New Generation Atmospheric Model AM4 and Cloud Climate Initiative

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Key changes in AM4 from AM3

- **Dynamic core:** hydrostatic FV^3, high-order divergence damping & model-top sponge layer
- **Aerosols and chemistry (AM4.0, AM4.1)**:
  - Full chemistry: 100km/49L 1Pa top + 17 aerosols + 82 gas tracers, interactive O3
  - Simple chemistry: 100km/33L 1hPa top + 17 aerosols + 4 gas tracers, prescribed O3
- **Radiation:** substantial recent updates
  - 10um CO2 + WV continuum + refitting to LBL spectroscopy + reduced SW time-step
- **Mountain gravity wave drag**: new formulation based on Garner (2005)
- **Moist convection:** two plume scheme developed based on UWShCu (Bretherton et al 2004)
- **Aerosol-cloud interactions:** significant modifications from AM3
  - Activation scheme (macro and micro) + convective rain and snow wet deposition
- **Surface fluxes:** new ocean roughness formulation based on COARE3.5
- **Large-scale clouds, cloud microphysics, PBL, and non-orographic gravity wave drag are the same as in AM3 except with** some parameter retuning

Key motivation: reduce previous model biases including mean climate, variability, and responses to forcings

AM4.0 simulations with prescribed SSTs and sea-ice

- **Short AMIP runs (1980-2014): 5 members**
- **Long AMIP runs (1870-2014): 3 members**

  runs with individual forcing agents on and off → time-varying forcings

- **Climatological runs: present-day climatological SSTs and sea-ice**

  prescribed PD or PI forcing agents → forcings
  2K SST warming → feedbacks and Cess sensitivity

- **Boundary condition and atmospheric forcing agents:**

  CMIP6 specification of SSTs, sea-ice, solar irradiances, volcanos, GHG and aerosol emissions

- **LM4.0 land model: static present-day vegetation and land use**

AM4.0 documentation papers (2018, JAMES)

Zhao, Golaz, Held, Guo, and 41 co-authors: The GFDL global atmosphere and land model AM4.0/LM4.0. Part I: simulation characteristics with prescribed SSTs Part II: model description, sensitivity studies and tuning strategies

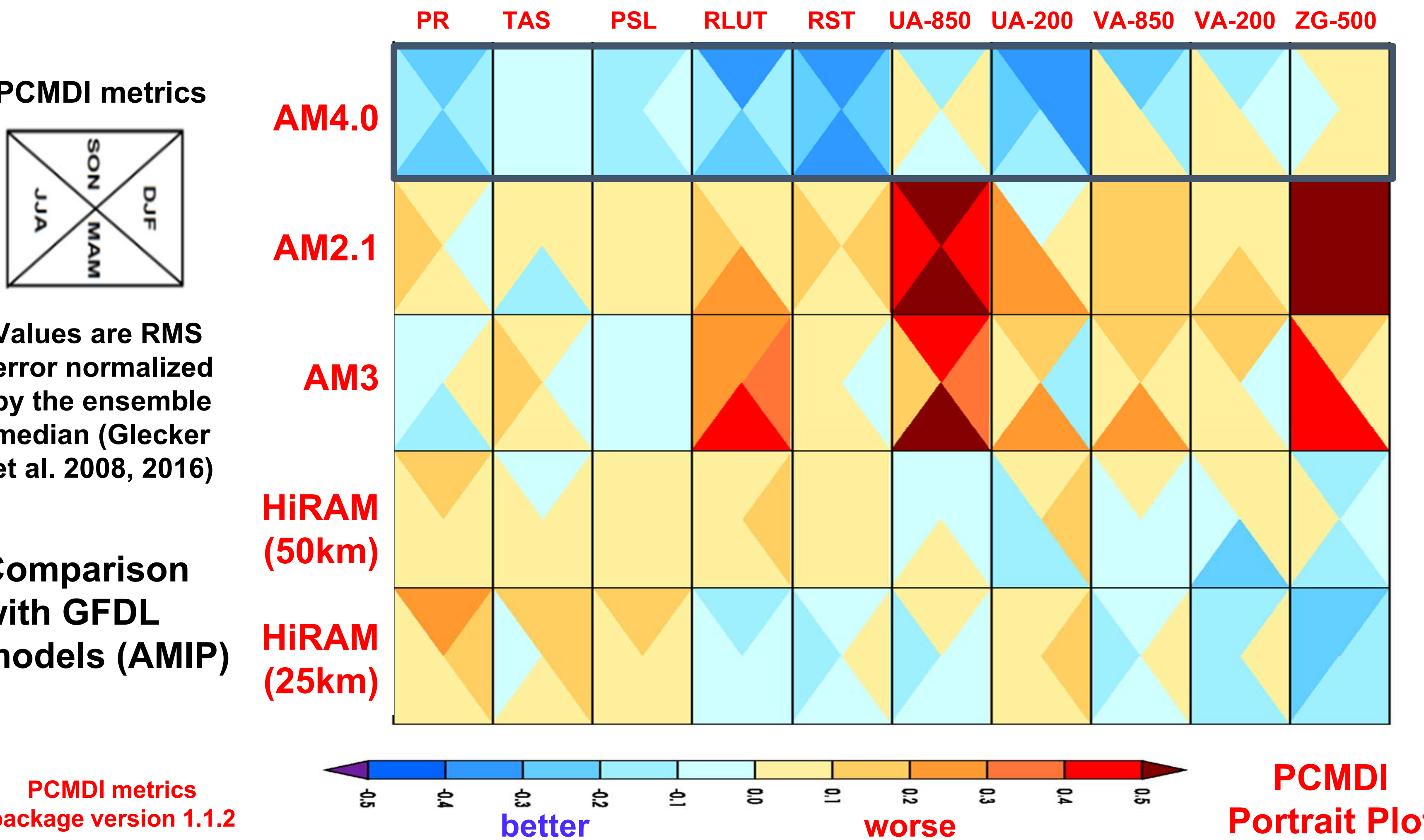
PCMDI portrait plot: comparison with previous GFDL models

PR: Precipitation; TAS: Surface air temperature; PSL: Sea-level pressure; RLUT: TOA Outgoing LW radiation; RST: TOA net SW radiation; UA-850 & UA-200: 850 and 200hPa zonal wind; VA-850 & VA-200: 850 and 200hPa meridional wind; ZG-500: 500hPa geopotential height.

PCMDI metrics

Values are RMS error normalized by the ensemble median (Glecker et al. 2008, 2016)

Comparison with GFDL models (AMIP)



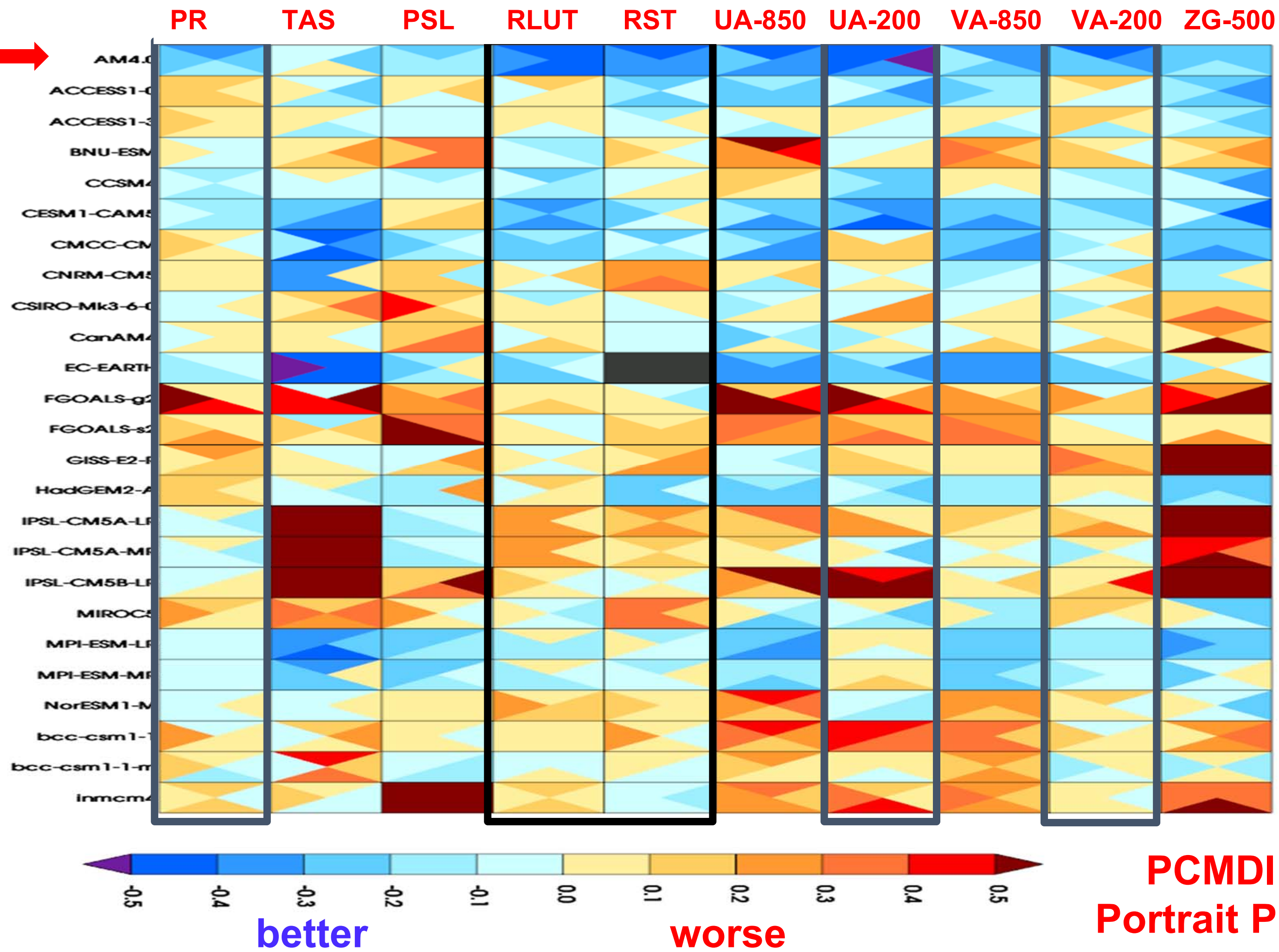
PCMDI metrics package version 1.1.2

PCMDI Portrait Plot

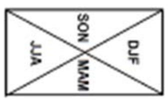
PCMDI portrait plot: comparison with CMIP5 models

PR: Precipitation; TAS: Surface air temperature; PSL: Sea-level pressure; RLUT: TOA Outgoing LW radiation; RST: TOA net SW radiation; UA-850 & UA-200: 850 and 200hPa zonal wind; VA-850 & VA-200: 850 and 200hPa meridional wind; ZG-500: 500hPa geopotential height.

