Challenges of predicting rainfall changes under global warming: back to fundamentals

J. David Neelin[1]

K. Hales[1], B. Langenbrunner[1], J. E. Meyerson[1], S. Sahany[1], B. Lintner[2], R. Neale[5], O. Peters[4], C. E. Holloway[3], M. Munnich[6], H. Su[7], C. Chou[8], J. McWilliams[1], A. Bracco[9], H. Luo[9]

- **Examples and issues with precipitation simulation: global warming, El Niño…**
- **Parameter sensitivity/optimization---implications**
- **The onset of strong convection: constraining climate model representations**
- **Outlook**

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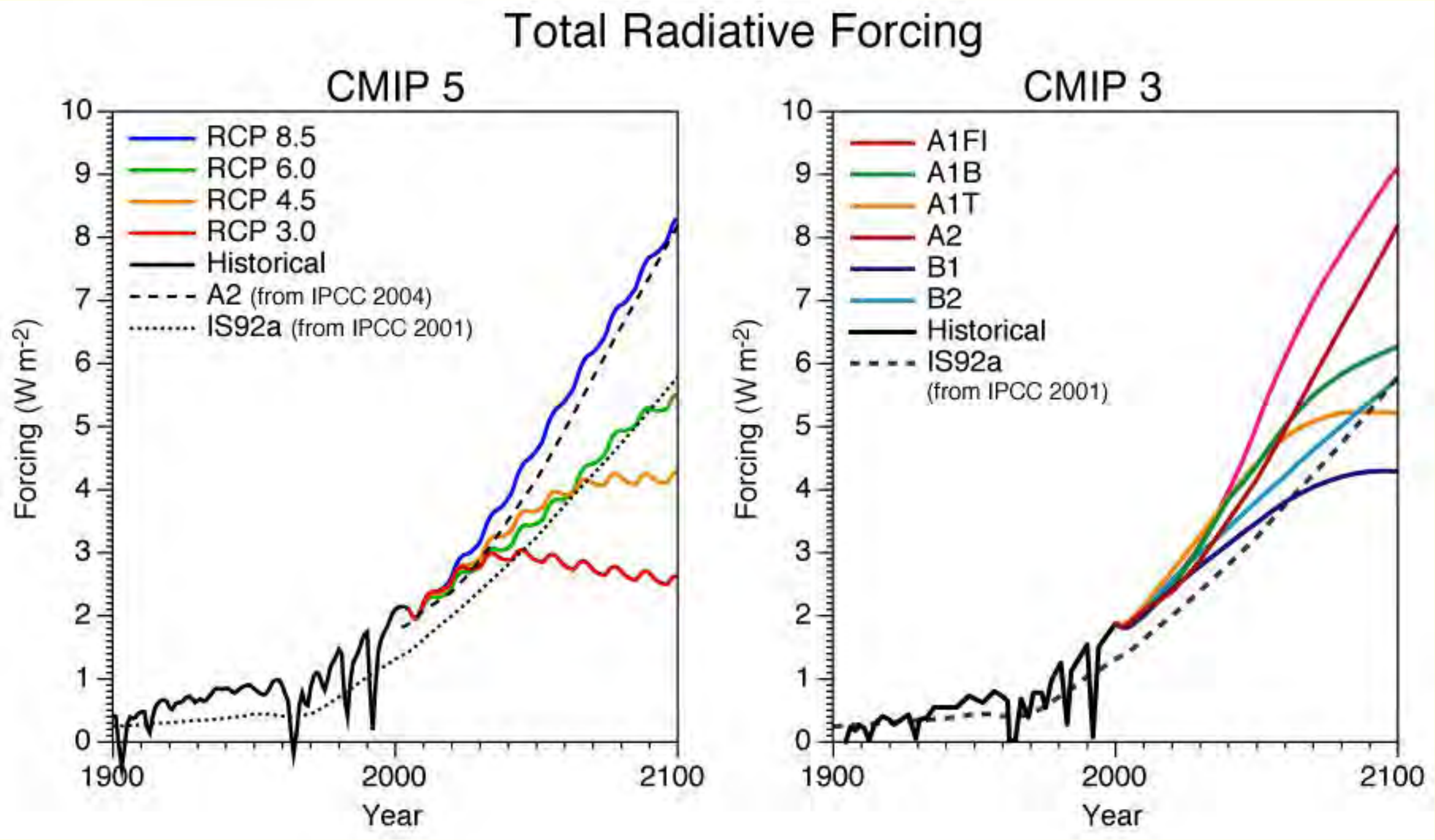
Global warming scenarios: IPCC* 2007 & ~2013



