
  - High ice number
- **Precipitation**
  - Lack of precipitation in TWP
  - Dry bias over Amazon
  - High precipitation over Andes
  - PDF is skewed
- **More on precipitation**
  - Central Pacific maximum likely leads to wrong Walker circulation and has negative impact on variabilities
  - Diurnal cycle
  - No MCS
- **Others**
  - Warm bias over NH mid- and high-latitude land
  - Overly strong wind stress over SO
  - Overly strong trade wind pushes cold tongue too far into the TWP
  - (Still) not enough aerosols in the Arctic
- **Issues related to the coupled system**
  - High climate sensitivity
  - Possible larger bias/response amplification

Now I have addressed them all.

What I have done

- Gustiness (i.e., subgrid wind) parameterization from *deep convections, shallow convections, and large eddies,* over both ocean and land

- Provide CLUBB-predicted subgrid temperature variability to ZM's parcel buoyancy calculation.

- CLUBB, microphysics, and deep convection retuning, involving a total of ~40 parameters. About half of them are new parameters.

- After EAMv1 was frozen in September 2016, 800+ simulations and 800+ x 3 standard climatology diagnostics has been done, providing a solid scientific foundation (at a cost of 60 Mi core hours per year).

- Mechanism diagnostics are performed to improve physical understanding

Green font indicates code modification

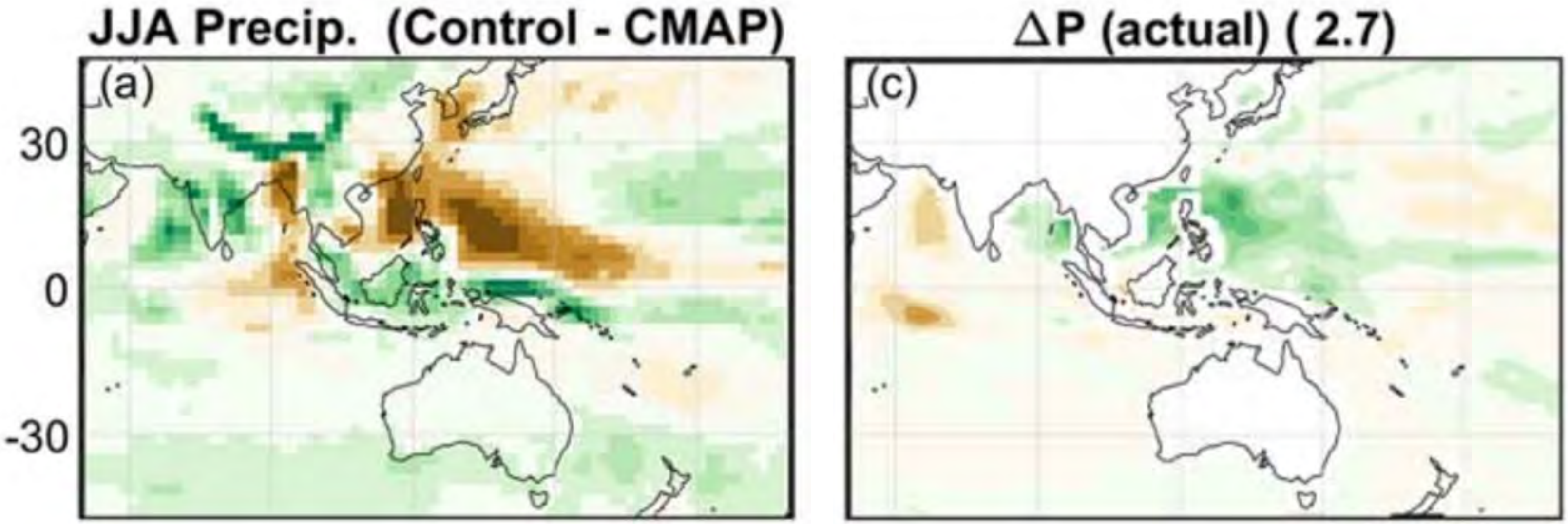
Convective (deep) gustiness (over ocean)

$$\bar{U}^2 = U_0^2 + U_g^2$$

$$U_0 = \|\bar{\mathbf{U}}\|$$

$$U_g = \begin{cases} \log(1.0 + 6.69R - 0.476R^2), & R < 6 \text{ cm/d} \\ 3.2\,\text{m/s}, & R \geq 6 \text{ cm/d} \end{cases}$$

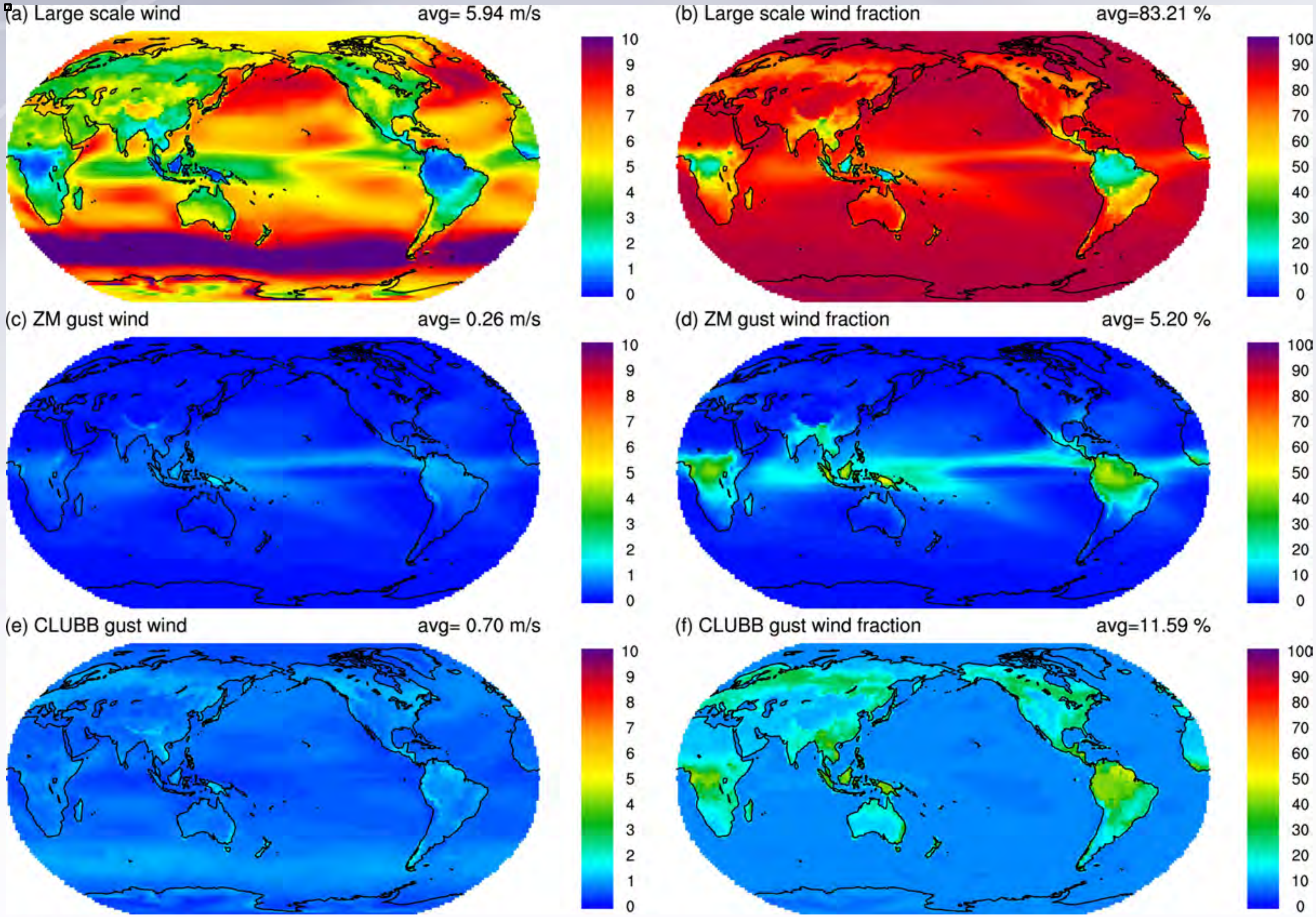
Redelsperger et al. (2000)



Harrop et al. (2018)

However, using this parameterization increases global mean precipitation bias, so retuning is required.