AM4.0 →



PCMDI metrics



Values are RMS error normalized by the ensemble median (Glecker et al. 2008, 2016)

Comparison with CMIP5 models (AMIP)

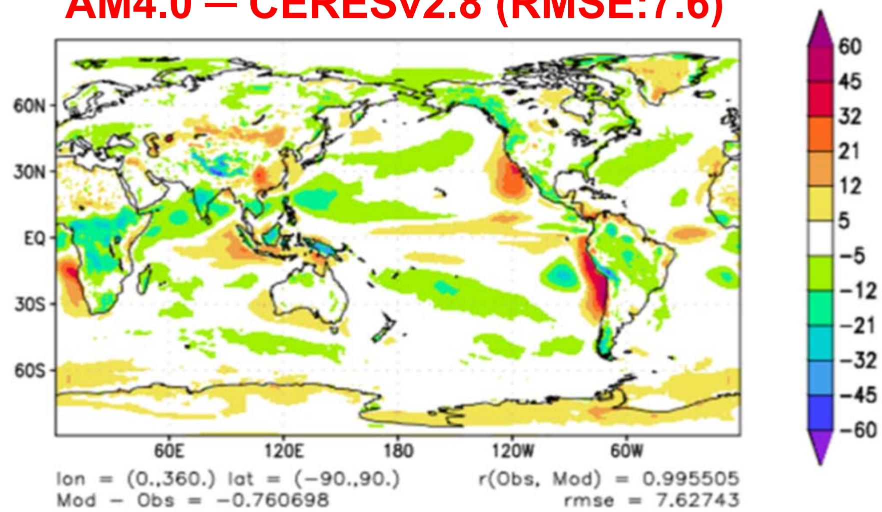
PCMDI metrics package version 1.1.2

PCMDI Portrait Plot

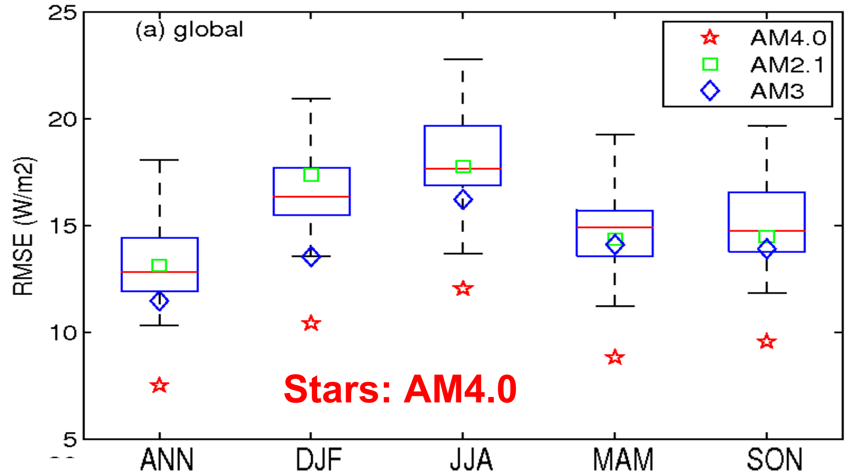
AM4 improves top-of-atmosphere shortwave radiation

comparison with AM2 AM3 and CMIP5 models (unit: W/m2)

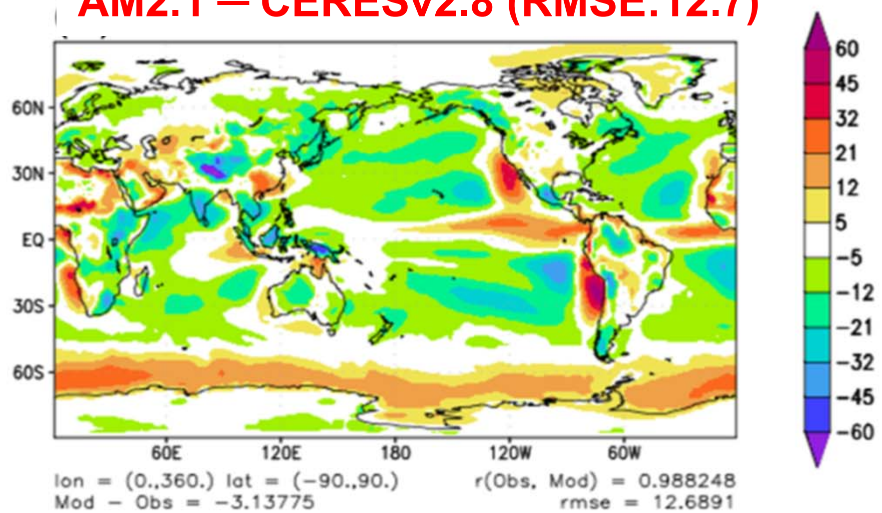
AM4.0 – CERESv2.8 (RMSE:7.6)



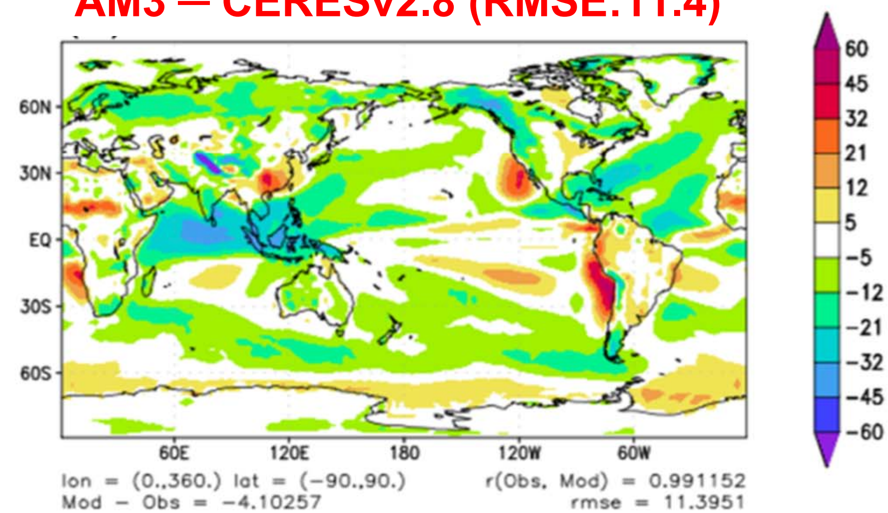
Comparison with CMIP5 models



AM2.1 – CERESv2.8 (RMSE:12.7)



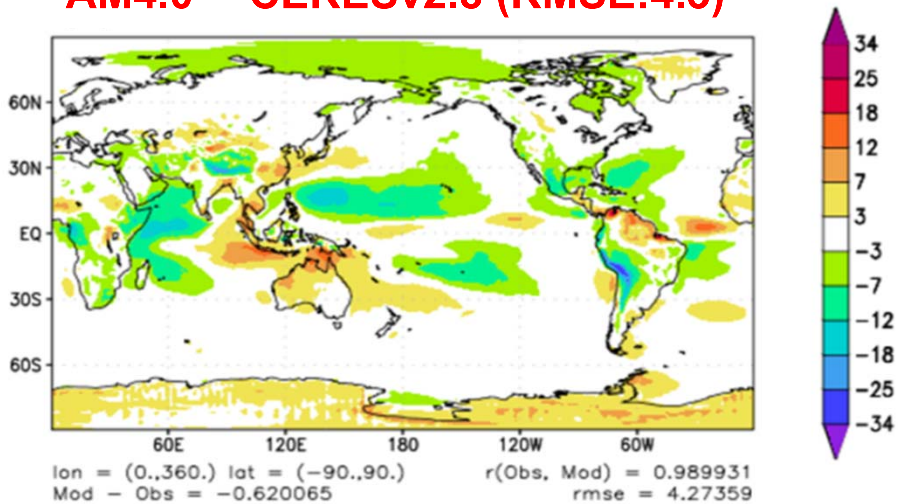
AM3 – CERESv2.8 (RMSE:11.4)



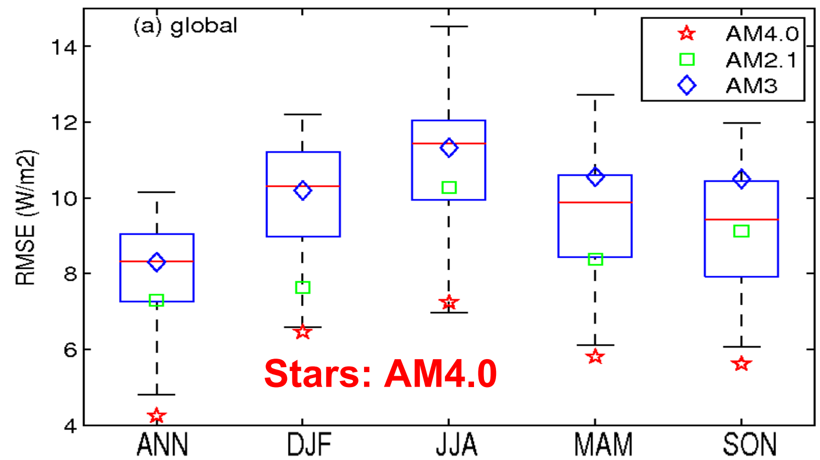
AM4 improves Outgoing Longwave Radiation

comparison with AM2 AM3 and CMIP5 models (unit: W/m2)

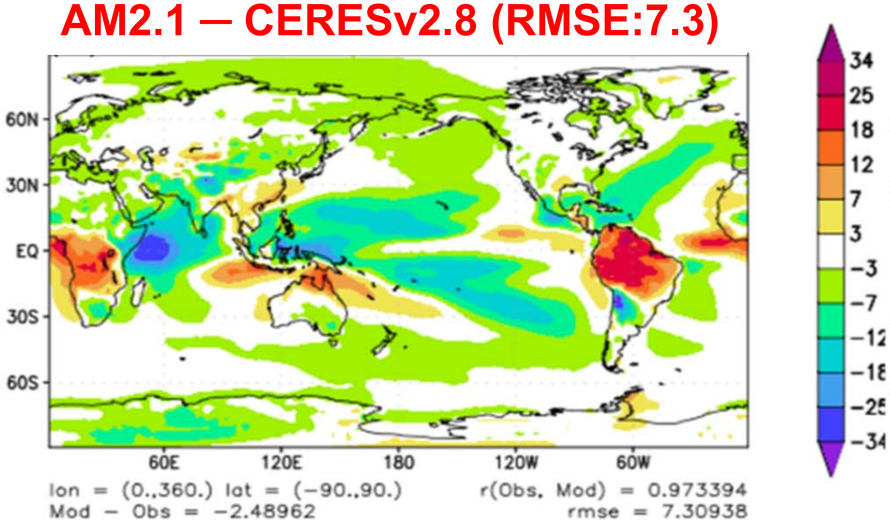
AM4.0 – CERESv2.8 (RMSE:4.3)