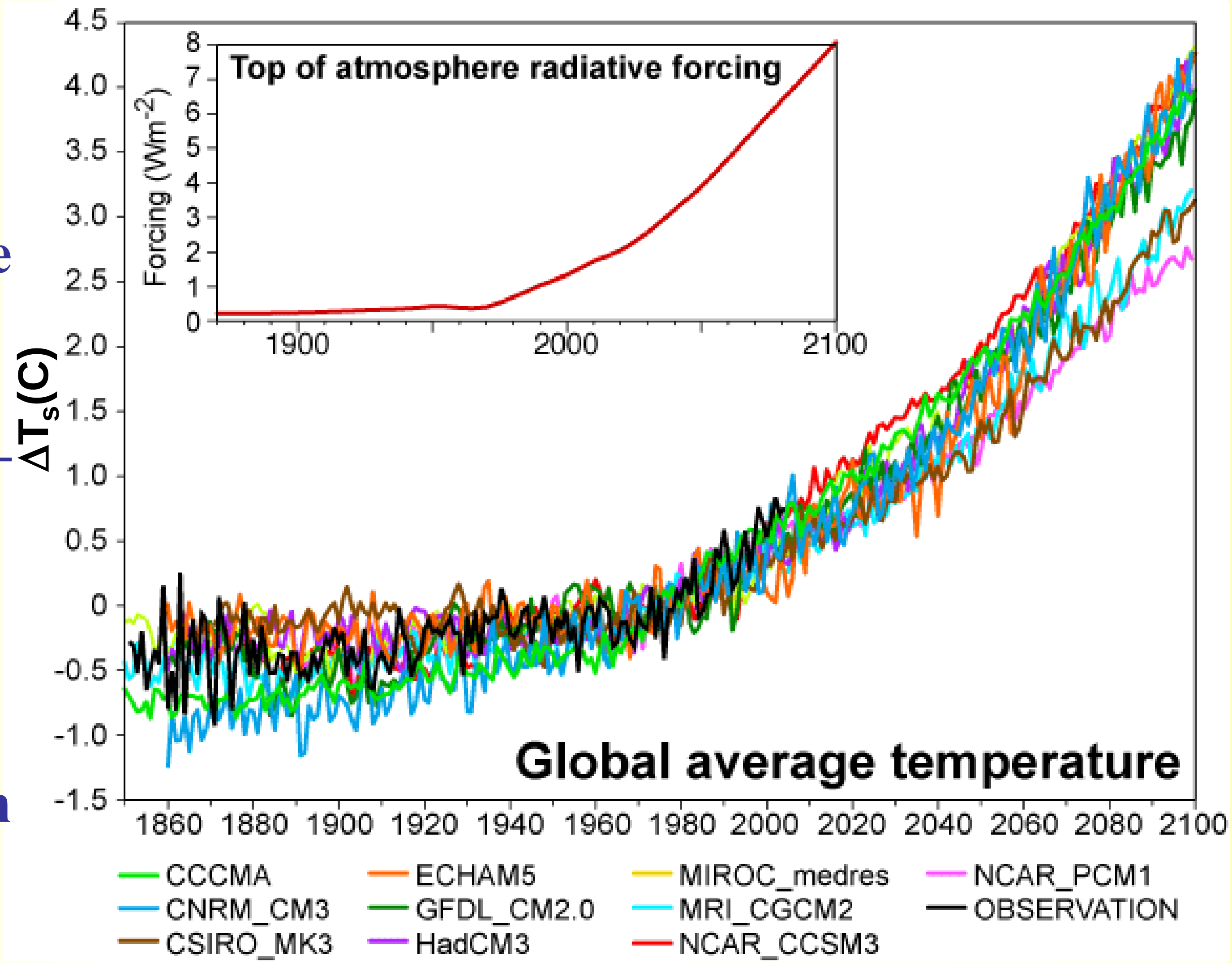
Inputs for Coupled Model Inter-Comparison Project (CMIP) 3 & 5 for *Intergovernmental Panel on Climate Change Assessment Reports 4 & 5

Historical period est. observed greenhouse gas + aerosol forcing, followed by "Representative Concentration Pathway" (RCP)

Global warming as simulated in climate models ~2007

- Global avg. sfc. air temp. change (ann. means rel. to 1901-1960 base period)

- Greenhouse gas + aerosol forcing: Est. observed, followed by SRES A2* scenario (inset) in 21st century

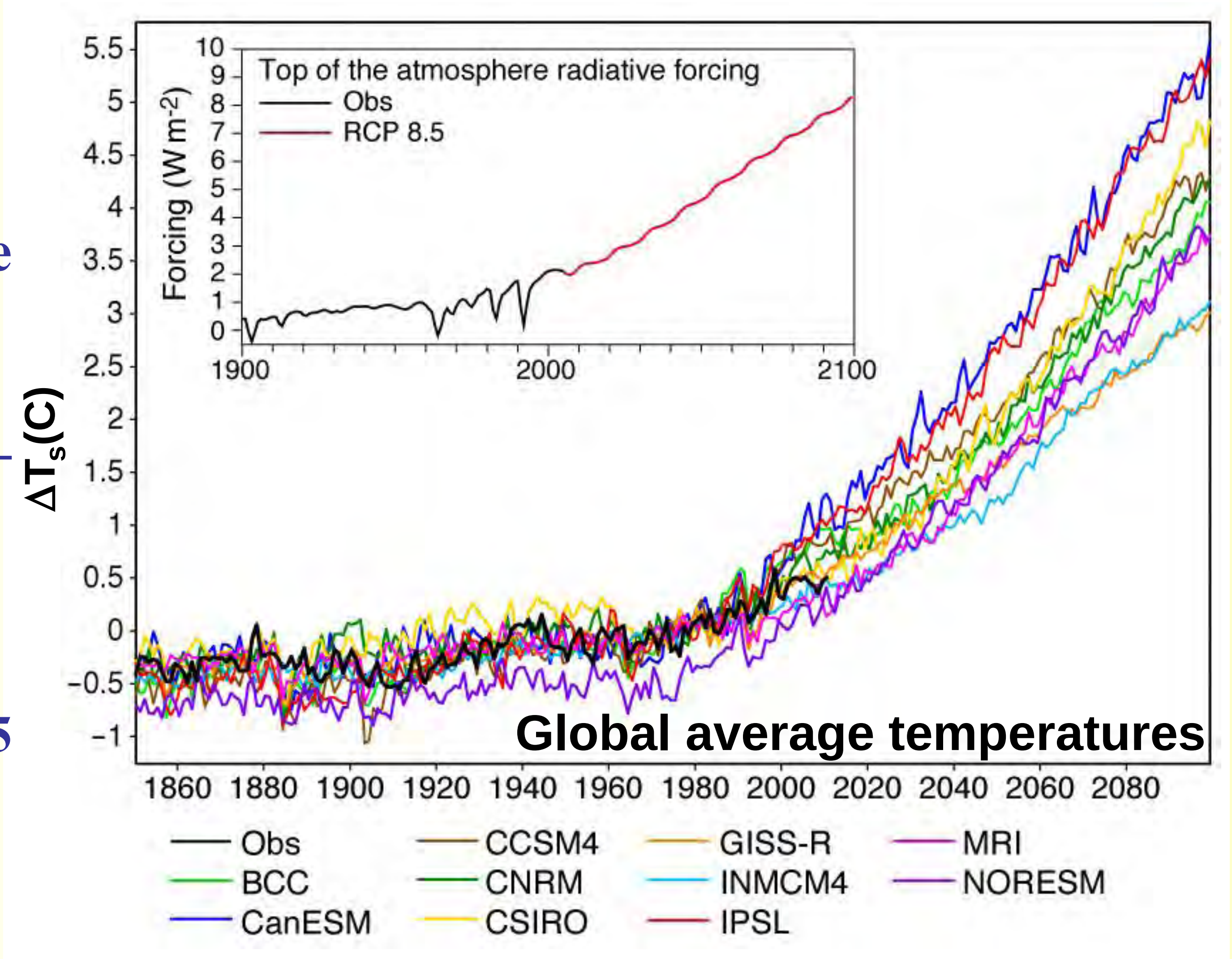


*SRES: Special Report on Emissions Scenarios

A2: uneven regional economic growth, high income toward non-fossil, population 15 billion in 2100; similar to an earlier "business-as-usual" scenario "IS92a"

Global warming as simulated in climate models CMIP5

- Global avg. sfc. air temp. change (ann. means rel. to 1961-1990 base period)
- Greenhouse gas + aerosol forcing: Est. observed followed by RCP8.5 from 2005



*Representative Concentration Pathway specified: not full Earth System Model, i.e., carbon cycle feedbacks etc. not active in runs shown here

Surface air temperature change for three models* 2080-2099 annual avg.