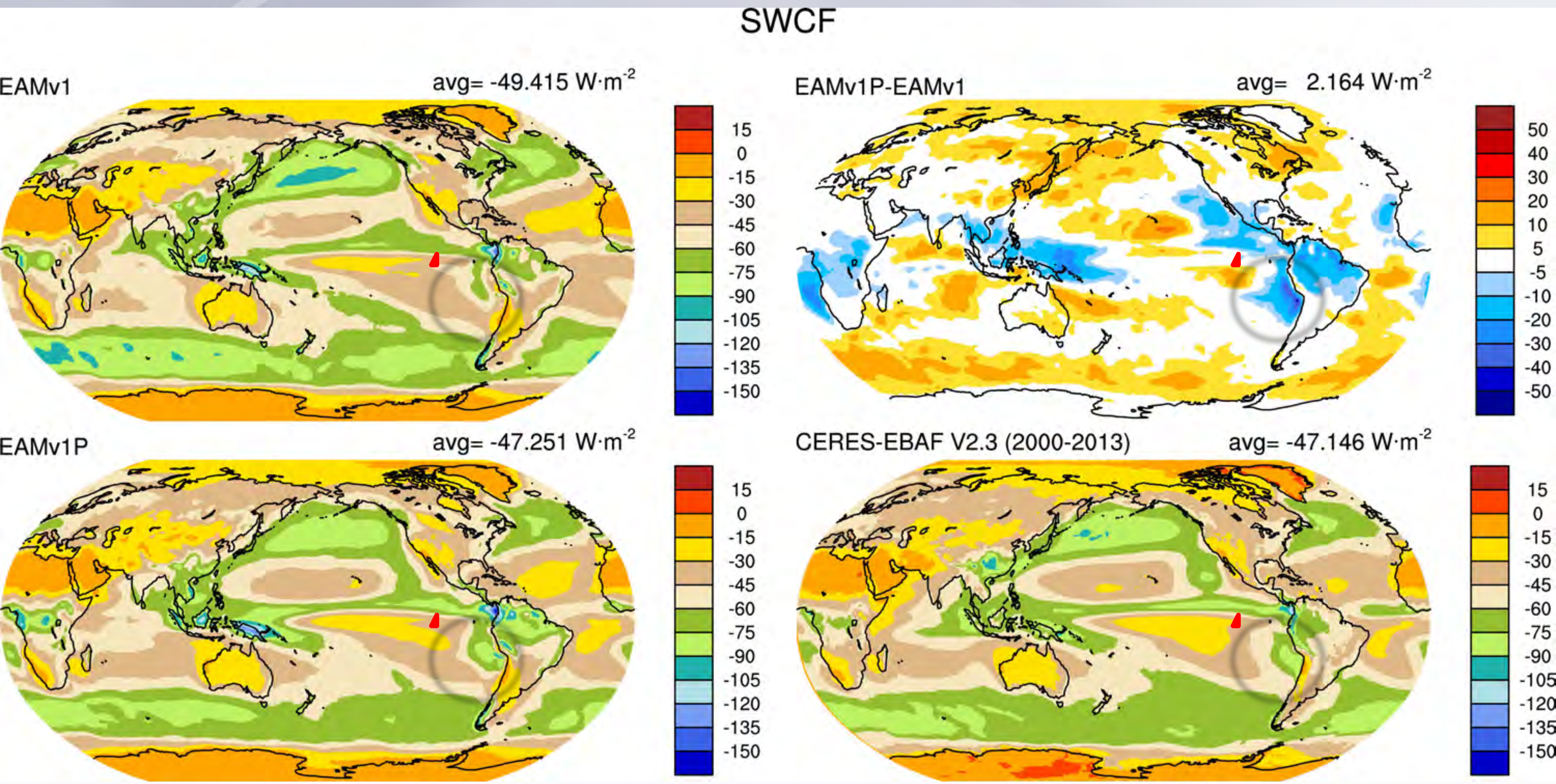
Subgrid (i.e., gust) winds make a large contribution to surface flux of heat, moisture, momentum, sea salt, and dust in the tropics and mid- and high-latitude land!



EAMv1 and previous generation GCMs have neglected this.