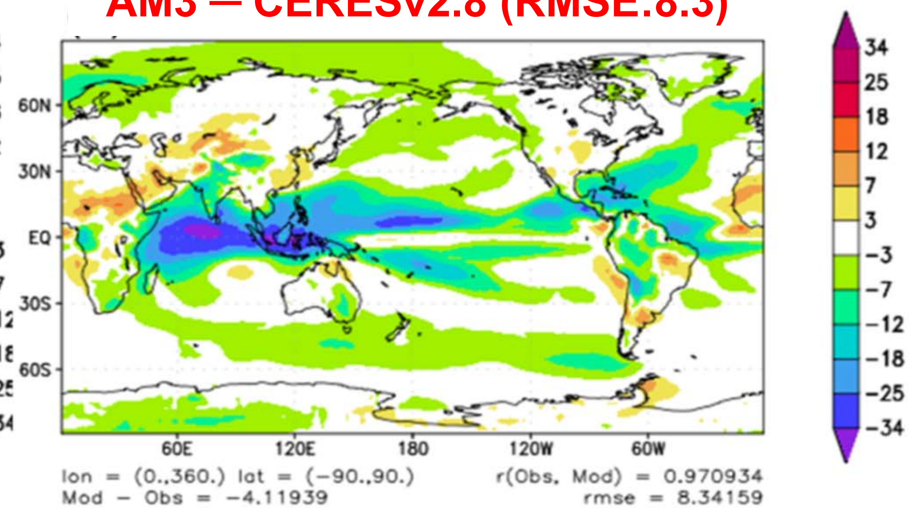
Comparison with CMIP5 models



AM2.1 – CERESv2.8 (RMSE:7.3)

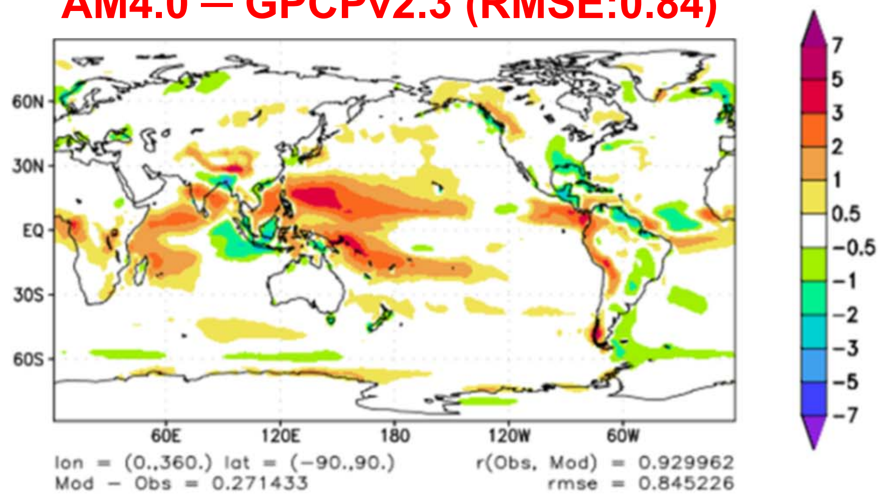


AM3 – CERESv2.8 (RMSE:8.3)

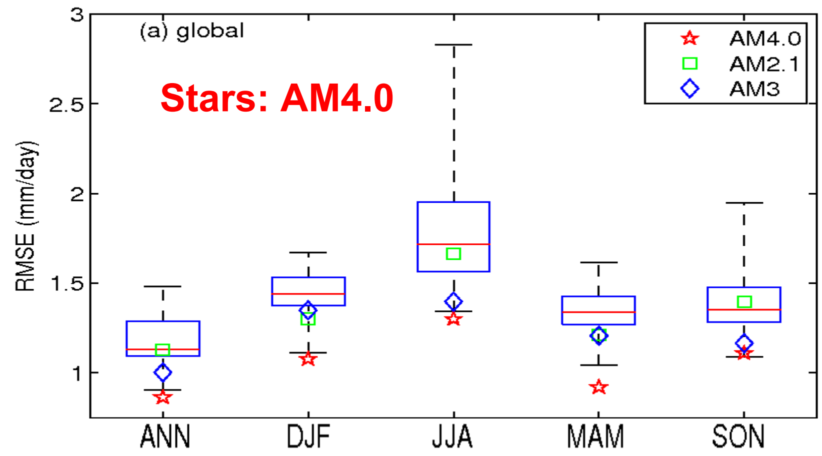


AM4 improves surface precipitation
comparison with AM2 AM3 and CMIP5 models (unit: mm/day)

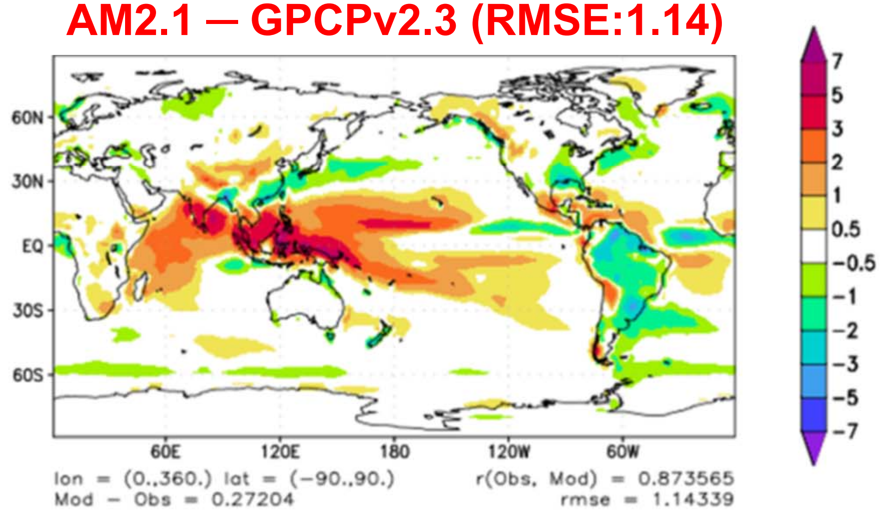
AM4.0 – GPCPv2.3 (RMSE:0.84)



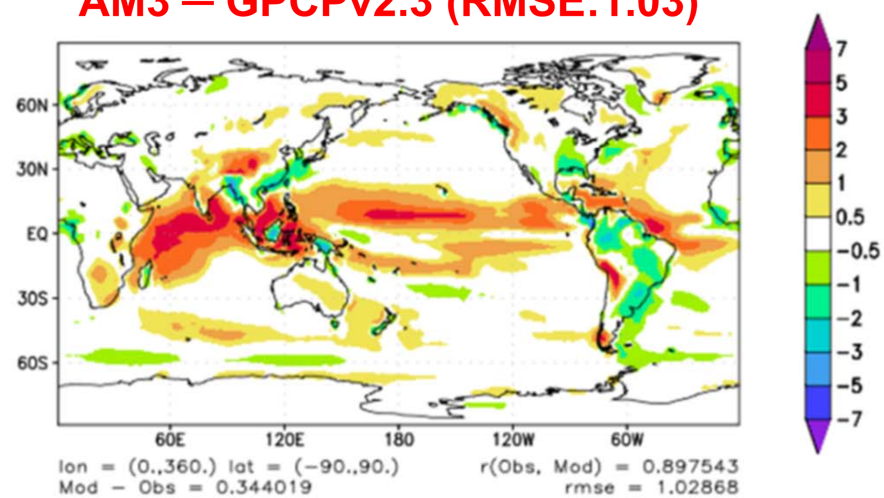
Comparison with CMIP5 models



AM2.1 – GPCPv2.3 (RMSE:1.14)



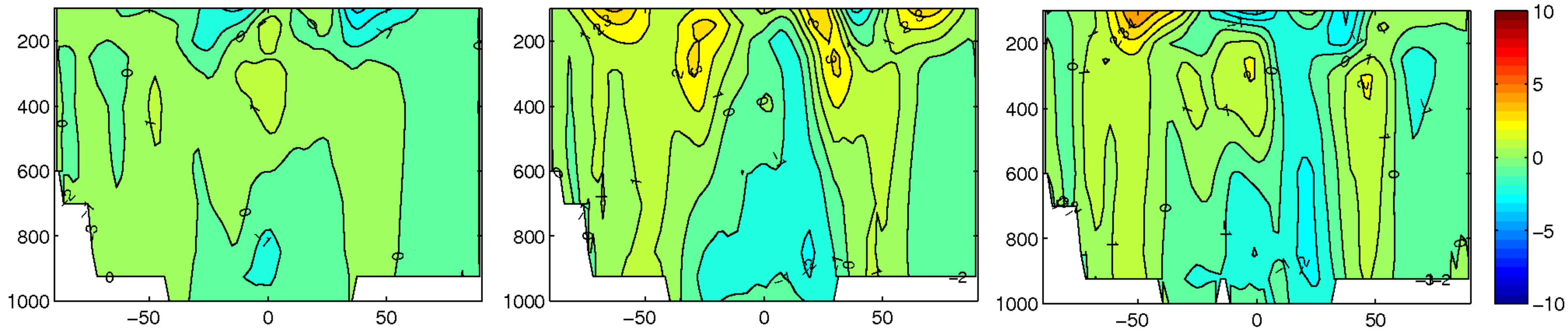
AM3 – GPCPv2.3 (RMSE:1.03)



AM4 improves zonal mean zonal wind and temperature
(comparison with AM2 and AM3)