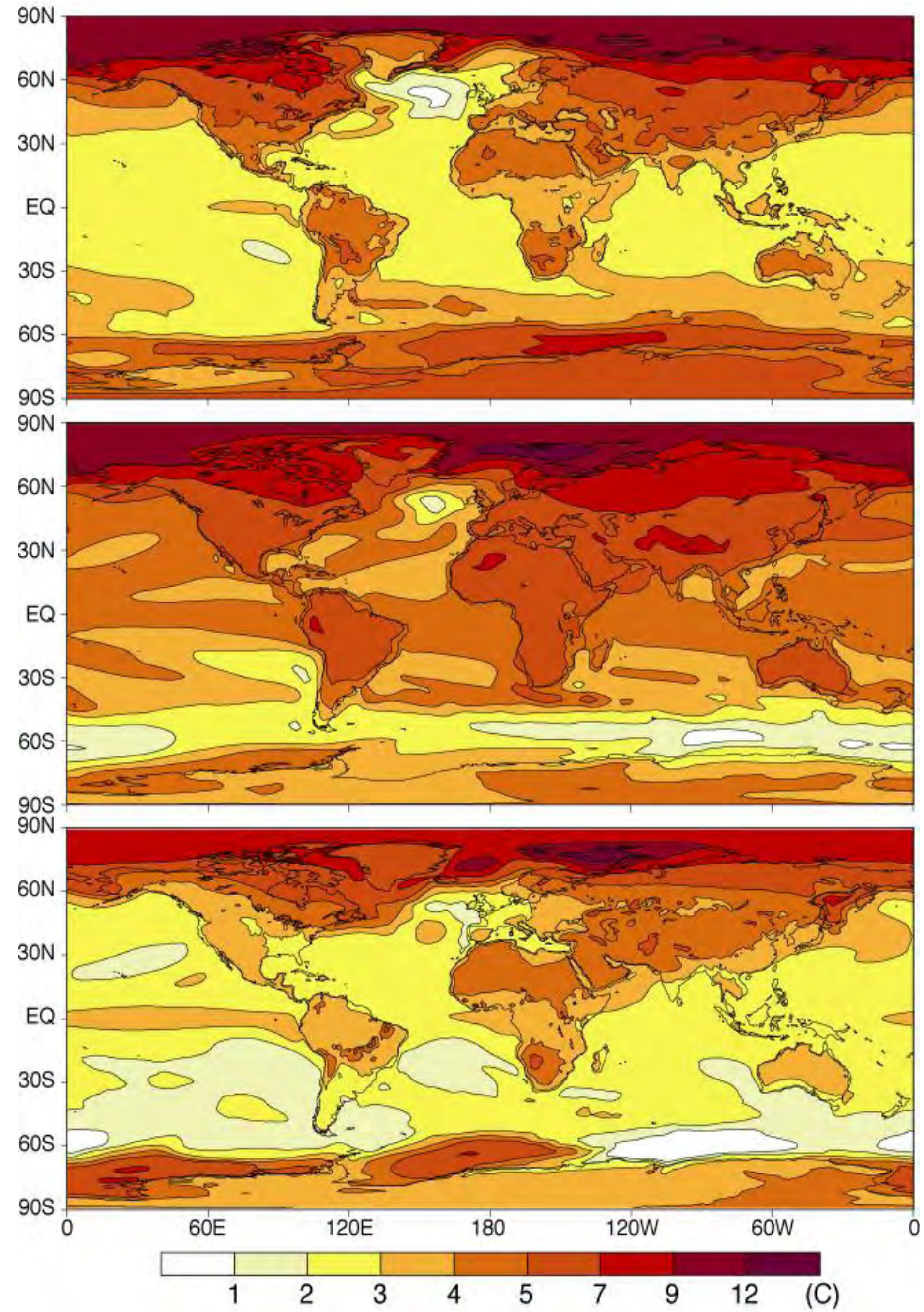
(rel. to 1961-90)

CMIP5

NCAR-CCSM4

IPSL-CM5A-R

MRI-CGCM3



***Unexplained acronyms denote climate model names**

Examples and issues with precipitation simulation: global warming, El Niño…

- **Severe problems with model disagreement on precipitation change at regional/seasonal scales, markedly so in tropics**
- **some agreement on large-scale or amplitude**
- **Poor simulation of El Niño remote precipitation anomalies**
- **Sensitivity to differences in model parameterizations**
- **Teleconnections of errors in other parts of the climate system to influence edges of convection zones/storm tracks**