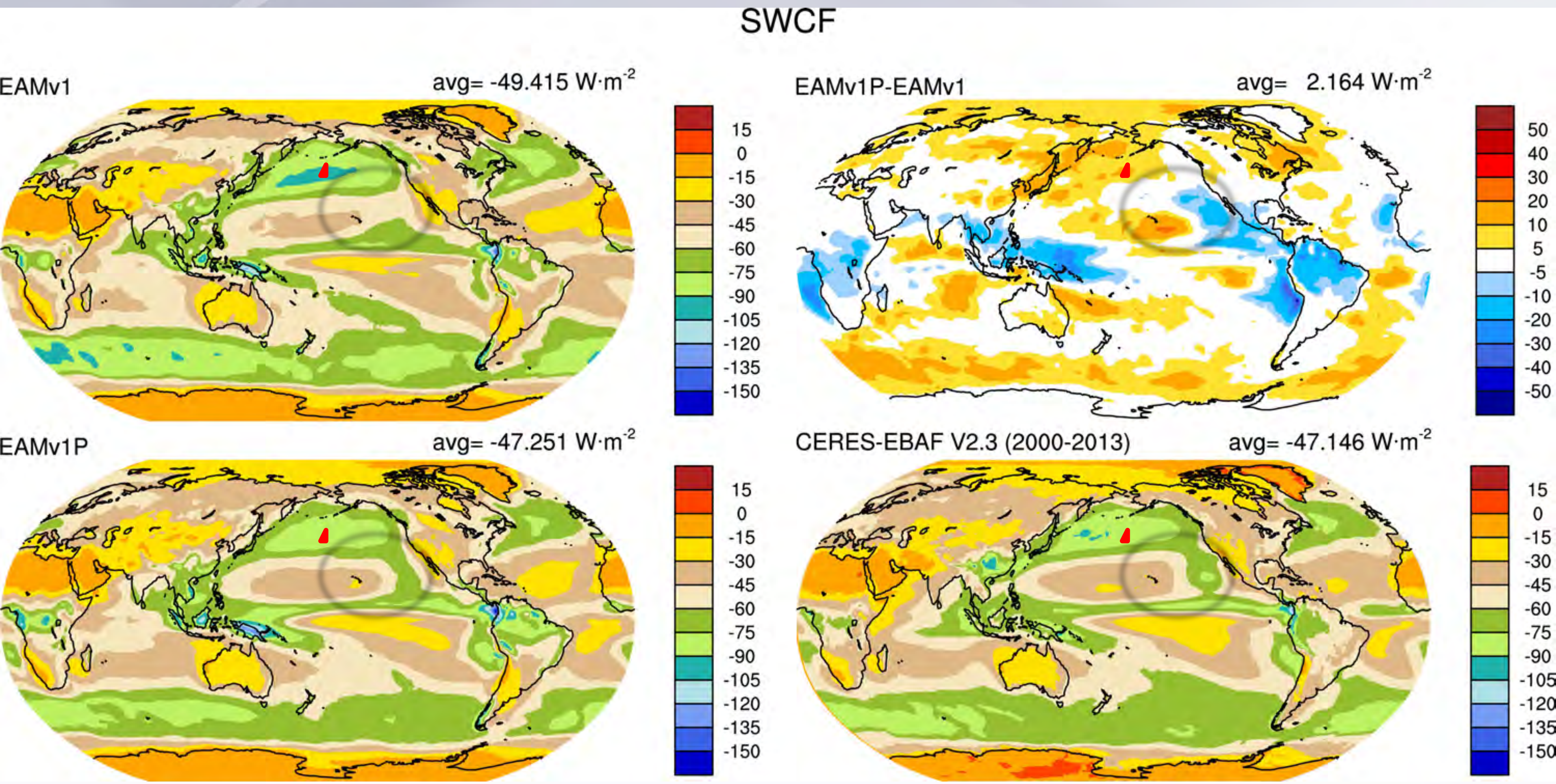
Results

Clouds



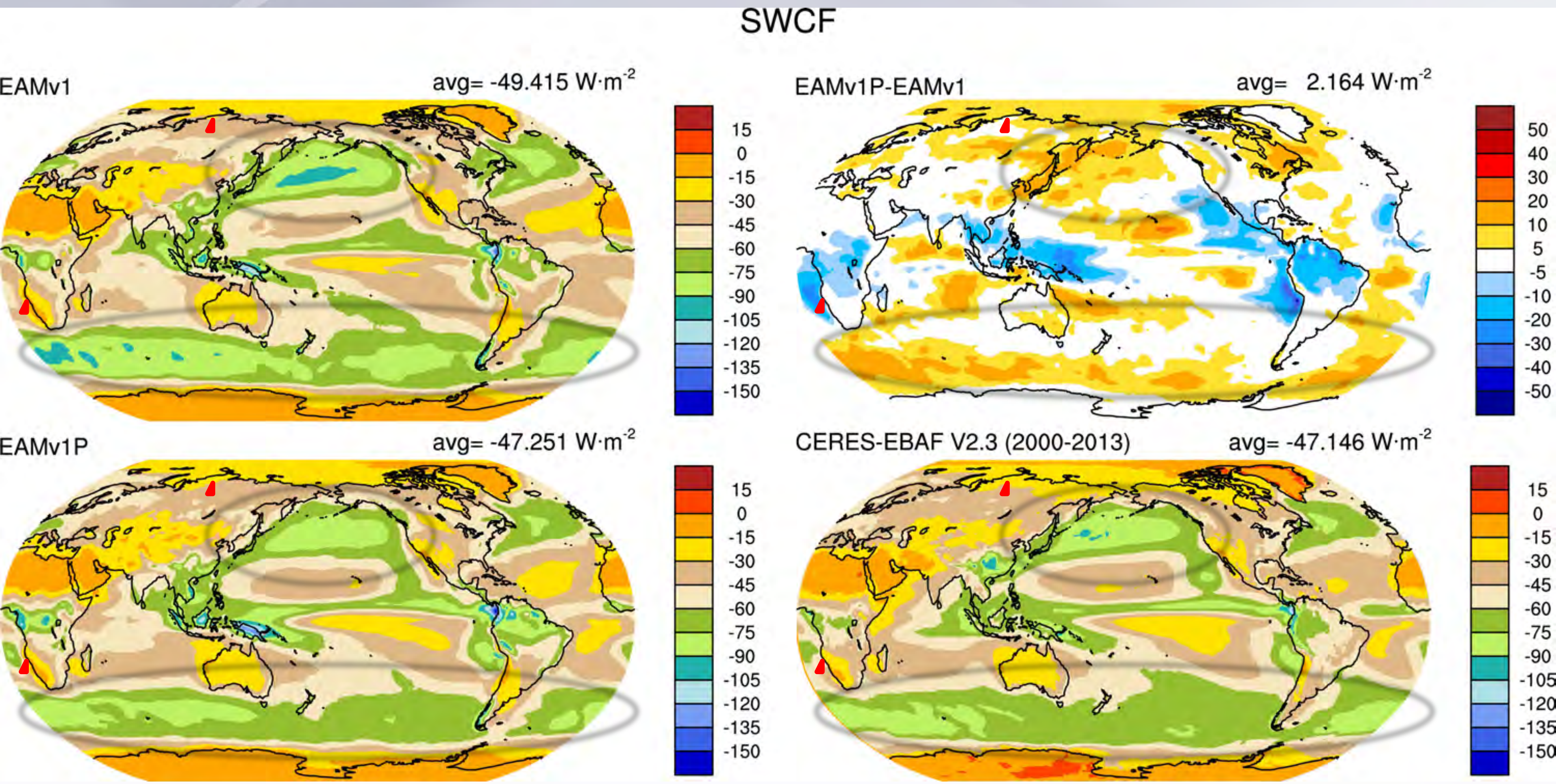
Stratocumulus

Clouds



Stratocumulus & Sc-to-Cu transition

Clouds



Stratocumulus & Sc-to-Cu transition

Storm track

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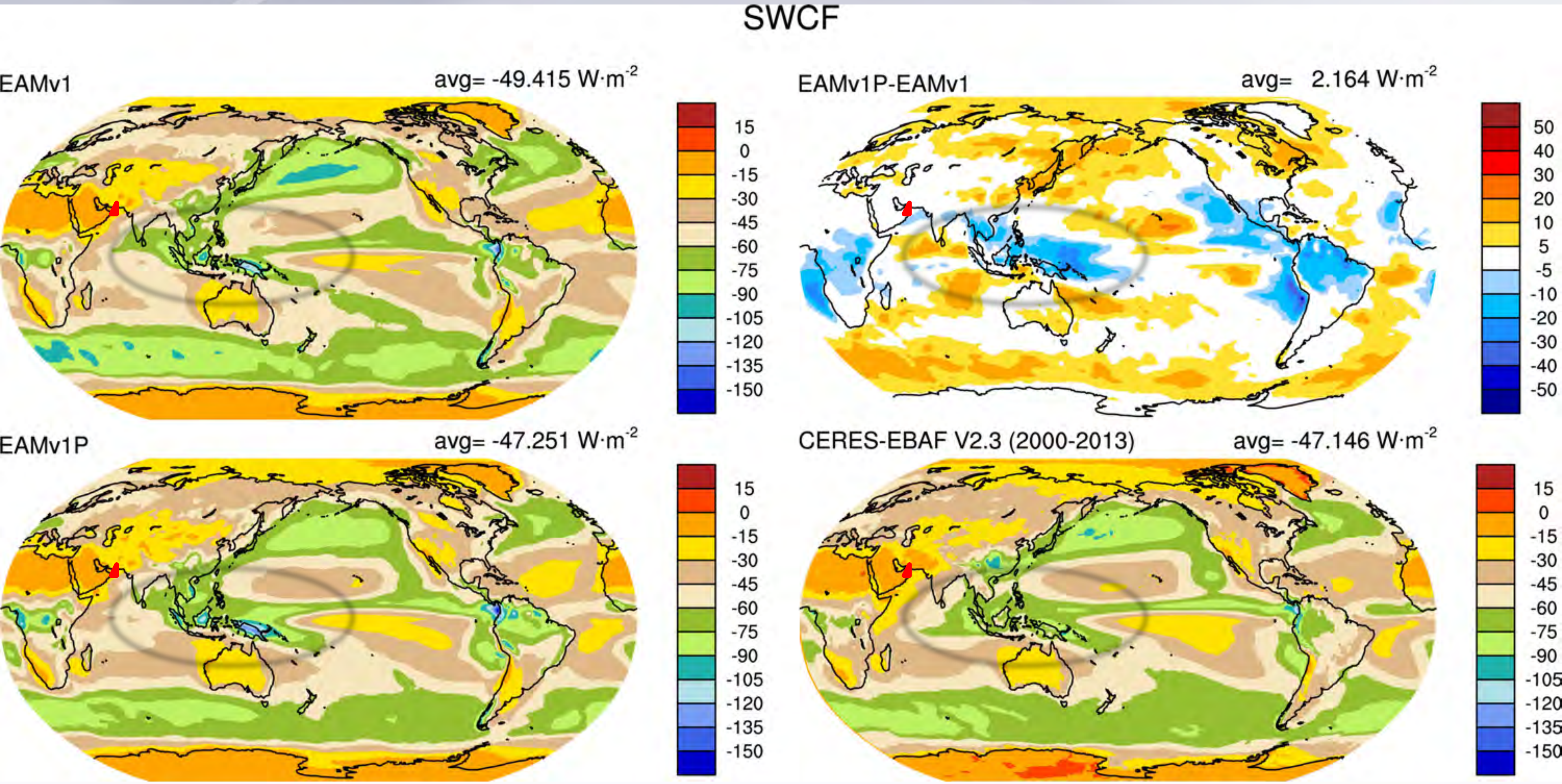
Clouds