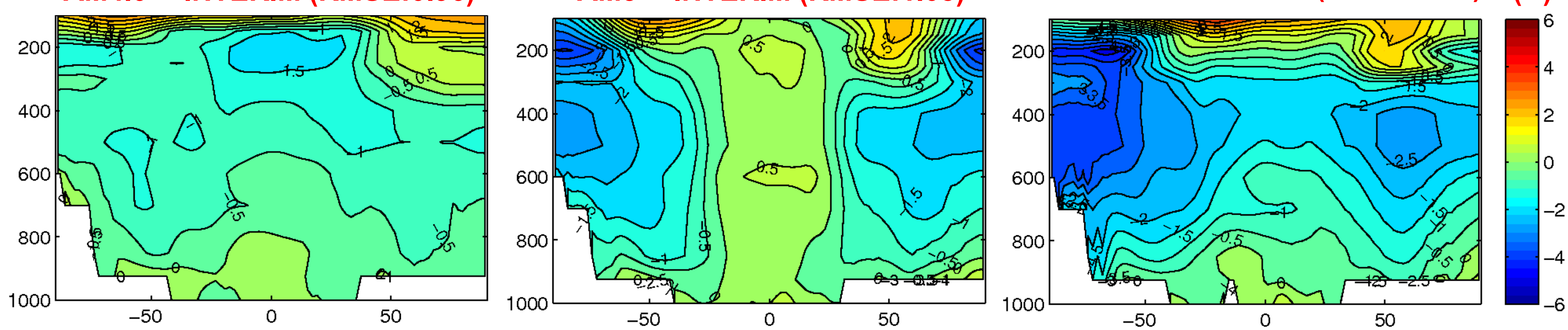
Annual mean zonal mean zonal wind

AM4.0 — INTERIM (RMSE:0.76) **AM3 — INTERIM (RMSE:1.52)** **AM2.1 — INTERIM (RMSE:1.52)** **(m/s)**



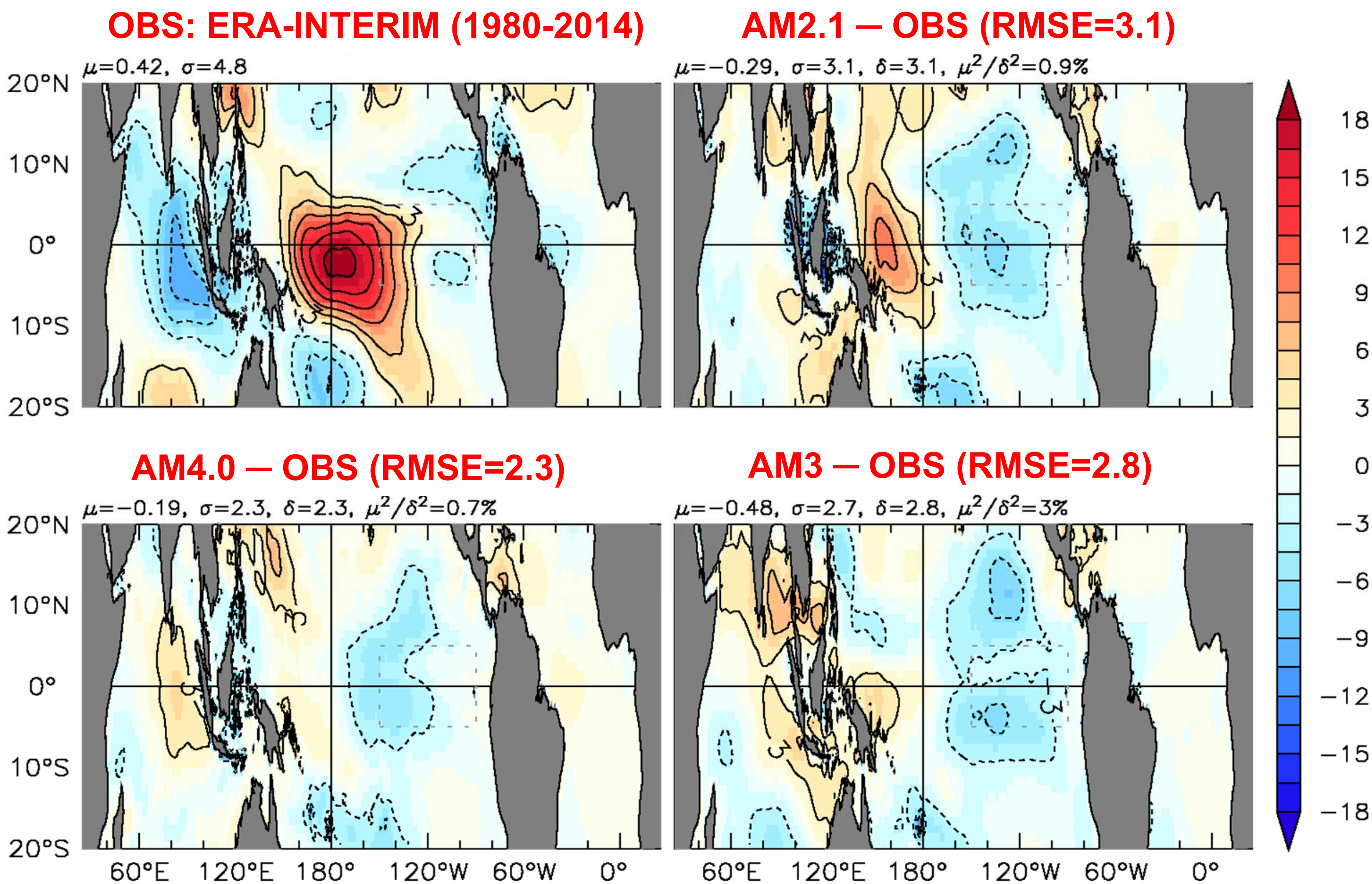
Annual mean zonal mean temperature

AM4.0 — INTERIM (RMSE:0.96) **AM3 — INTERIM (RMSE:1.05)** **AM2.1 — INTERIM (RMSE:1.87)** **(K)**

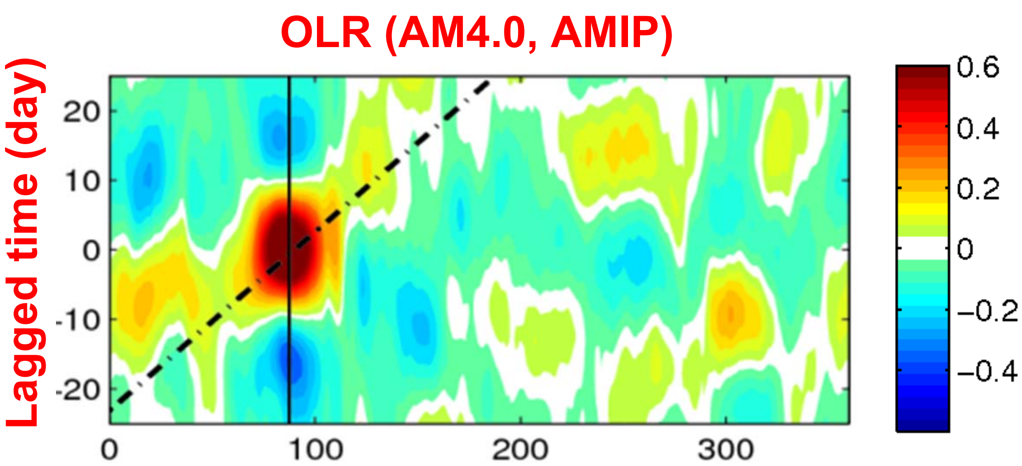


AM4 improves surface wind stress response to ENSO SST anomalies

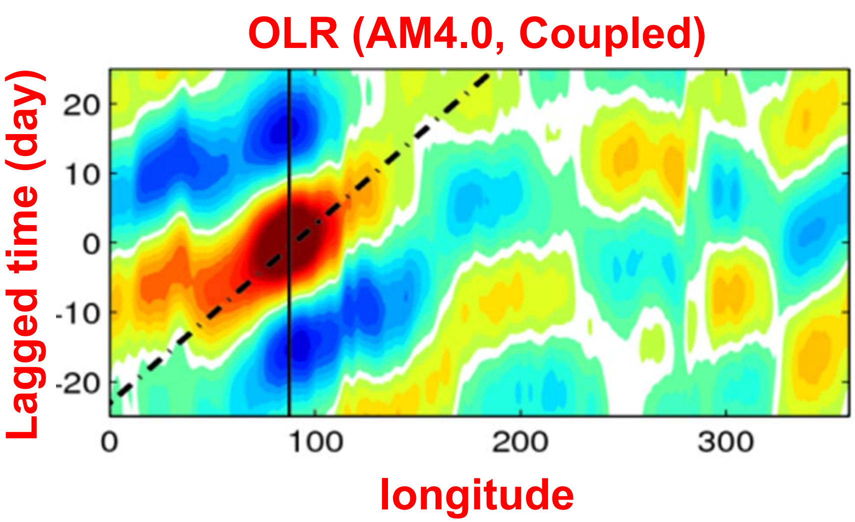
comparison with AM2 and AM3 (mPa/K)

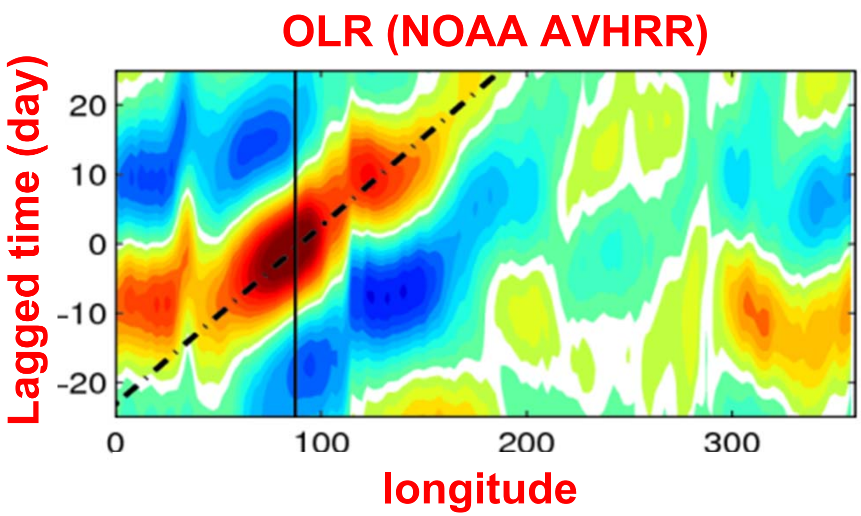


AM4 improves coupled simulation of Madden-Julian Oscillation
(Lag-Longitude-Diagram; winter season)



Lag correlation between central Indian ocean OLR and associated near equatorial OLR at all longitudes