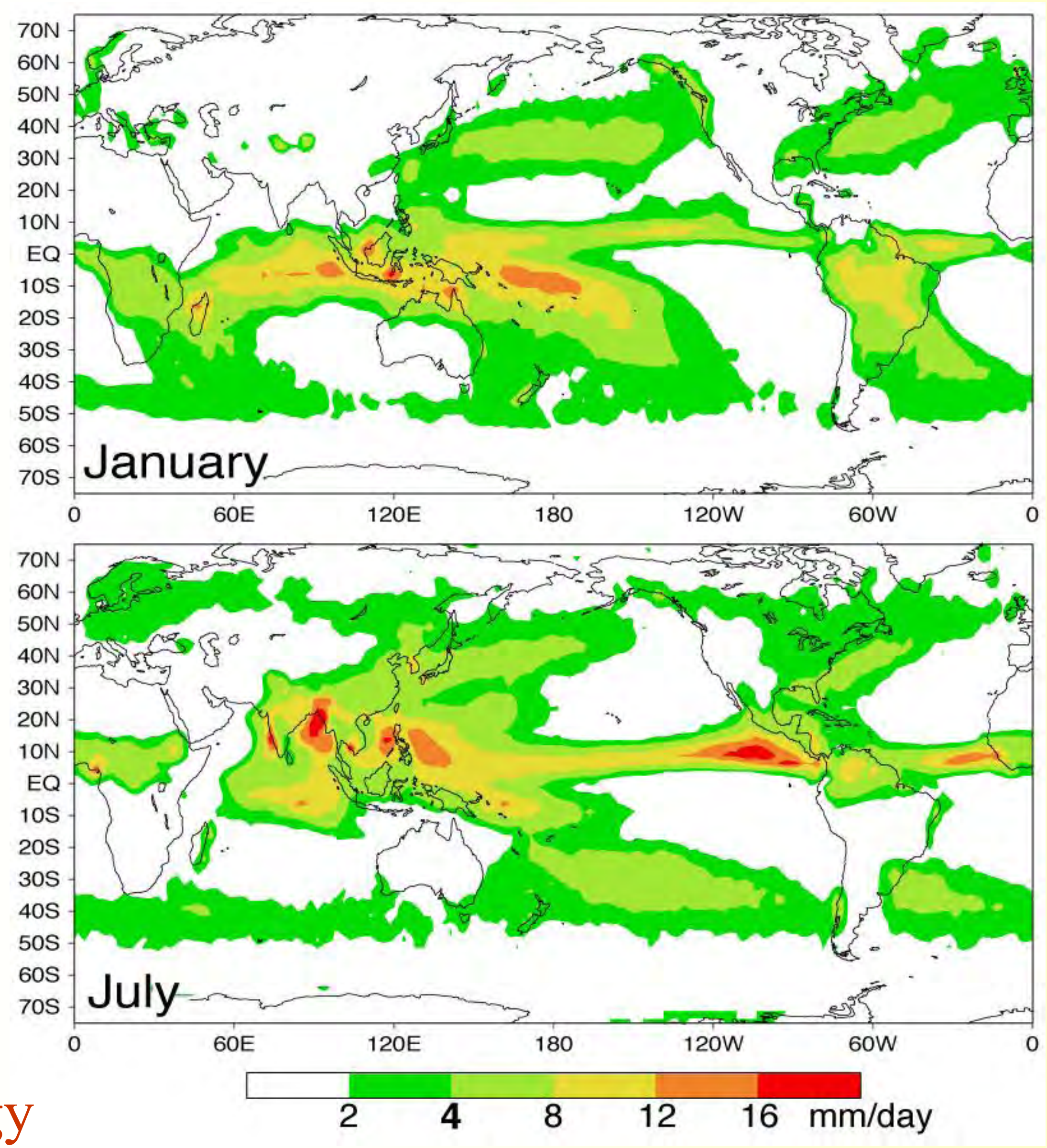
e.g., IPCC 2001, 2007; Wetherald & Manabe 2002; Trenberth et al 2003; Neelin et al. 2003; Maloney and Hartmann 2001; Joseph and Nigam 2006; Biasutti et al. 2006; Dai 2006; Tost et al. 2006; Bretherton 2007, Frierson, ...

Precipitation: climatology (CMAP*: 1979-2008)

January

Note intense tropical moist convection zones (intertropical convergence zones)

July



Later: **4** mm/day contour as indicator of precip. climatology

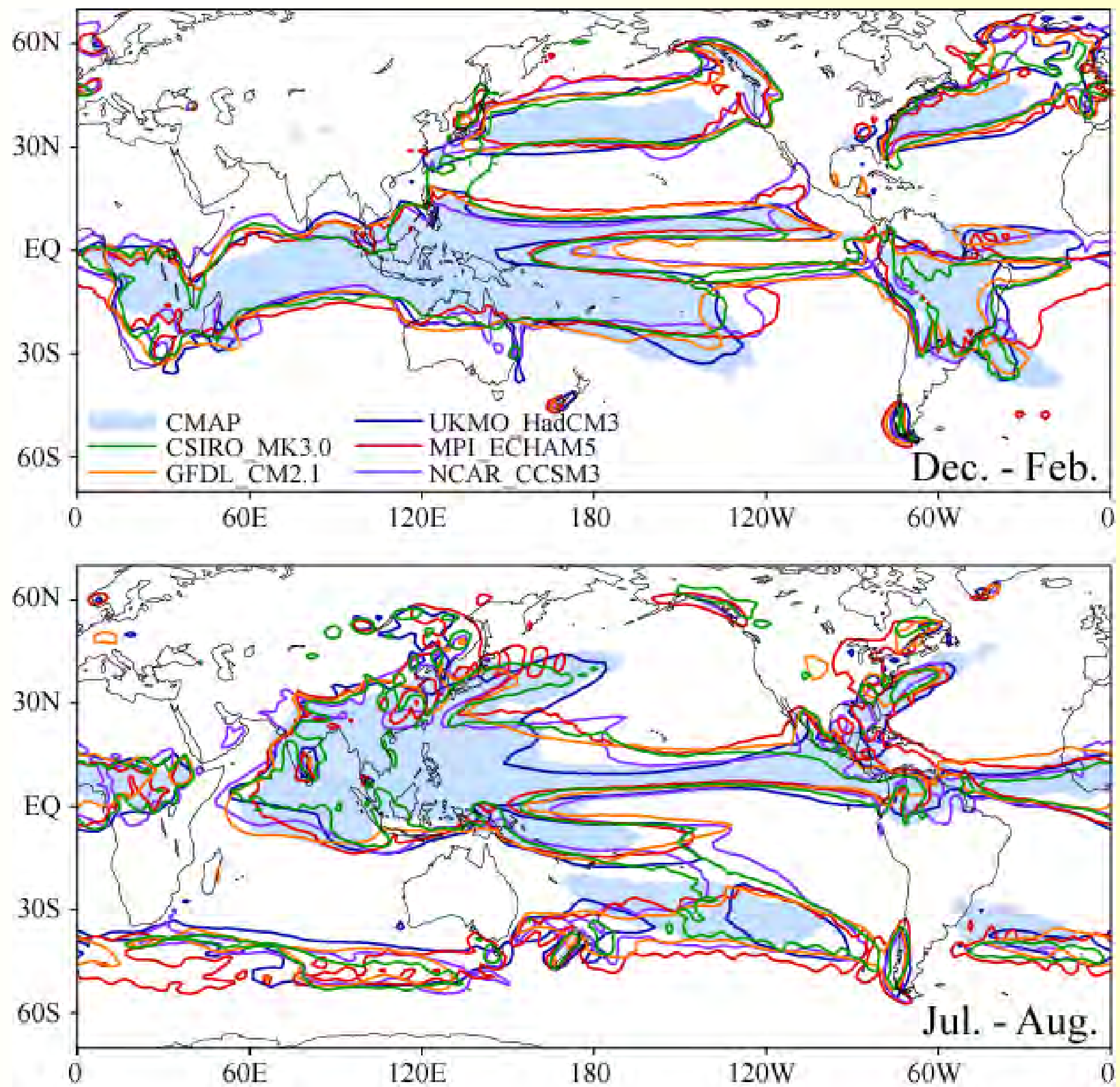
*CPC Merged Analysis of Precipitation (CMAP)