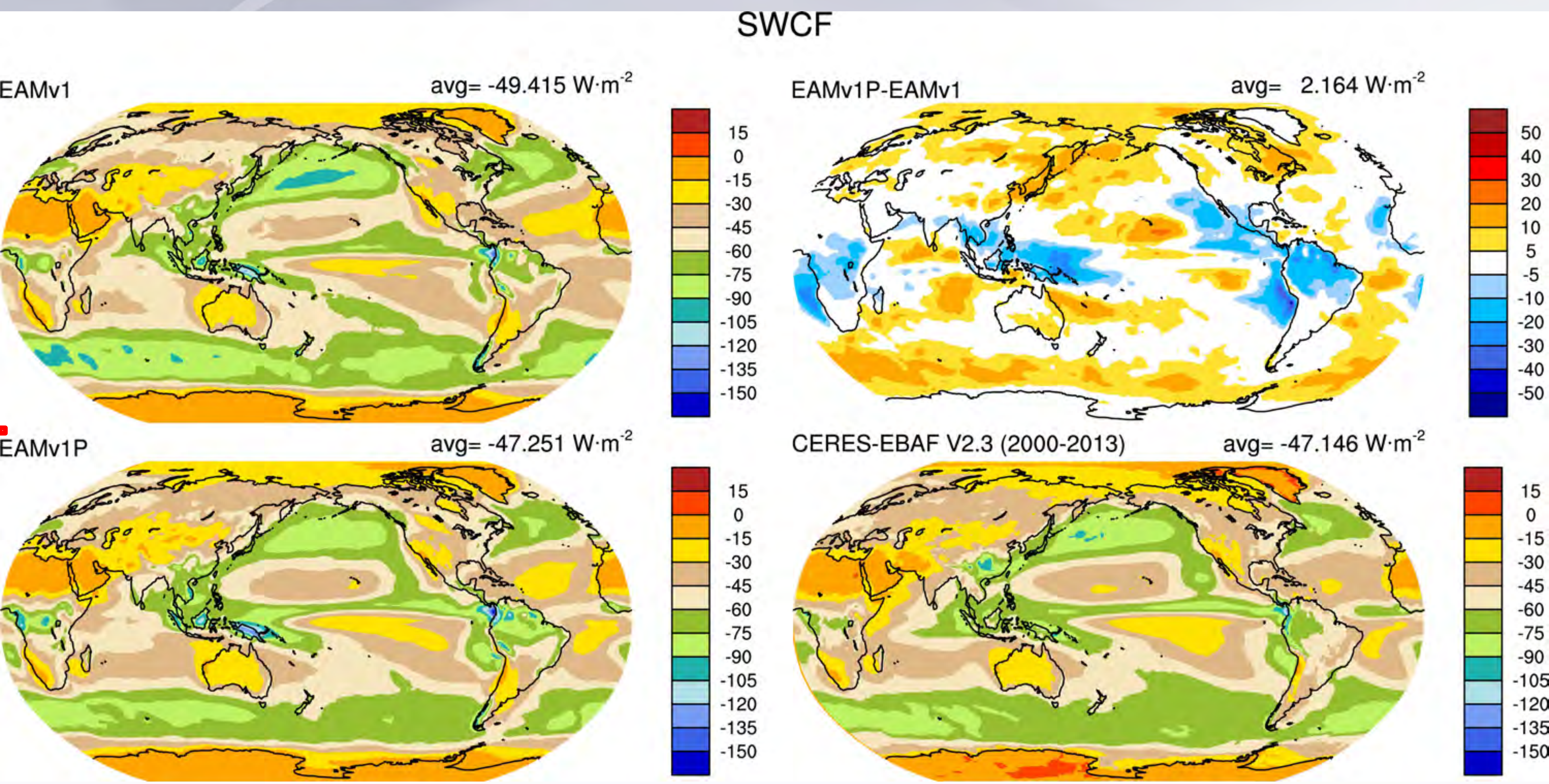


Stratocumulus & Sc-to-Cu transition

Storm track

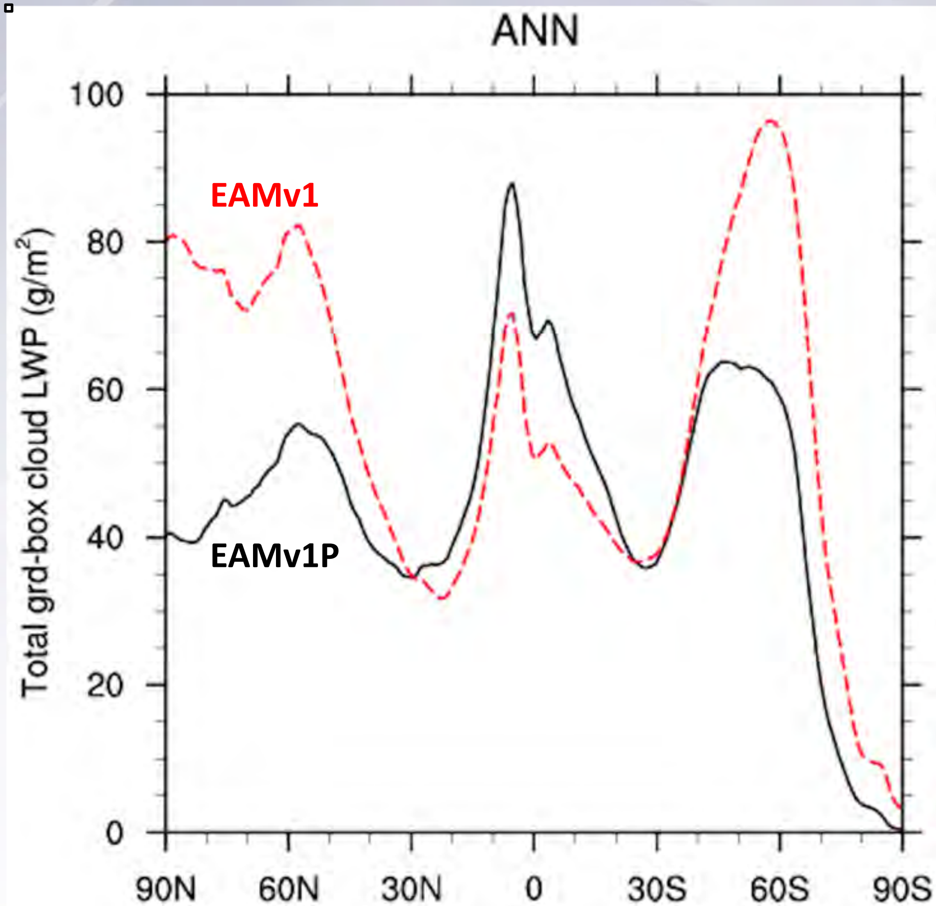
Pacific warm pool & SPCZ

Clouds: *Remarkable resemblance between EAMv1P and CERES-EBAF!*
Clouds form at right place & right time, with right magnitude & right areal extent!



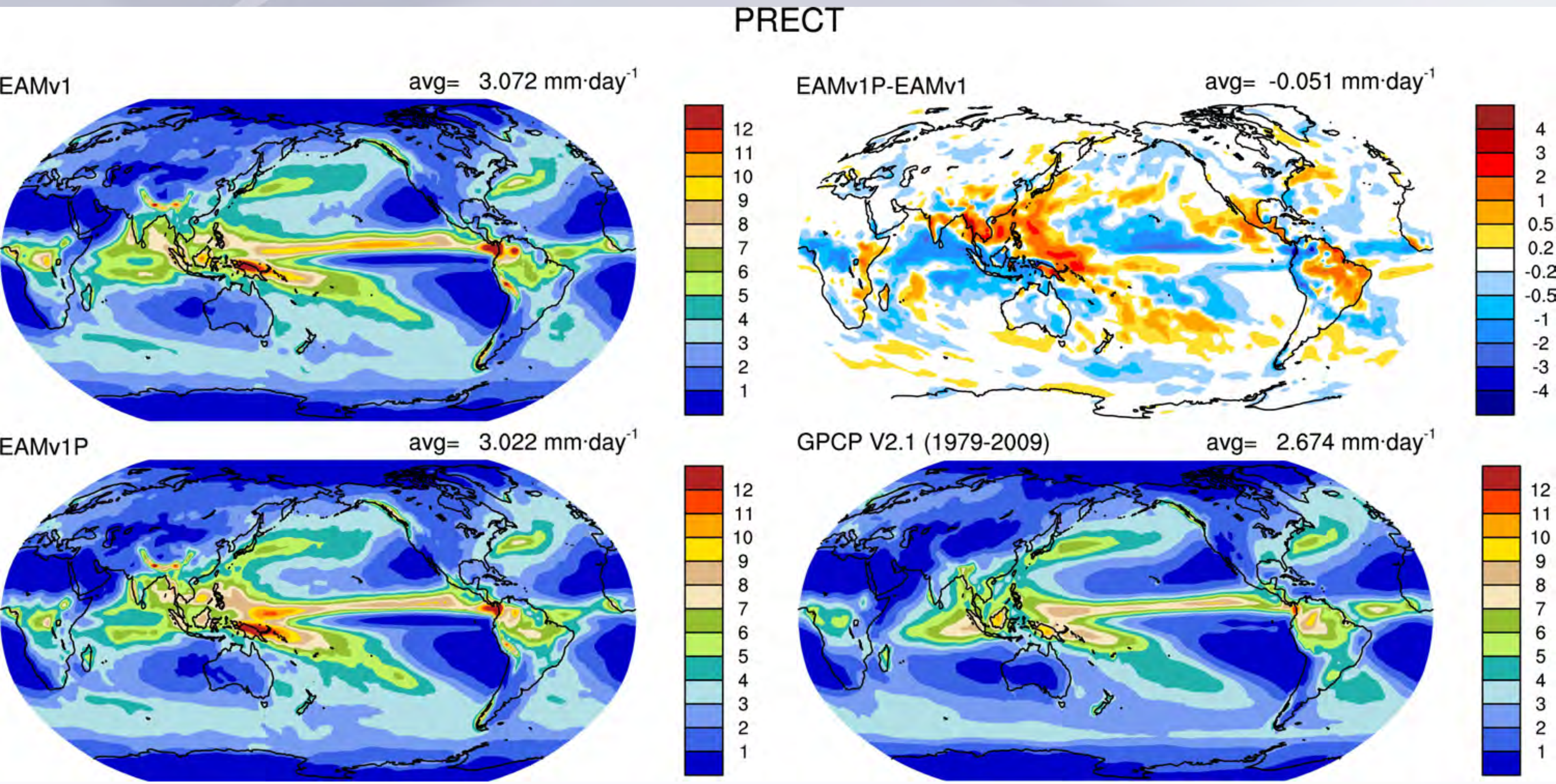
Stratocumulus & Sc-to-Cu transition
Storm track
Pacific warm pool & SPCZ

High-latitude clouds and cloud phase are also significantly improved!



- The new configuration produces much more realistic meridional distribution of LWP (and IWP), despite the observational uncertainty (especially at high-latitudes).
- Cloud phase bias is also reduced, globally!
- Climate sensitivity is expected to reduce.

Precipitation: *Significant improvements over Amazon, Andes, TWP, and tropical ocean! Reduction of double ITCZ bias!*



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With new tunings and better integration of physics (to enhance "atmospheric memory"), I expect MCS, PDF and diurnal cycle, etc., to improve/change, too.