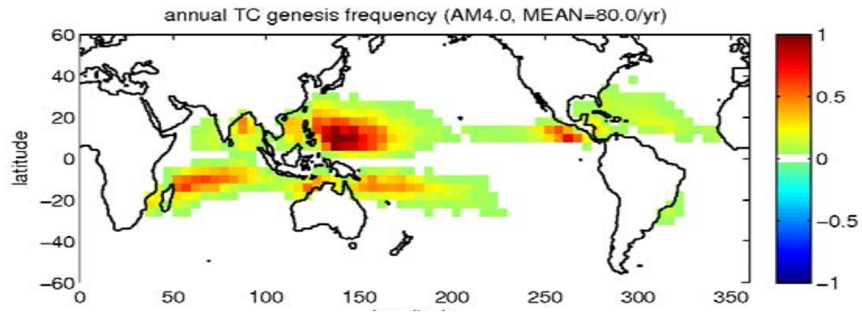




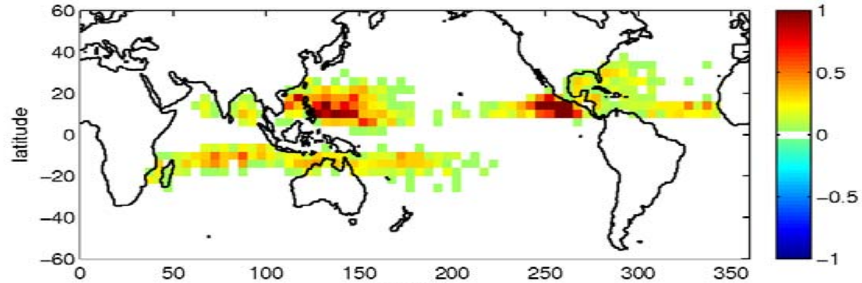
AM4 improves simulations of tropical cyclone statistics

tropical cyclone frequency and seasonal cycle

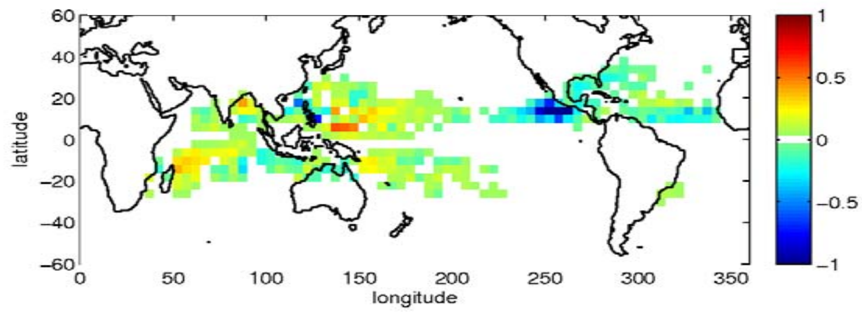
AM4.0 annual TC genesis frequency



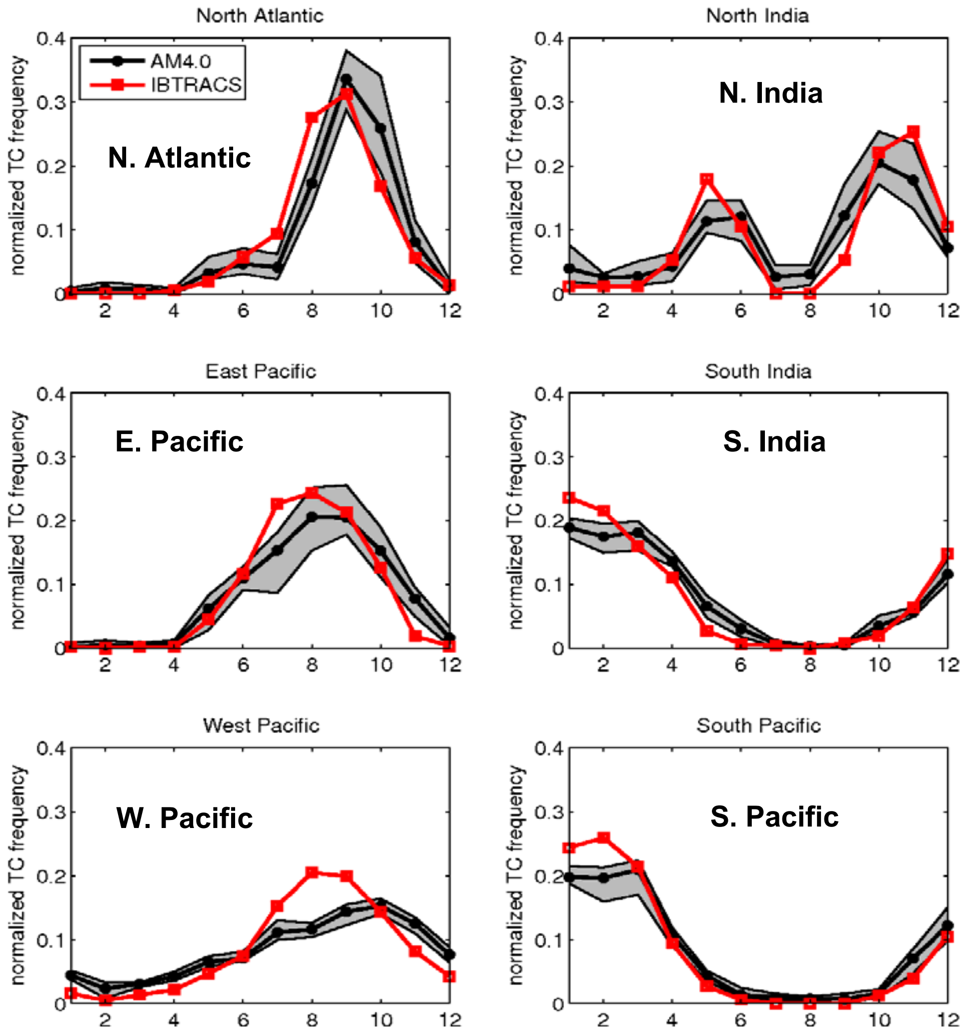
OBS: IBTRAC



AM4.0 minus IBTRAC



AM4.0 seasonal cycle of TC genesis frequency



GFDL Cloud Climate Initiative (CCI)

Key questions to address:

1. How can we enhance our ability in GCM representations of convection and clouds and through this improve model fidelity in future predictions?
2. How will clouds respond to global warming and other forcing and feed back on climate change through impacts on the Earth radiation budget?

Past efforts have emphasized mostly on reducing AM4 cloud associated biases and understanding AM4's climate sensitivity.

Moving forward, what can we do to address the above questions with special emphasis on GFDL uniqueness, strength, practicality, and relevancy to the NOAA-OAR missions?

Key areas for future research & development under CCI

Global Cloud System Resolving Model (GCSRM) Dev. & App.

- Short hindcast experiments with cloud-oriented diagnostics & evaluation
- Regional cloud resolving model: nested or idealized setting

Scale-aware representations of clouds in seamless models

- Utilizing GCSRM/CRM/LES for cloud parameterizations (2 CPT & Vulcan ML)
- Test parameterizations in hindcast experiments across all temporal scales

Studies of convection cloud climate connections using GCMs

- In-depth understanding of GFDL models' climate sensitivities, cloud feedbacks, and aerosol-cloud effects.
- Multi-model studies with observations with a goal of finding emergent constraints for cloud feedback and climate sensitivity
- Effects of convection & cloud representation for studies of weather and climate extremes

Summary

- AM4 has an improved horizontal resolution, a new convection and mountain drag parameterization with radiative transfer, aerosol-cloud interactions significantly updated. AM4 predicts aerosols from emissions with two options in the complexity of atmospheric chemistry.
- AM4 forced by observed SSTs produces superior quality than most CMIP5 models in simulations of TOA radiative fluxes, clouds, and precipitation. It also improves simulations of aerosols, MJO, TC statistics, and response to ENSO SSTA compared to AM3/AM2.
- Past CCI activities emphasized on reducing AM4 cloud biases and understanding AM4's climate sensitivity. Future efforts will focus on process level understanding and modeling convection and clouds using global cloud system resolving models.

Selected Papers Published Under GFDL CCI

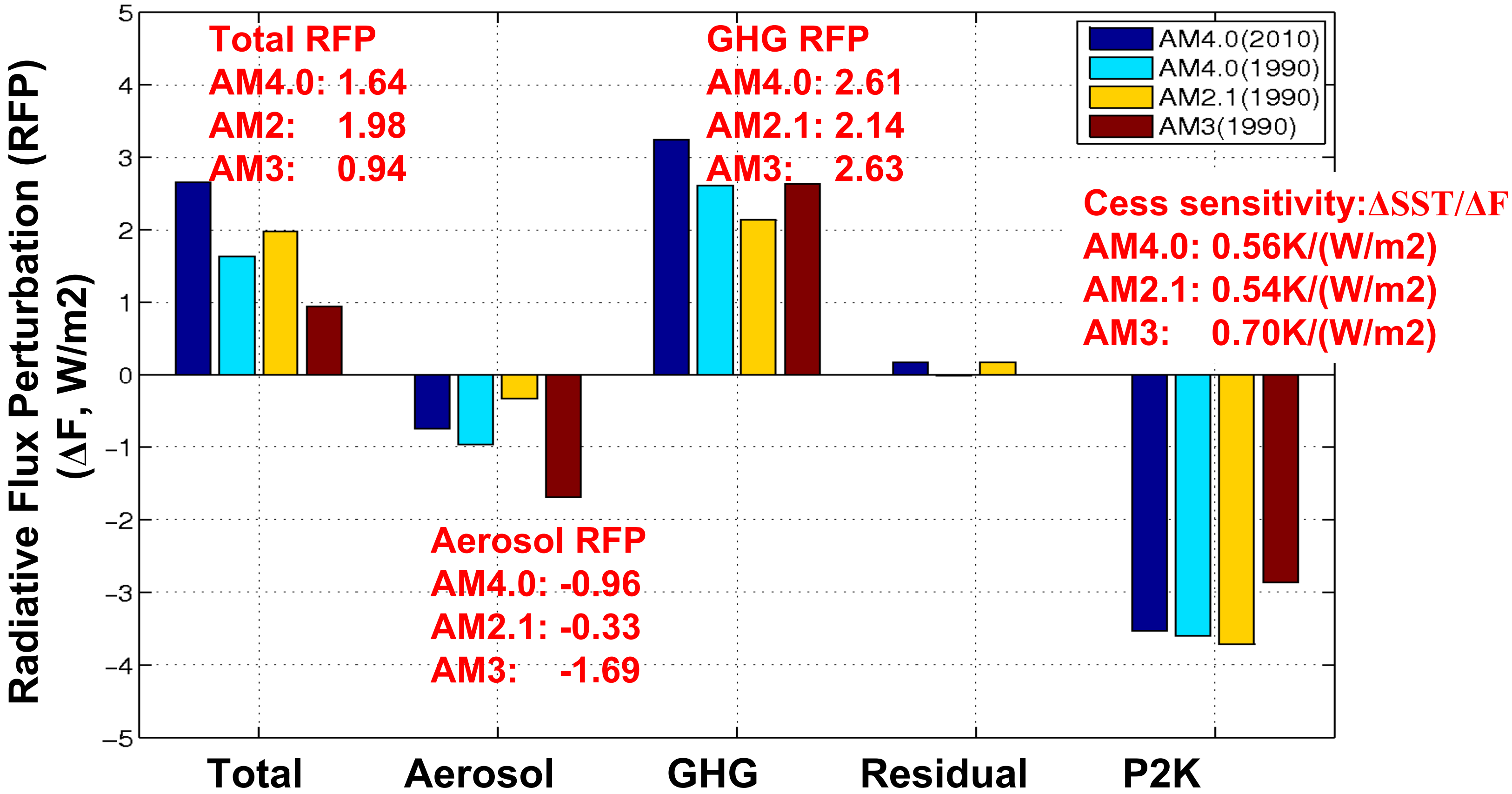
Towards an improved representation of convection and clouds in global climate models:

- *Zhao, M, J-C Golaz, IM Held, H. Guo, and 41 co-authors, 2018a: The GFDL global atmosphere and land model AM4.0/LM4.0. Part I: simulation characteristics with prescribed SSTs. JAMES,10(3), DOI:10.1002/2017MS001208*
- *Zhao, M, J-C Golaz, IM Held, H. Guo, and 41 co-authors, 2018: The GFDL global atmosphere and land model AM4.0/LM4.0. Part II: model description, sensitivity studies and tuning strategies. JAMES. 10(3), DOI: 10.1002/2017MS001209*
- *Guo, H, J-C Golaz, LJ Donner, B. Wyman, M. Zhao, and P. Ginoux, 2015: CLUBB as a unified cloud parameterization: opportunities and challenges. Geophysical Research Letters, 42(11), DOI:10.1002/2015GL063672 .*
- *B. Xiang, M. Zhao, X. Jiang, S-J Lin, T. Li, X. Fu, and GA Vecchi, 2015: The 3-4 Week MJO Prediction Skill in a GFDL Coupled Model. Journal of Climate, 28(13), DOI:10.1175/JCLI-D-15-0102.1 .*
- *Xiang, B., S-J Lin, M Zhao, GA Vecchi, T. Li, X. Jiang, LM Harris, and J-H Chen, 2015: Beyond weather time scale prediction for Hurricane Sandy and Super Typhoon Haiyan in a global climate model. Monthly Weather Review, 143(2), DOI:10.1175/MWR-D-14-00227.1 .*

Towards an improved understanding of cloud feedback and climate sensitivity:

- *Zhao, M, 2014: An Investigation of the Connections among Convection, Clouds, and Climate Sensitivity in a Global Climate Model. Journal of Climate, 27(5), DOI:10.1175/JCLI-D-13-00145.1 .*
- *Zhao, M, J-C Golaz, IM Held, V Ramaswamy, S-J Lin, Y Ming, P Ginoux, B Wyman, L.J. Donner, D.J Paynter, and Huan Guo, 2016: Uncertainty in model climate sensitivity traced to representations of cumulus precipitation microphysics. Journal of Climate, DOI:10.1175/JCLI-D-15-0191.1*
- *Donner, LJ, T O'Brien, D. Rieger, B. Vogel, and WF Cooke, 2016: Are atmospheric updrafts a key to unlocking climate forcing and sensitivity? Atmospheric Chemistry and Physics, 16(20), DOI:10.5194/acp-16-12983-2016.*
- *Xiang, B, M Zhao, IM Held, and J-C Golaz, 2017: Predicting the severity of spurious "double ITCZ" problem in CMIP5 coupled models from AMIP simulations. Geophysical Research Letters, 44(3), DOI:10.1002/2016GL071992.*
- *Ming, Y, and IM Held, 2017: Modeling Water Vapor and Clouds as Passive Tracers in an Idealized GCM. Journal of Climate. DOI:10.1175/JCLI-D-16-0812.1.*
- *L.G. Silvers, D. Paynter, and M. Zhao, 2018: The diversity of cloud responses to twentieth-century sea surface temperatures. Geophysical Research Letters. 45(1), DOI:10.1002/2017GL075583*
- *Paynter, D.J., T.L. Frolicher, L.W. Horowitz, and L.G. Silvers,* 2018 Equilibrium Climate Sensitivity Obtained from Multi-Millennial Runs of Two GFDL Climate Models. Journal of Geophysical Research: Atmospheres, 123(4), DOI:10.1002/2017JD027885.
- *Max, Popp and L.G. Silvers, 2017: Double and Single ITCZs with and without Clouds. Journal of Climate, 30(22), DOI:10.1175/JCLI-D-17-0062.1.*

AM4 reduces negative aerosol cloud effect and CESS sensitivity compared to AM3, and this should help coupled model historical simulation



Total RFP = F{GHG(PD),Aero(PD),…,SST(PD)} – F{GHG(PI), Aero(PI), …,SST(PD)}

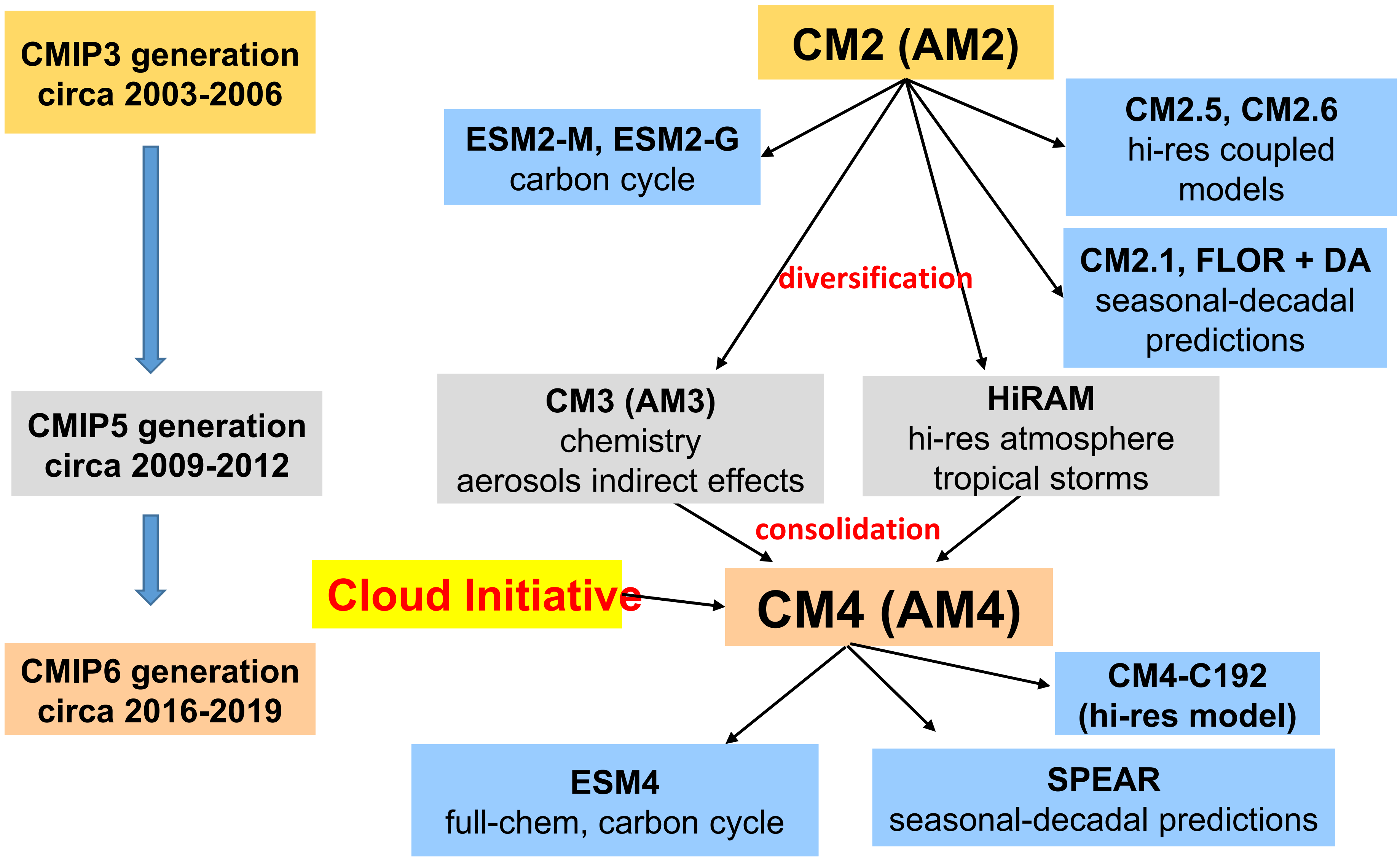
Aerosol RFP= F{GHG(PI), Aero(PD),…,SST(PD)} – F{GHG(PI), Aero(PI), …,SST(PD)}

GHG RFP = F{GHG(PD),Aero(PI),…, SST(PD)} – F{GHG(PI), Aero(PI), …,SST(PD)}

Residual = Total RFP – Aerosol RFP – GHG RFP

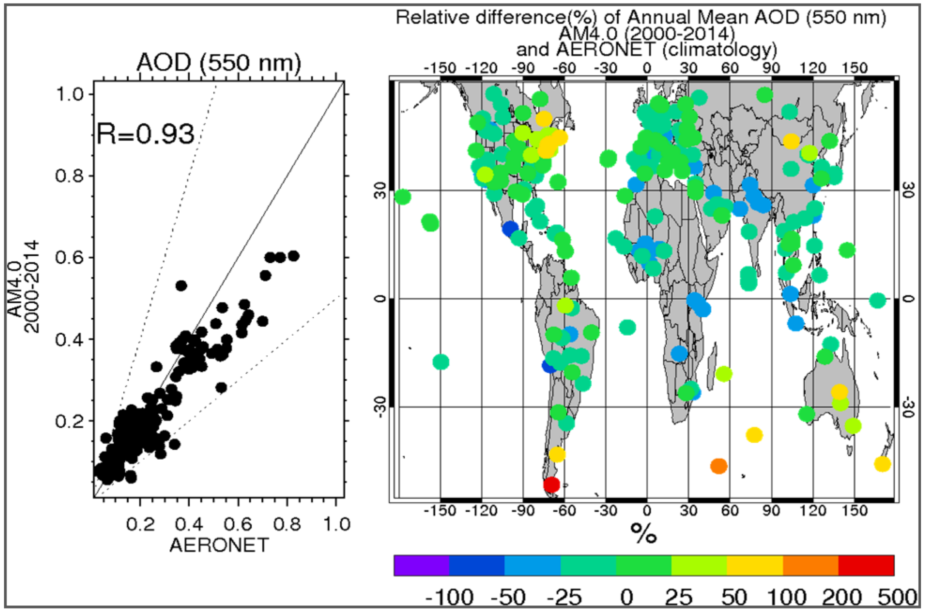
P2K = F{GHG(PD),Aero(PD),…,SST(PD)+2K}– F {GHG(PD),Aero(PD),…,SST(PD)}