Observed (CMAP) and CMIP3 coupled models 4 mm/day precip. contour

Coupled simulation climatology (20th century run, 1979-2000)

December-February precipitation climatology

June - August precipitation climatology



CPC Merged Analysis of Precipitation (CMAP)

Neelin, 2011, *Climate Change and Climate Modeling* Cambridge UP

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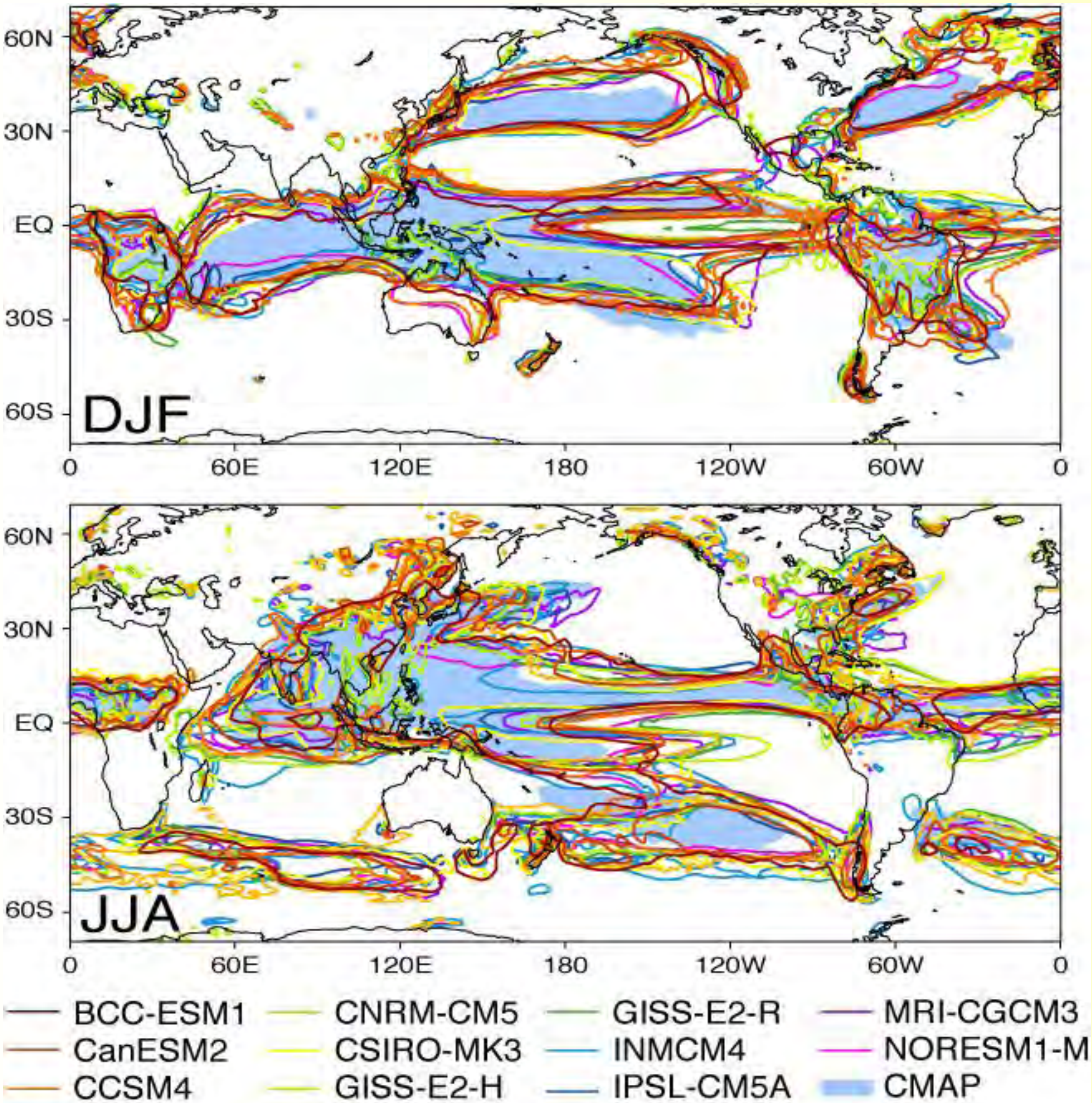


Coupled Model Intercomparison Project (CMIP5)