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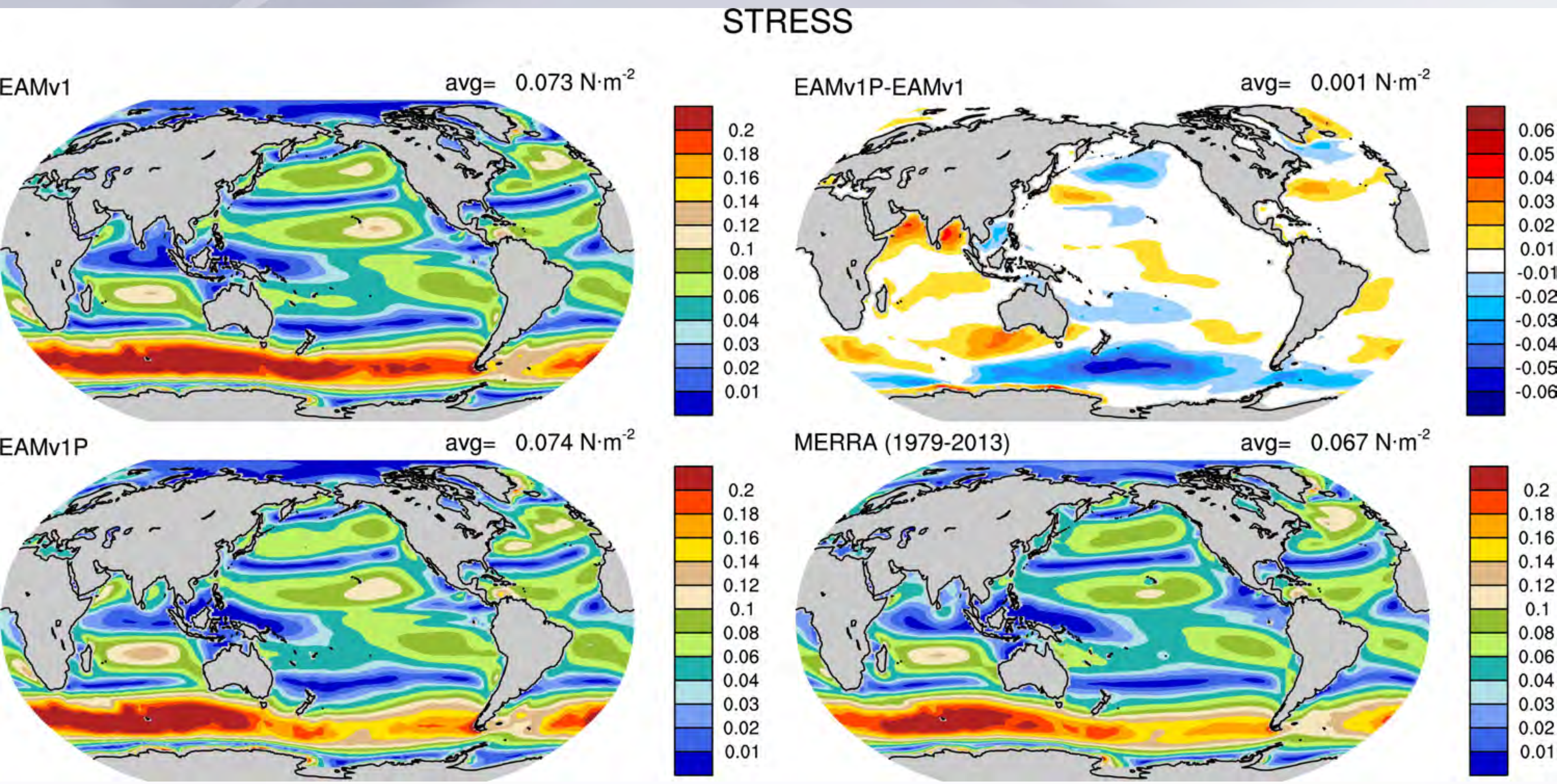
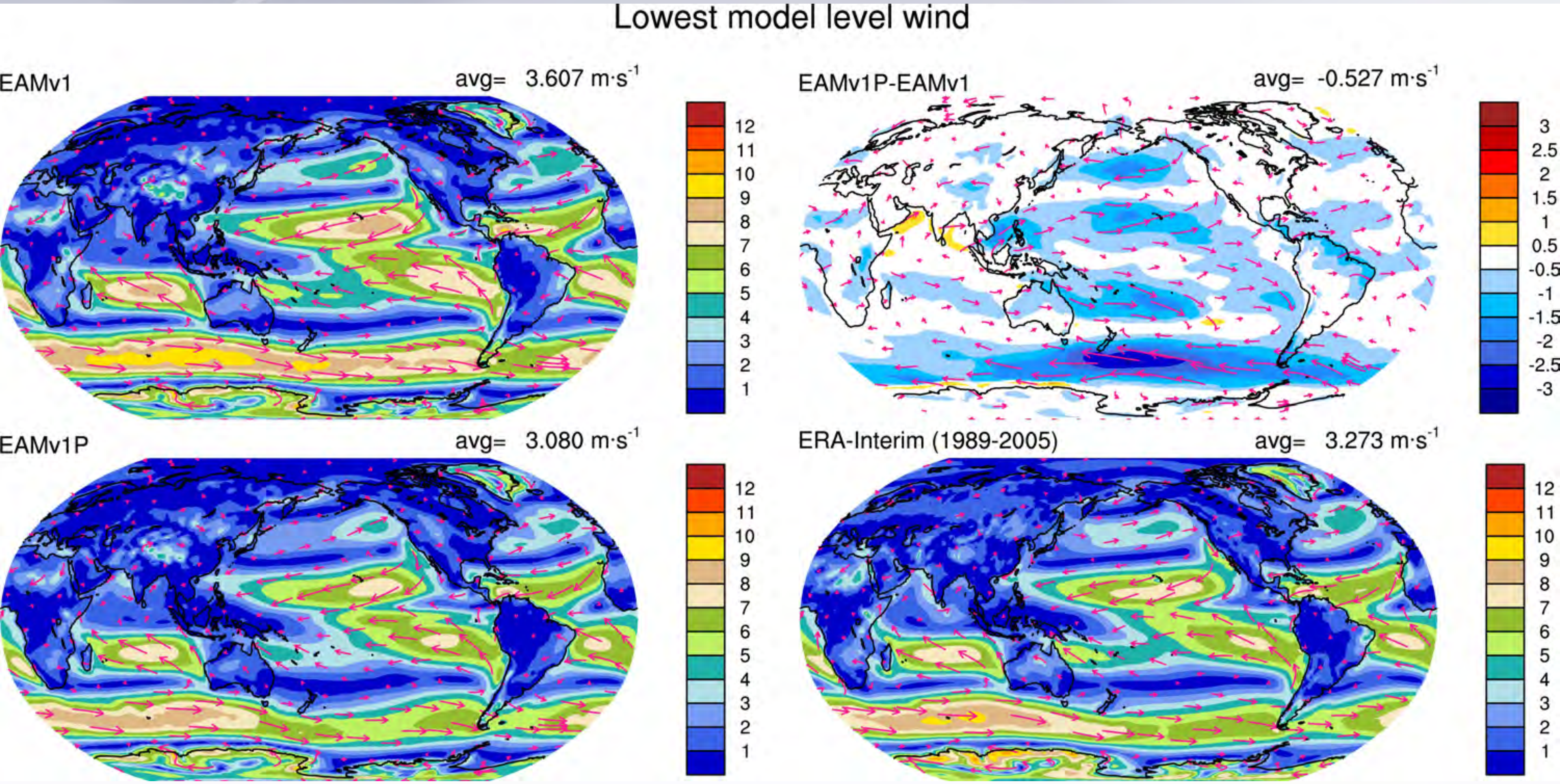
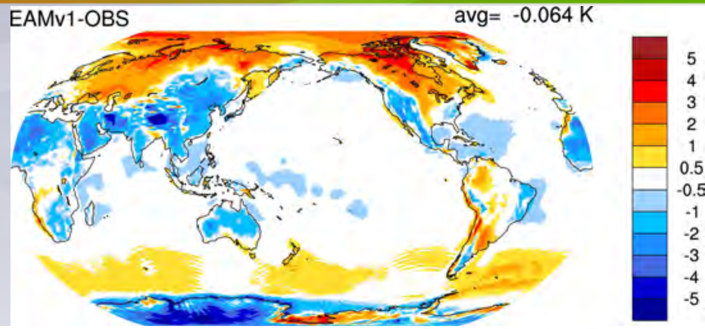
Surface stress: *Significant reduction of bias over Southern Ocean!*