Recent history of GFDL global climate models



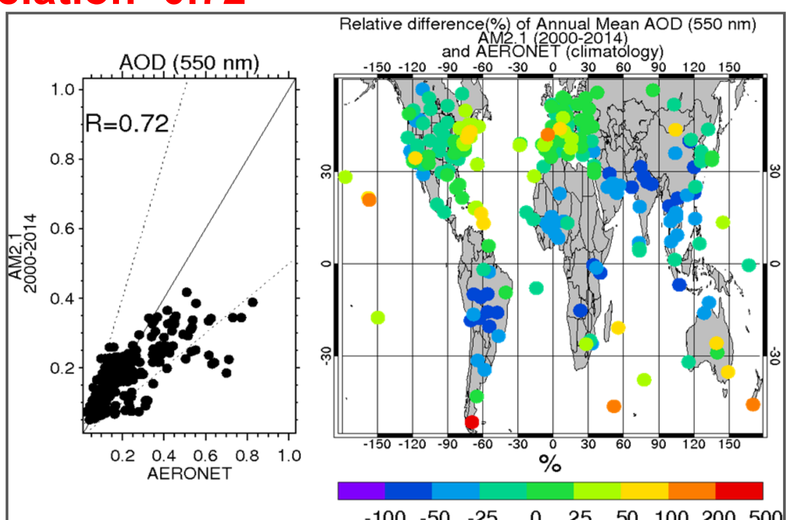
AM4 improves aerosol optical depth comparison with AM2.1 and AM3 (OBS: AERONET)

AM4.0-vs-OBS correlation=0.93

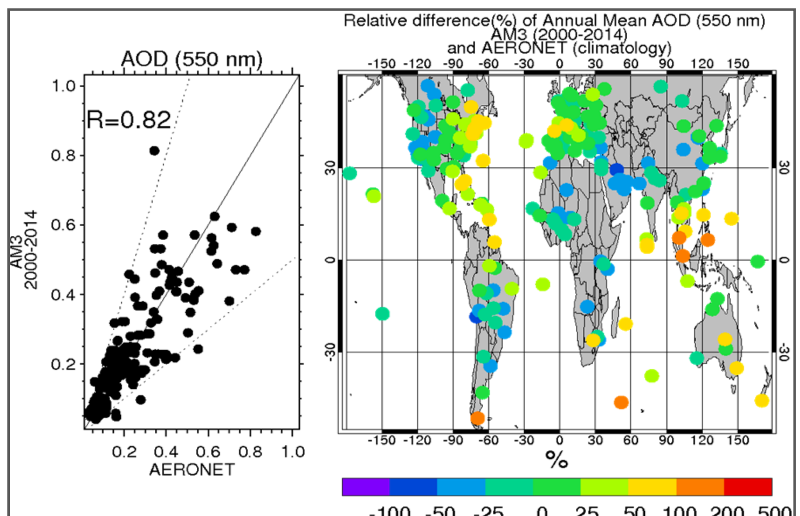


Color: percent error compared to AERONET

AM2.1-vs-OBS correlation=0.72

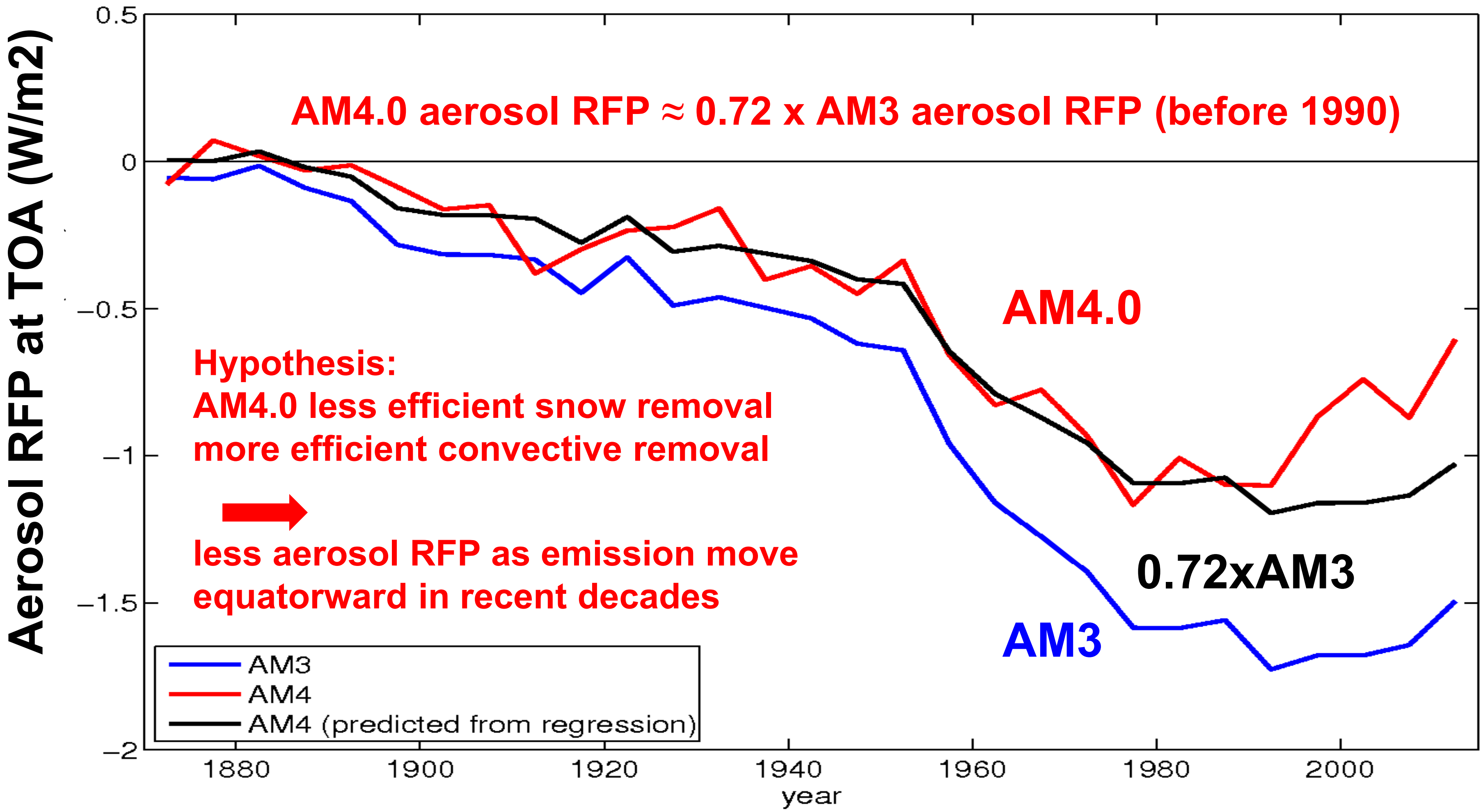


AM3-vs-OBS correlation=0.82



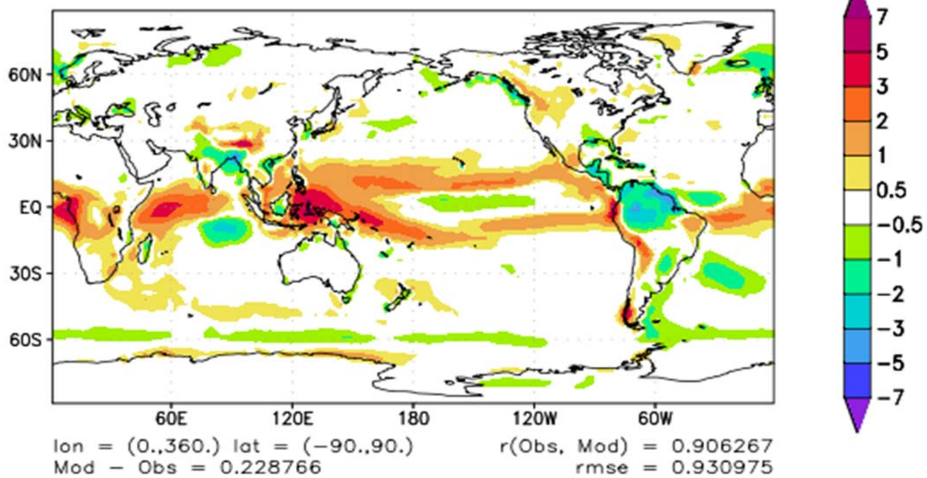
AM4 reduces aerosol RFP compared to AM3 and this should help the coupled model simulation of historical SST