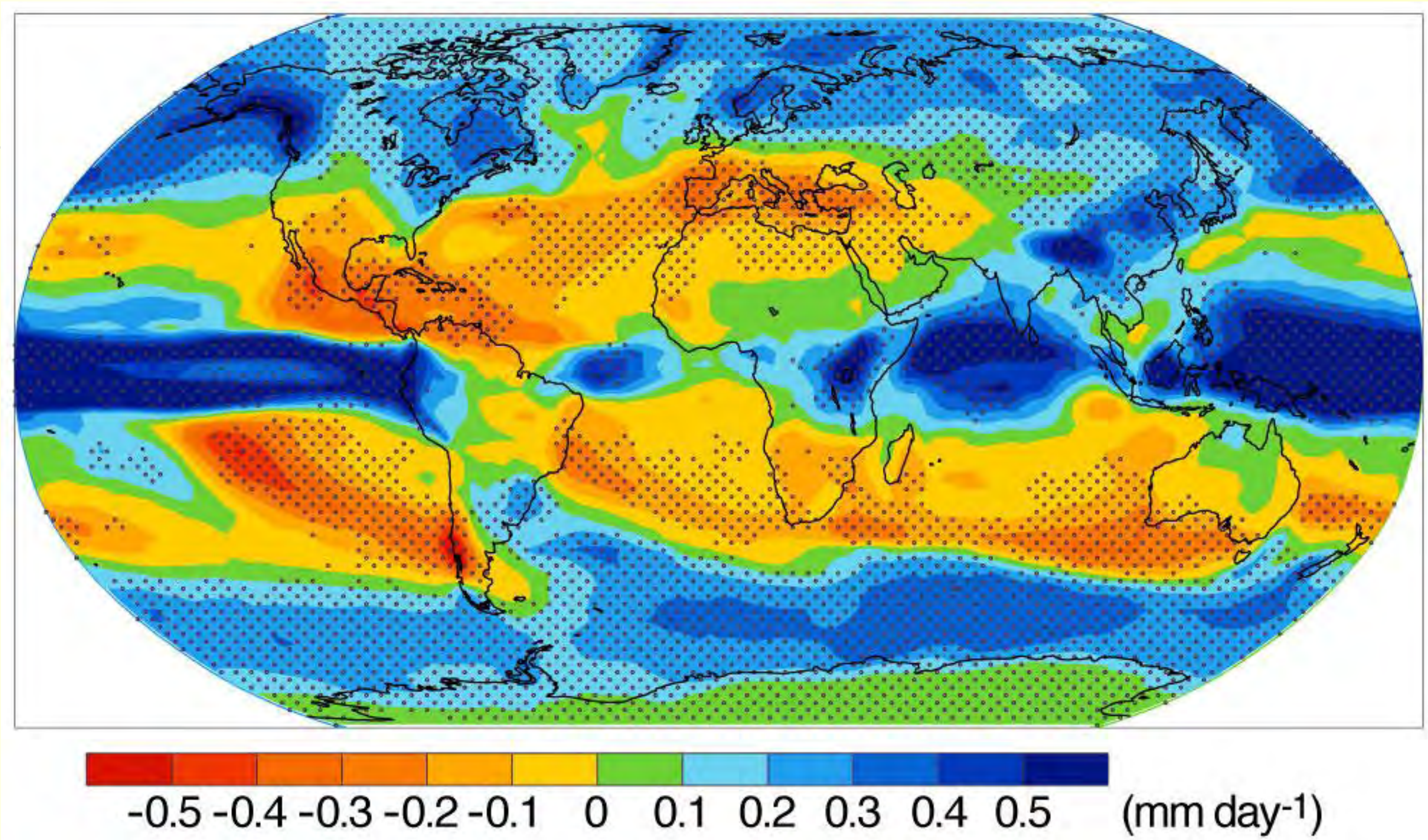
Analysis: J. Meyerson

IPCC 2007 multi-model, annual mean precipitation change (2080-2099 relative to 1980-1999)

High latitudes wetter

Subtropics dryer/expand

Deep tropics wetter



Stippled where 80% of the models agree on sign of the mean change. Note typical magnitudes <0.5mm/d.

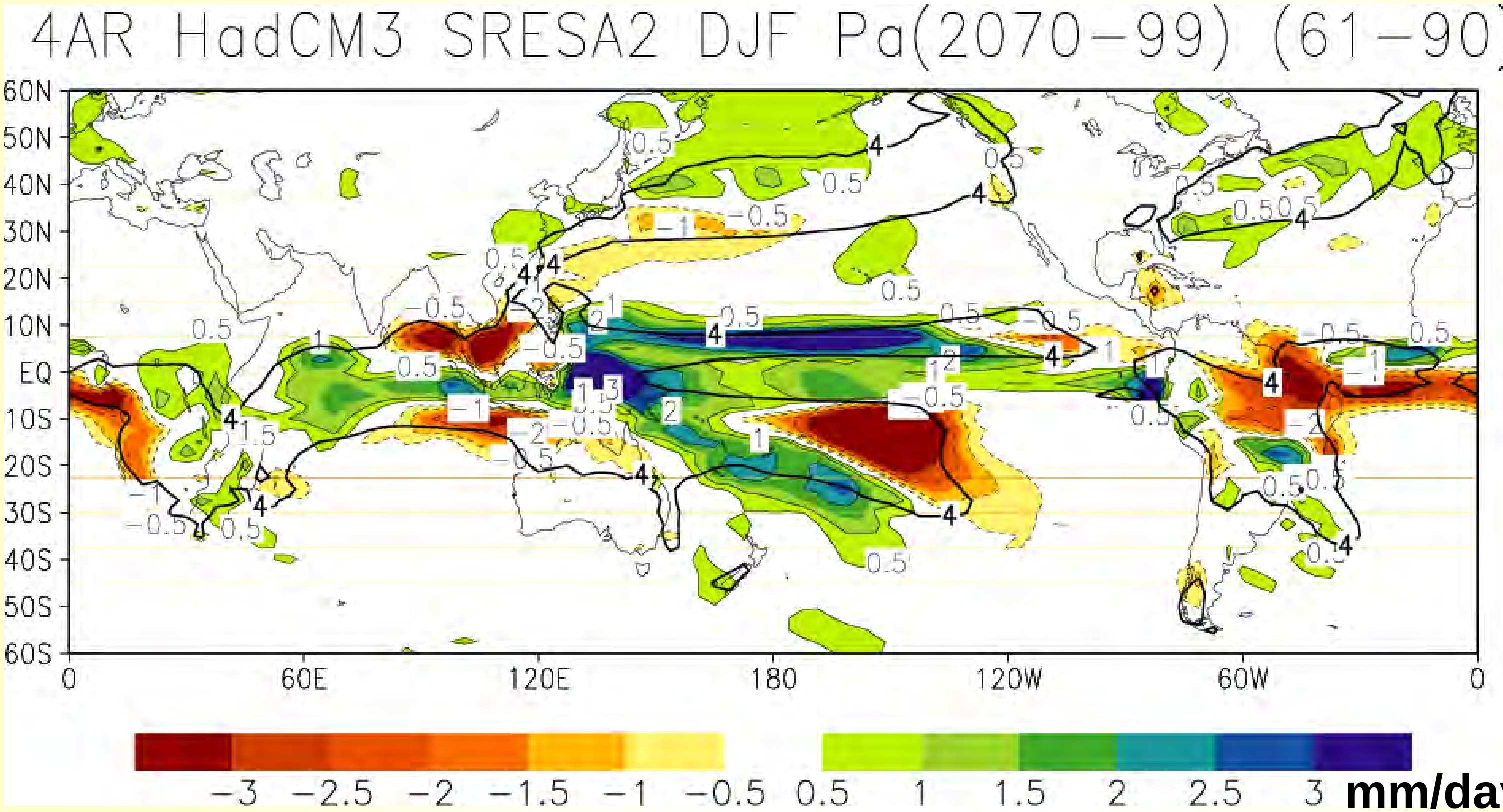
IPCC 4th Assessment Report (WG1 2007, chpt 10; A1B Scenario)

Fourth Assessment report models

- **Data archive at Lawrence Livermore National Labs, Program on Model Diagnostics and Intercomparison**
- **SRES A2 scenario (heterogeneous world, growing population,…) for greenhouse gases, aerosol forcing**

Neelin, Munnich, Su, Meyerson and Holloway , 2006, *PNAS*

Precipitation change: HadCM3, Dec.-Feb., 2070-2099 avg minus 1961-90 avg.