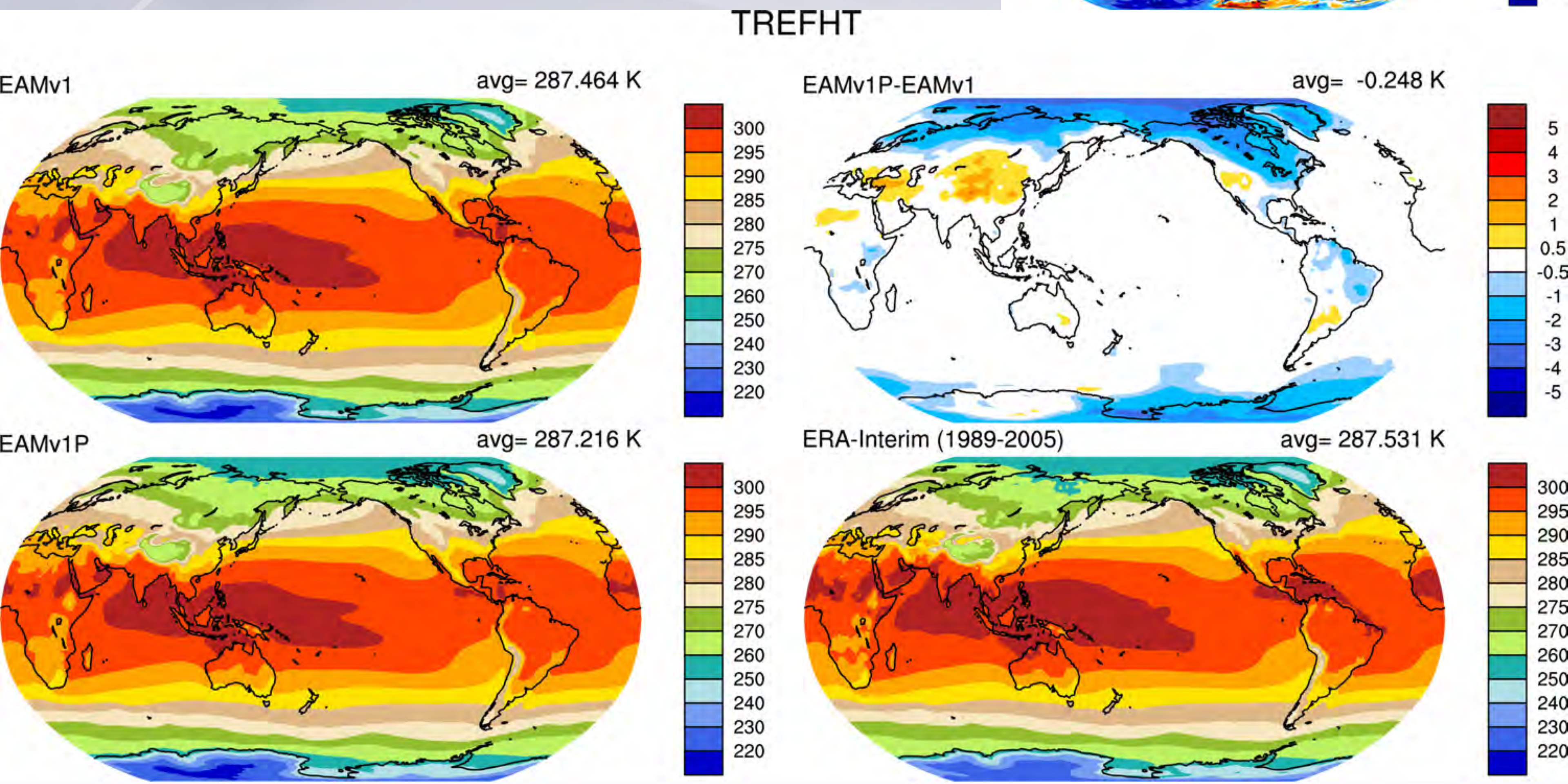


Surface wind: *Correcting biases in the tropics and SO!*

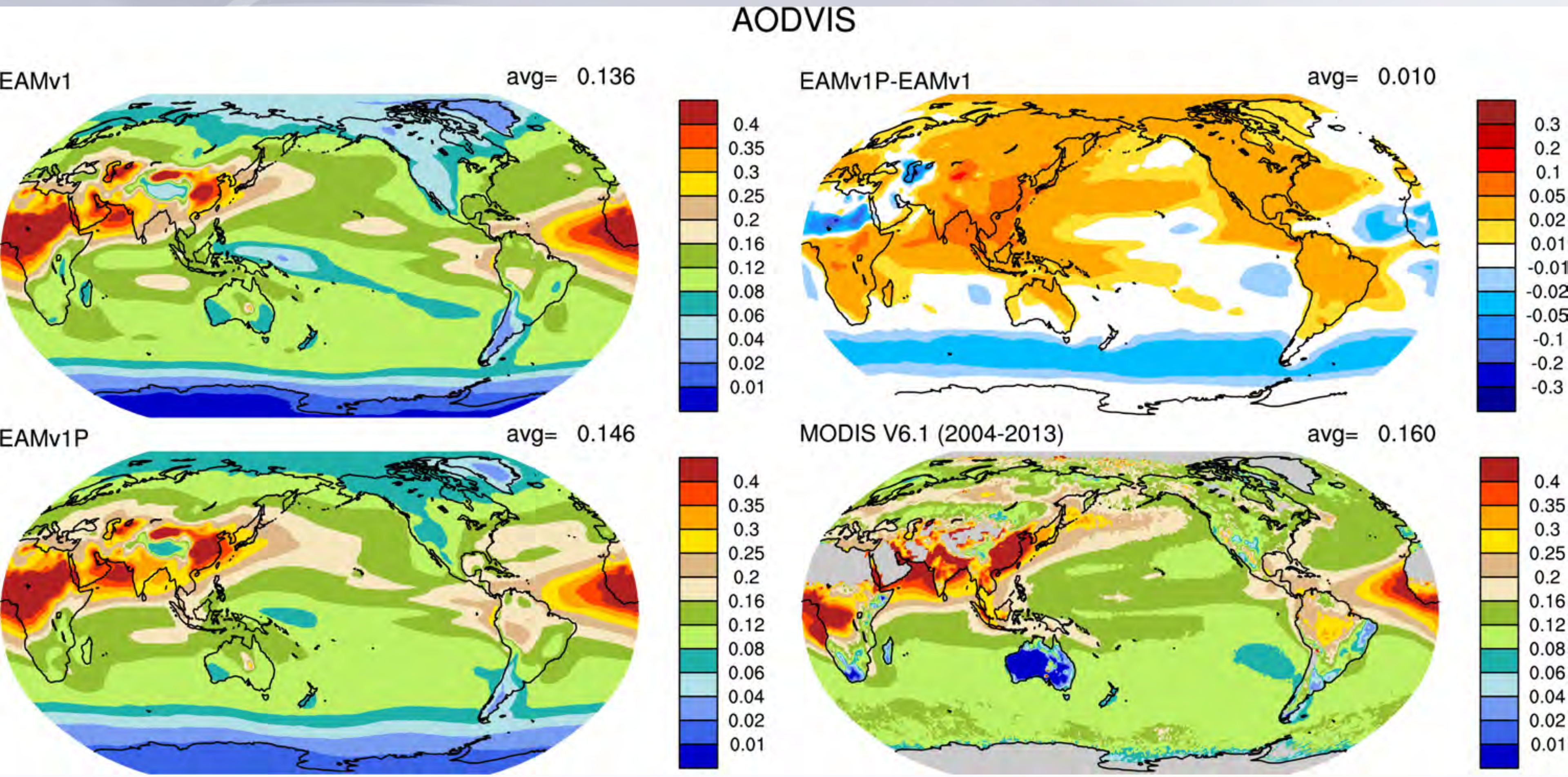


Surface temperature: *Significant reduction of bias over NH mid- and high-latitudes*





Aerosols: *Significant improvement on long-range aerosol transport!*



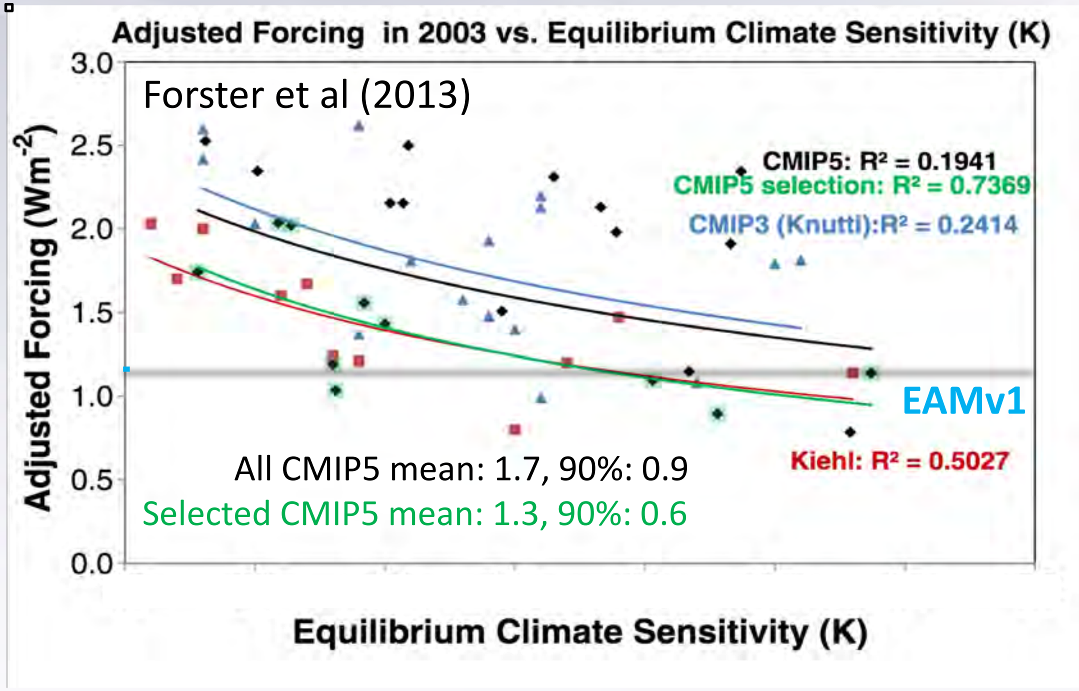
Changes in clouds and precipitation allows longer range transport (aerosol burden increases by 40% in the Arctic)!

Lesson learned: When clouds and convections are calibrated to produce better present-day cloud climatology, other long-standing climate model biases are also gone/reduced.

Models are built to predict the future. So, in addition to climatology, we need to assess system response to forcings, too.

EAMv1P, which produces significantly **more realistic present day climate**, is expected to produce …

	EAMv1	EAMv1P
Adjusted forcing *Selected CMIP5:* *1.3 ± 0.6*	**1.20**	
AIF *Stevens: -0.3 to -1.0* *AR5 (likely): 0 to -1.2* *AR5 models: -0.5 to -2.5*	**-1.02** SW:-1.56 LW: 0.54 **S = -44**	
Cloud feedback *AR5 mean: 0.6* *AR5 range: -0.2 to 2.0*	**0.21** SW: 0.34 LW:-0.13	
PD-PI RESTOM Diff CERES-EBAF: 0.81	**0.49**	



EAMv1P, which produces significantly more realistic present day climate, is expected to produce **significantly lower equilibrium climate sensitivity**

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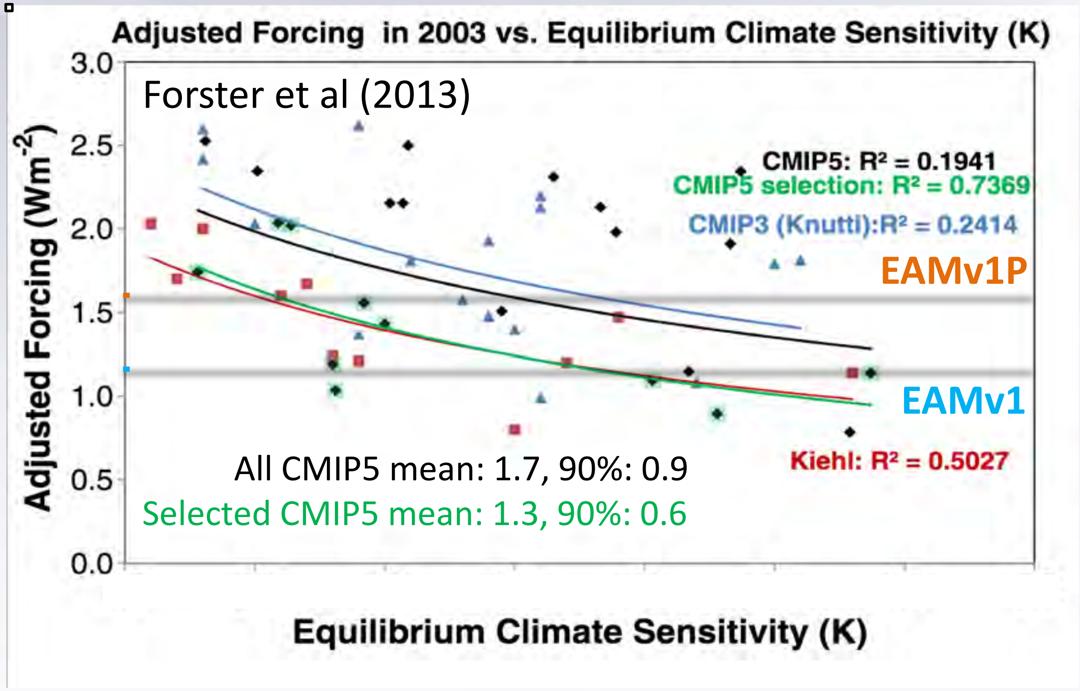
Cloud feedback *AR5 mean: 0.6* *AR5 range: -0.2 to 2.0*	**0.21** SW: 0.34 LW:-0.13	**0.01** SW: 0.32 LW:-0.31
PD-PI RESTOM Diff CERES-EBAF: 0.81	**0.49**	**0.86**



- The new configuration produces weaker AIF, higher AF and CF, and, hence, lower climate sensitivity.
- It seems that the changes are toward the *desired* direction.
- No evidence to say which one is *correct*. Bottom-up (process-level) evaluation is necessary.