Aerosol RFP(t) = F{GHG(PI),Aero(t),…,SST(t)} – F{GHG(PI),Aero(PI),…,SST(t)}

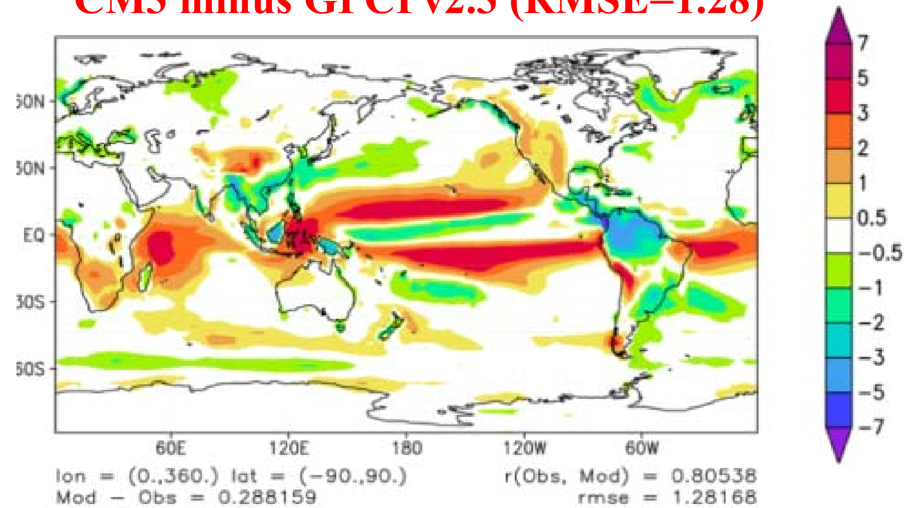


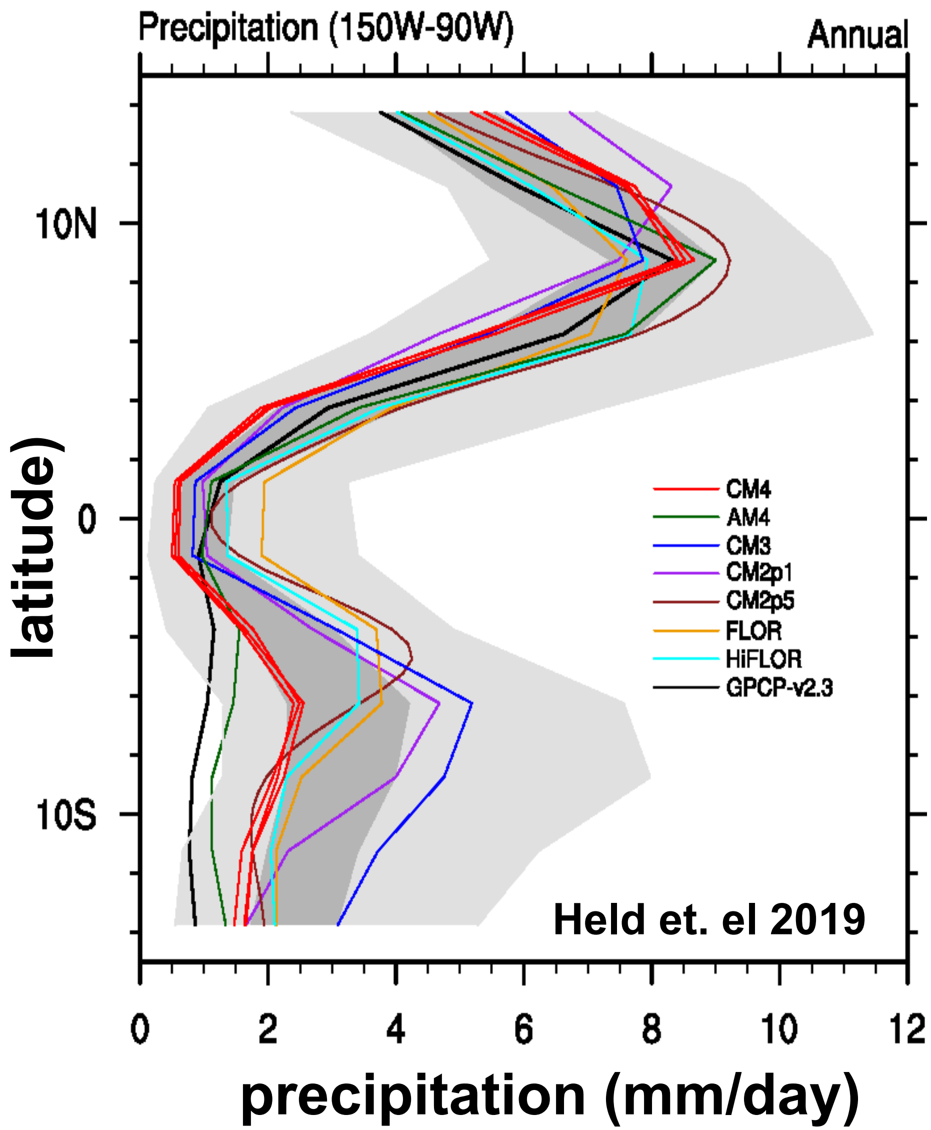
CM4 produces much reduced double ITCZ bias compared to previous GFDL models and most CMIP5 models

CM4 minus GPCPv2.3 (RMSE=0.93)

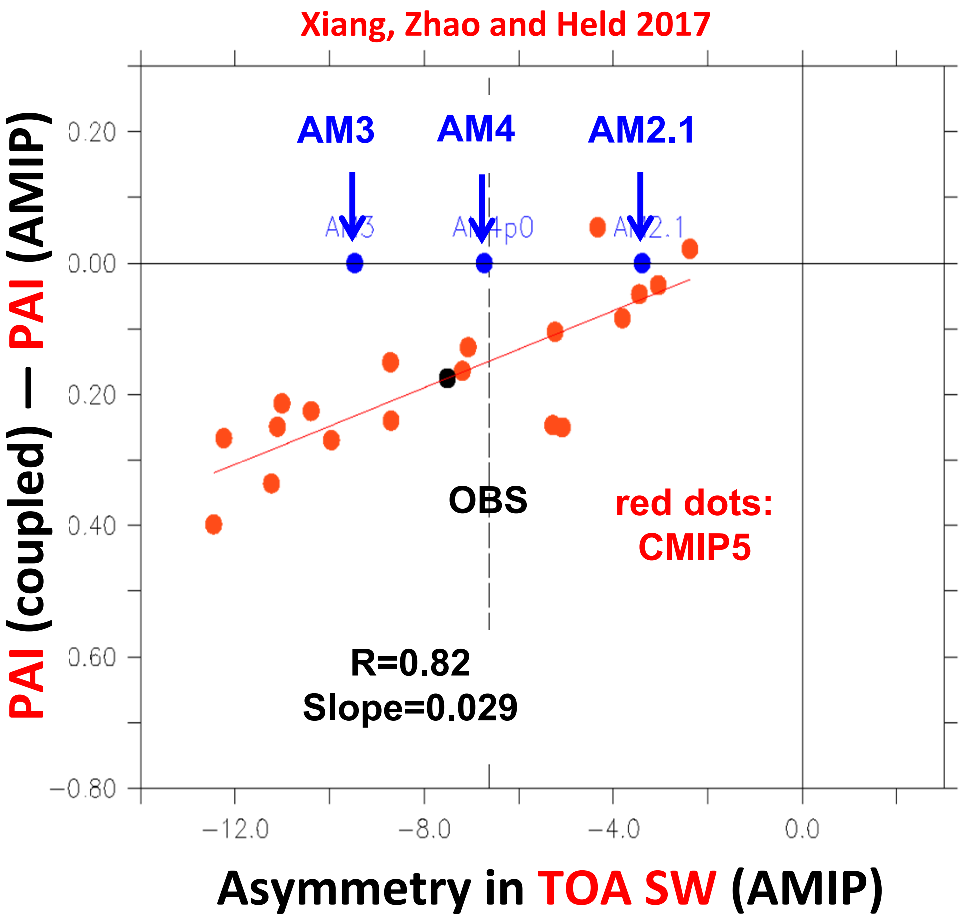


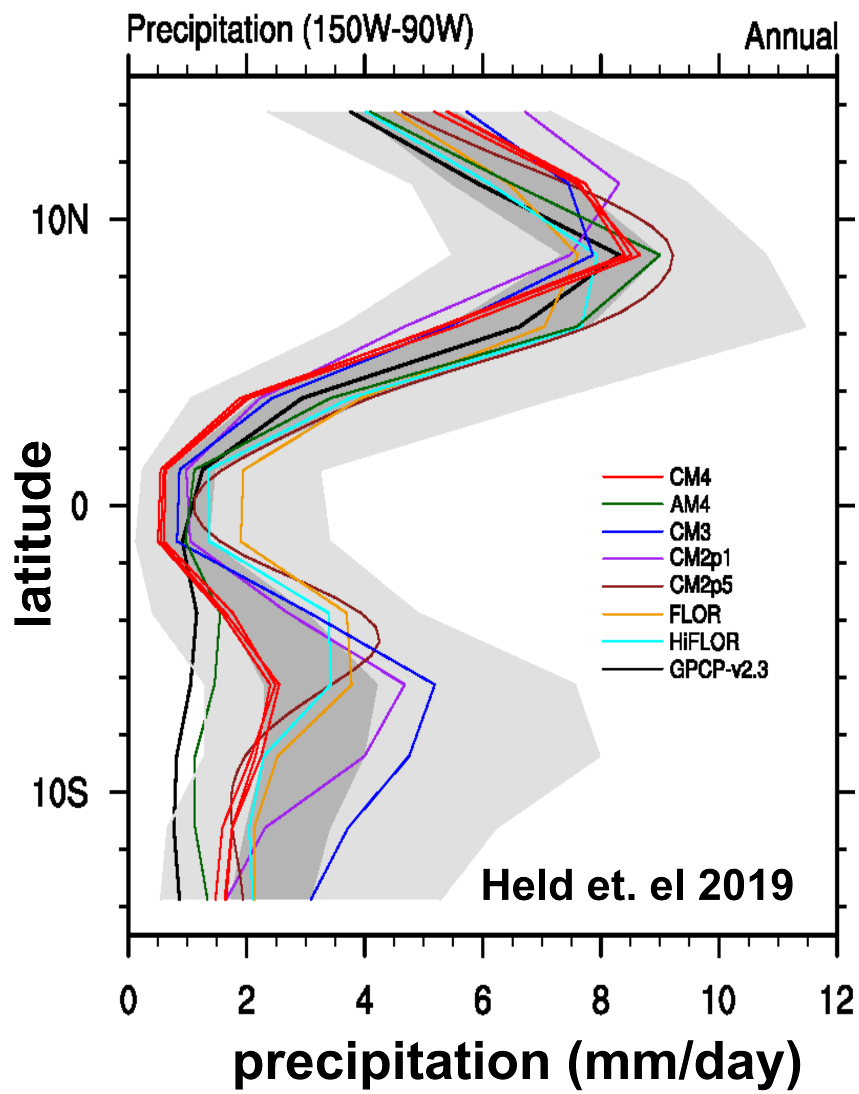
CM3 minus GPCPv2.3 (RMSE=1.28)





AM4 reduces the coupled model double ITCZ problem comparison with previous GFDL models and CMIP5 models





$$PAI = \frac{P_{NHTropic} - P_{SHTropic}}{P_{Tropic}} \qquad RAI = SW_{TOANHTropi} - SW_{TOASHTropi}$$