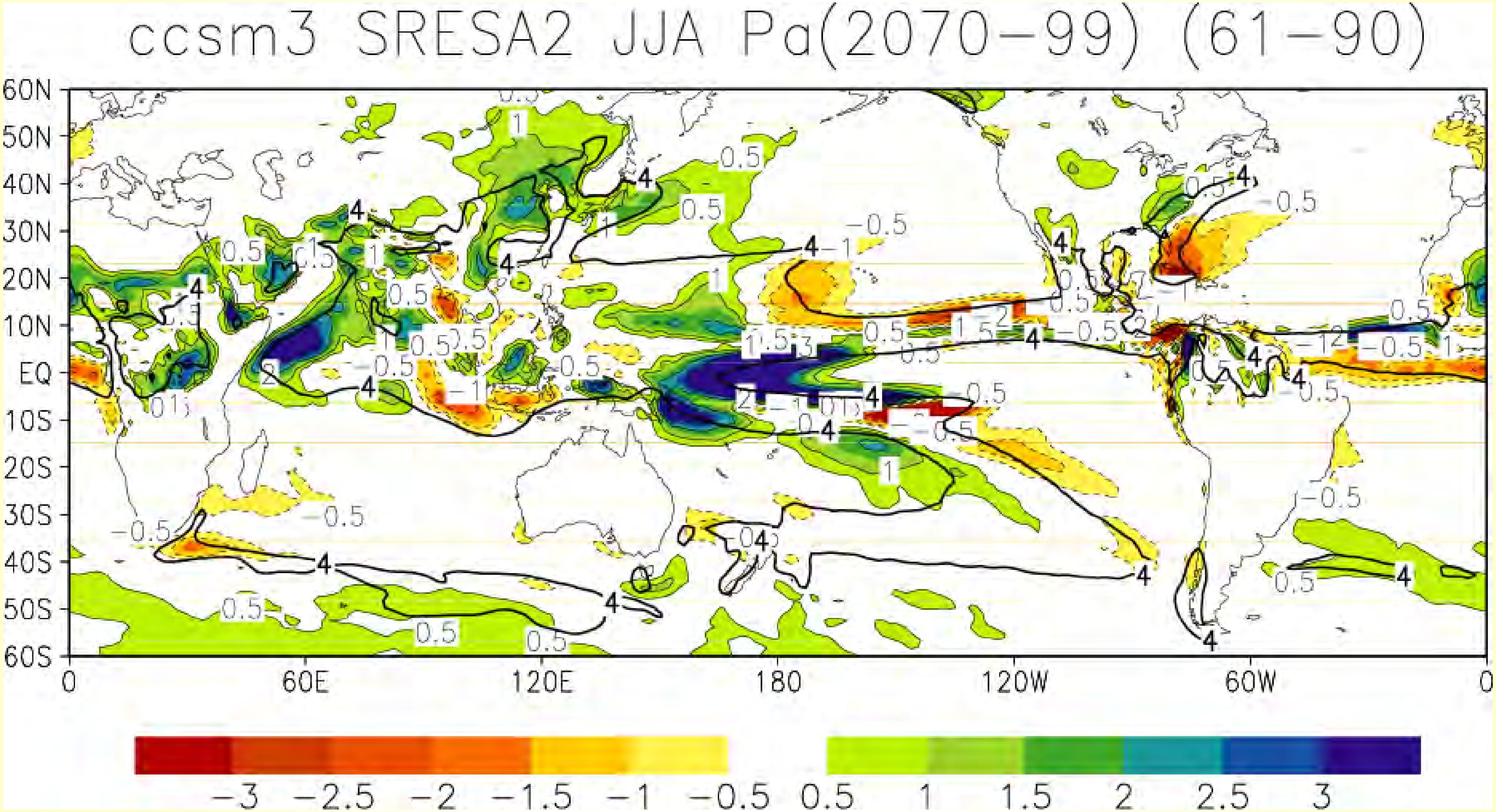
mm/day

4 mm/day model climatology black contour for reference

CMIP3

NCAR_CCSM3