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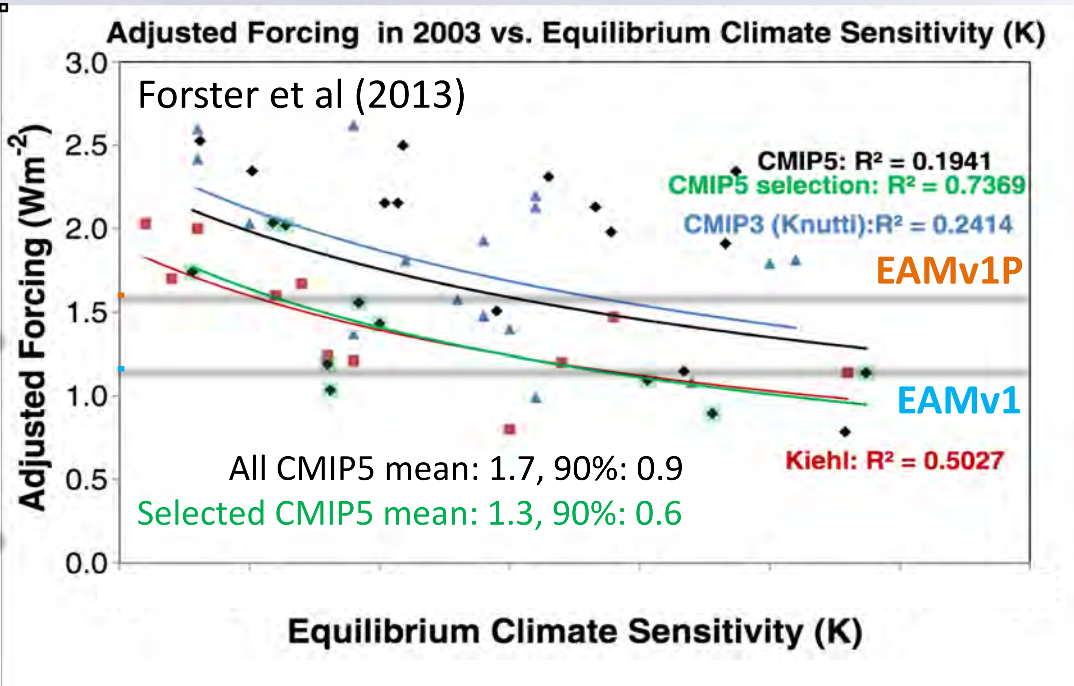


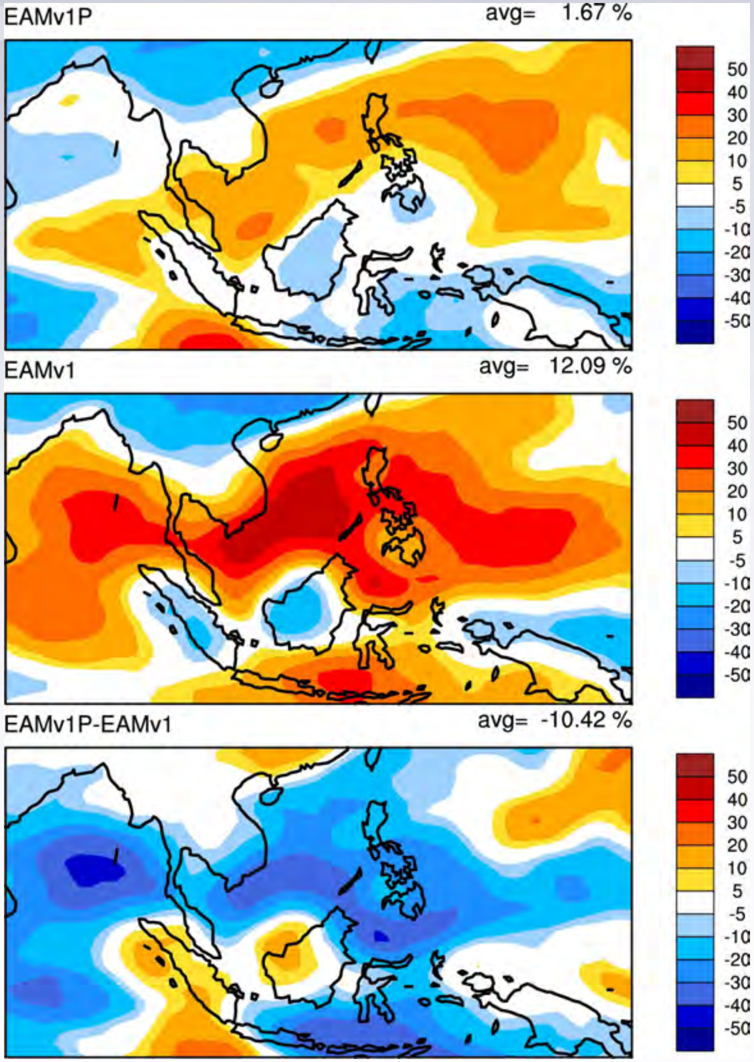
- The new configuration produces weaker AIF, higher AF and CF, and, hence, lower climate sensitivity.
- It seems that the changes are toward the *desired* direction.
- No evidence to say which one is *correct*. Bottom-up (process-level) evaluation is necessary.
- Change of LW component of AIF is due like to sulfate size threshold, but for cloud feedback it is less clear though the largest signal comes from TWP.

What has been changed?

- **Gustiness** → enhances precipitation over TWP
- **Ice condensate size detrained from deep convection** (reduced) → increase ice number
- **Autoconversion for deep convection** (reduced) → produce more cirrus
- **Deep convective cloud fraction** (reduced) → more realistic high cloud fraction
- **Deep convective detrainment rate** (increased) → improve shallow cu
- **Deep convection launching level** (lowered) → useful when coupled with ocean
- **Deep convective precipitation evaporation efficiency** (increased) → moistening lower troposphere produces better/stronger precipitation
- **Deep convective downdraft fraction** (increased) → enhance convective mixing
- **Ice sedimentation** (increased) → reduces high clouds in subtropics

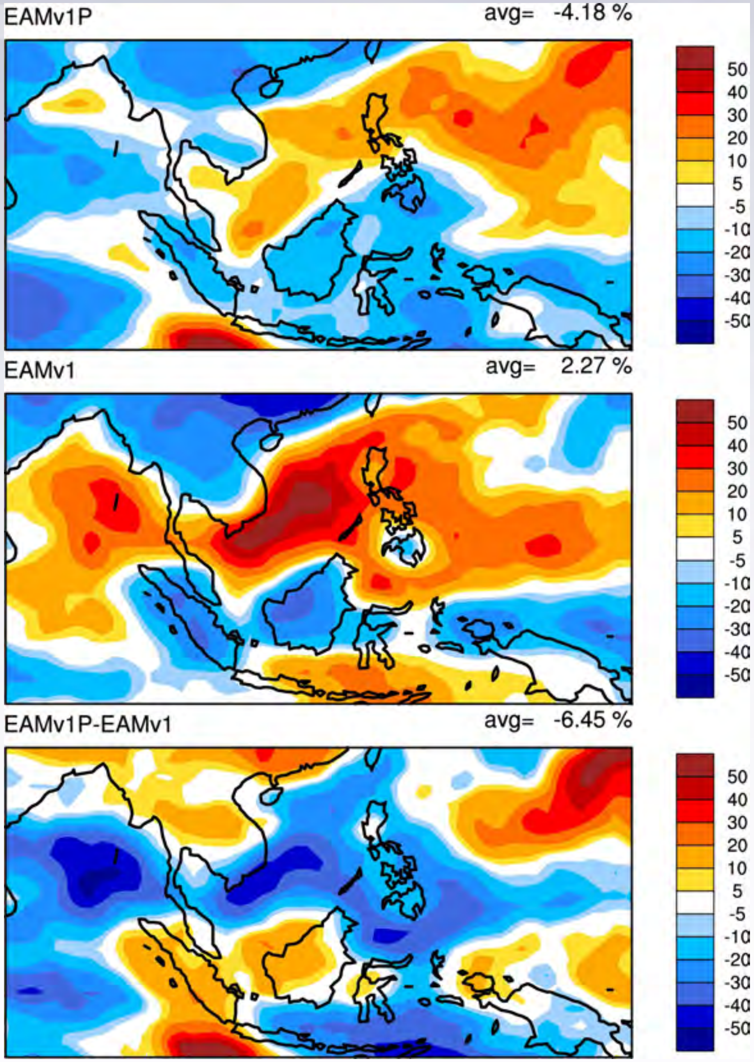
preliminary

LWCRE responses over TWP differ a lot!



preliminary

IWP responses consistent with LWCRE responses!



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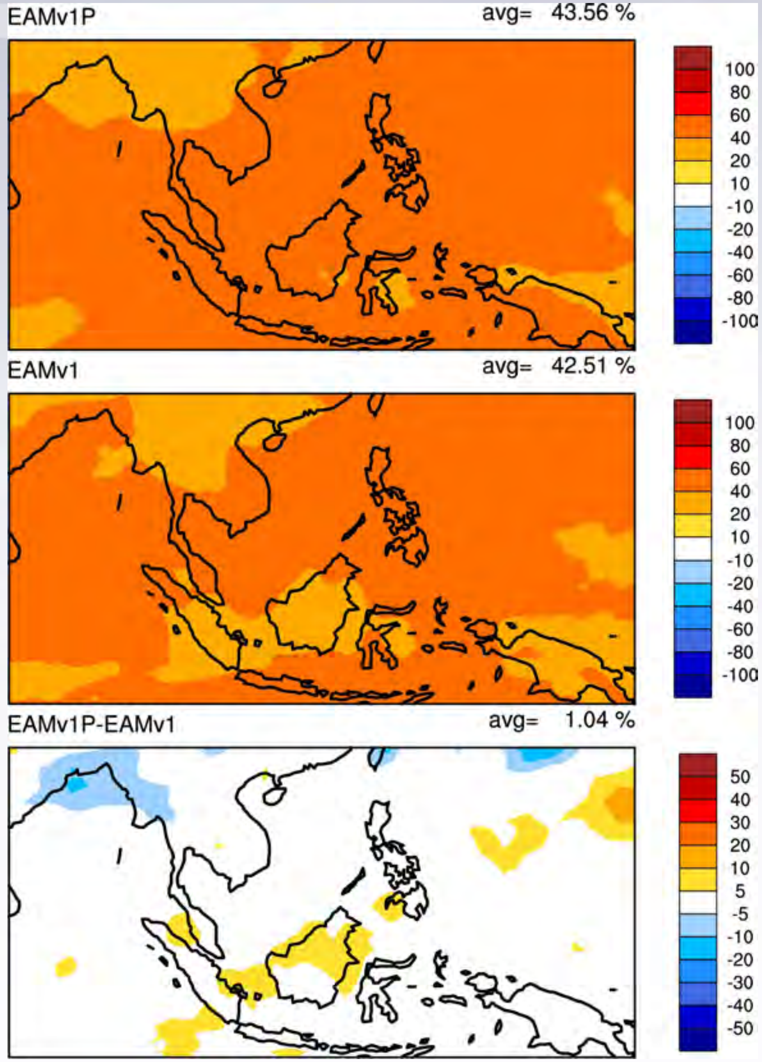
preliminary

Similar microphysical property responses



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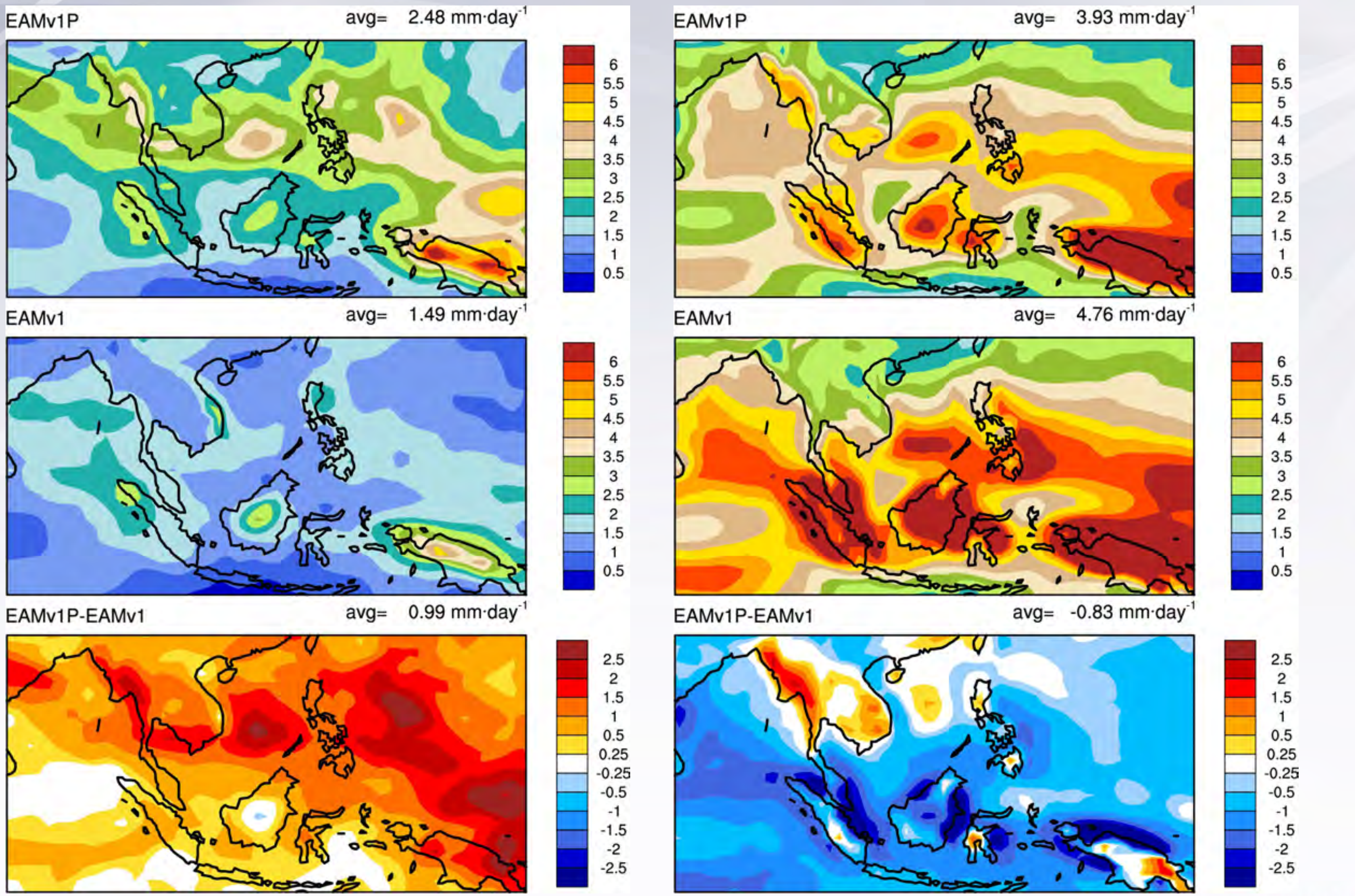
preliminary

New model state: Higher resolved scale precipitation fraction, weaker parameterized convection activity.

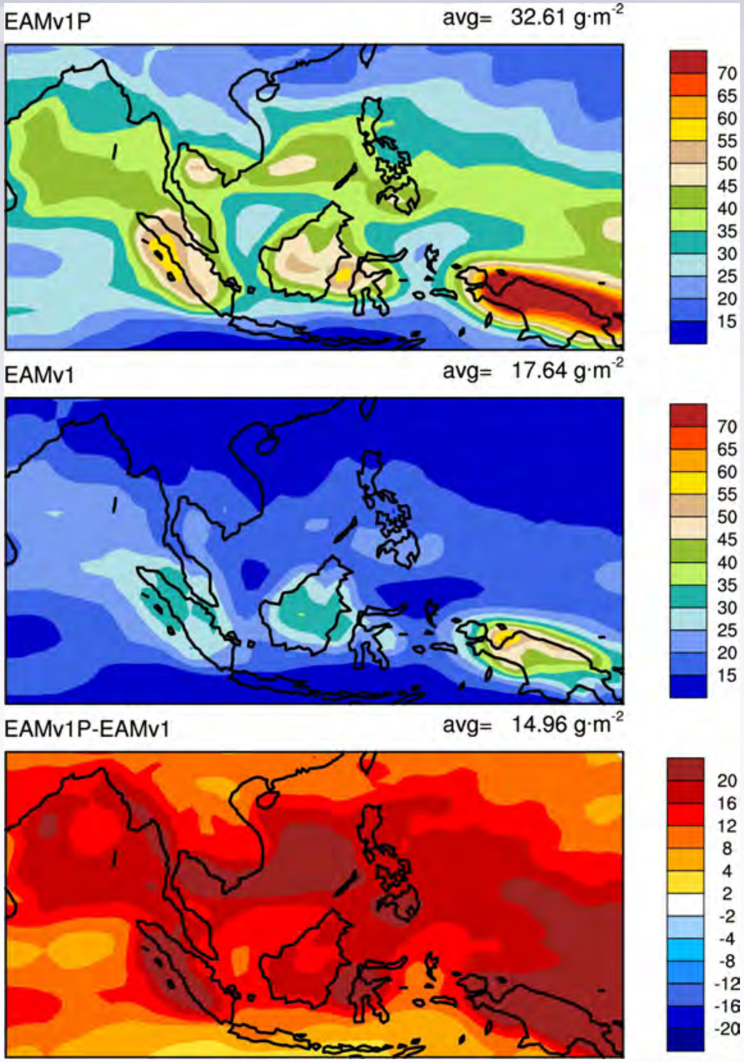


resolved

parameterized

preliminary

New model state: A lot more high/ice cirrus



Hypotheses

- The new model has more high clouds, which can induce a negative feedback to surface warming that stabilizes the atmosphere.

- The new model has more resolved and less parameterized cloud/convections, which reduces the sensitivity to surface warming.

- The new model's gustiness parameterization produces the triggering effect (kicking off the circulation feedback) like the surface warming to the old model, so its responses to additional forcing is relatively more linear than the old model.

We need to prove that these mechanisms exist in the model and in the real world.

How do we constrain the model's process representations?

- **Gustiness** → enhances precipitation over TWP
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- Are there metrics for mechanisms/processes that can be derived from observations?
- Compare ML/DL-derived rules with parameterizations?

Summary

- A new configuration EAMv1P has been created. The new configuration produces a much more realistic present day climate than EAMv1. The new configuration produces weaker AIF/CF, and much stronger adjusted forcing, and is likely to produce a significantly lower equilibrium climate sensitivity.

- This is achieved by (1) retuning clouds and convections (toward more observationally and/or physically justifiable values) and (2) better integration of physics. No new physics parameterization was developed, but new physics can be introduced through tuning and the better integration of existing physics.

- The tuning has been guided by top-down model validation approach (constrain model cloud characteristics). The bottom-up model validation approach (constrain model cloud processes) is necessary and is on the way.

- The change in LW portion of AIF can be explained by sulfate size threshold, but that of cloud feedback is a combination of several things, causing a weaker parameterized deep convection response (to surface warming) over TWP. This requires further investigation. Constraining the model is a challenging and yet necessary task.