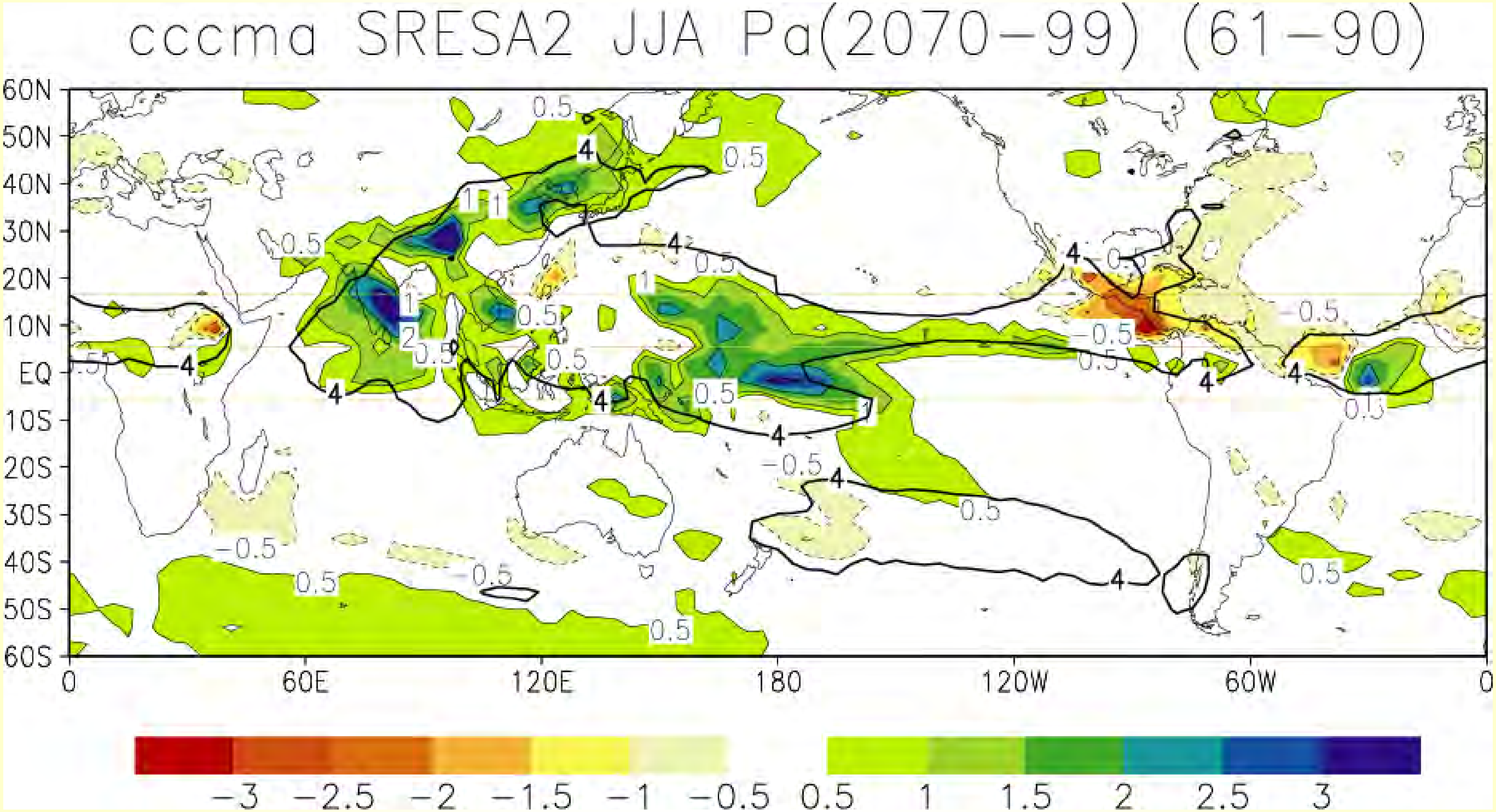
JJA Prec. Anom.



CMIP3

CCCMA

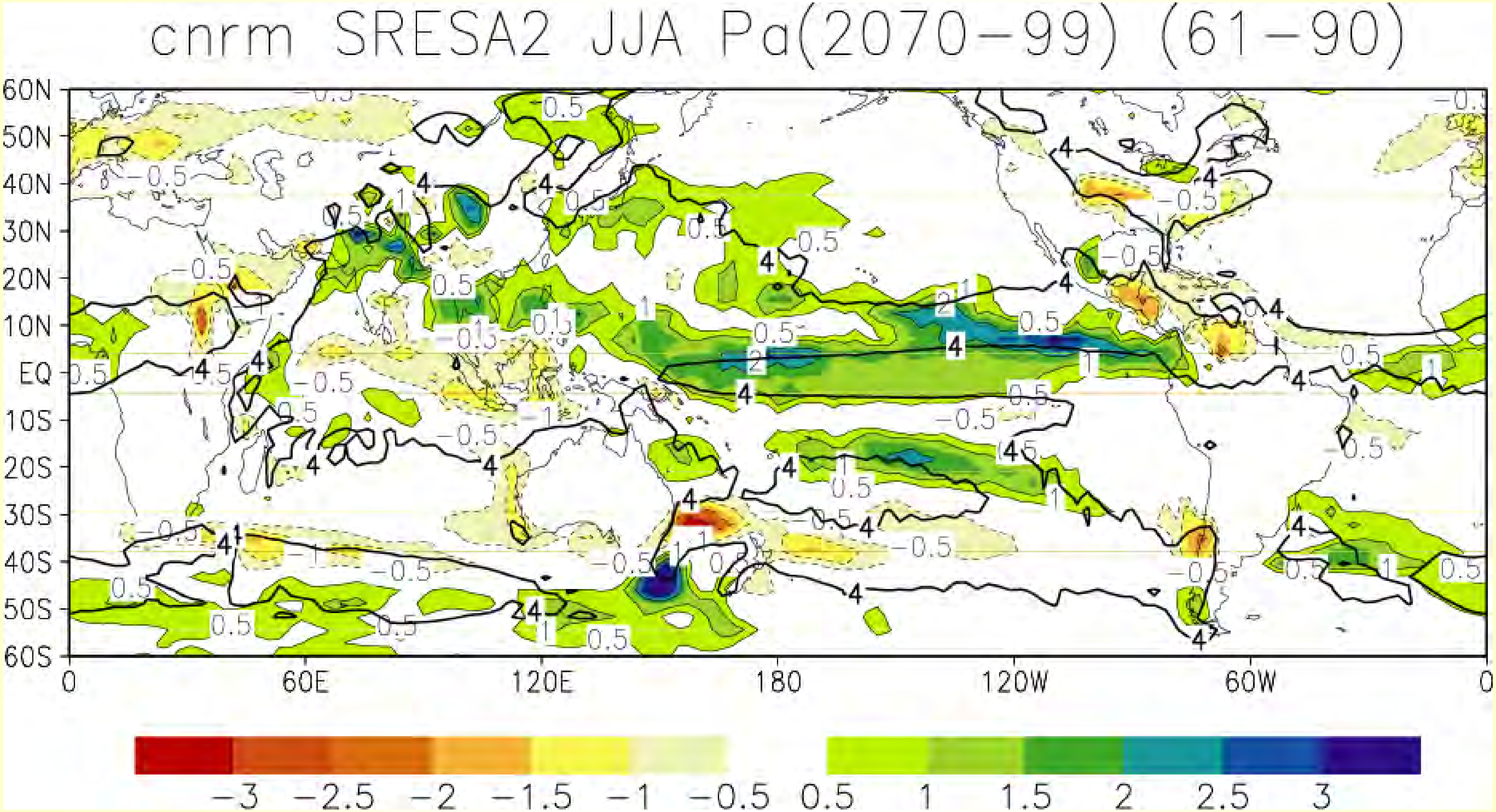
JJA Prec. Anom.



CMIP3

CNRM_CM3

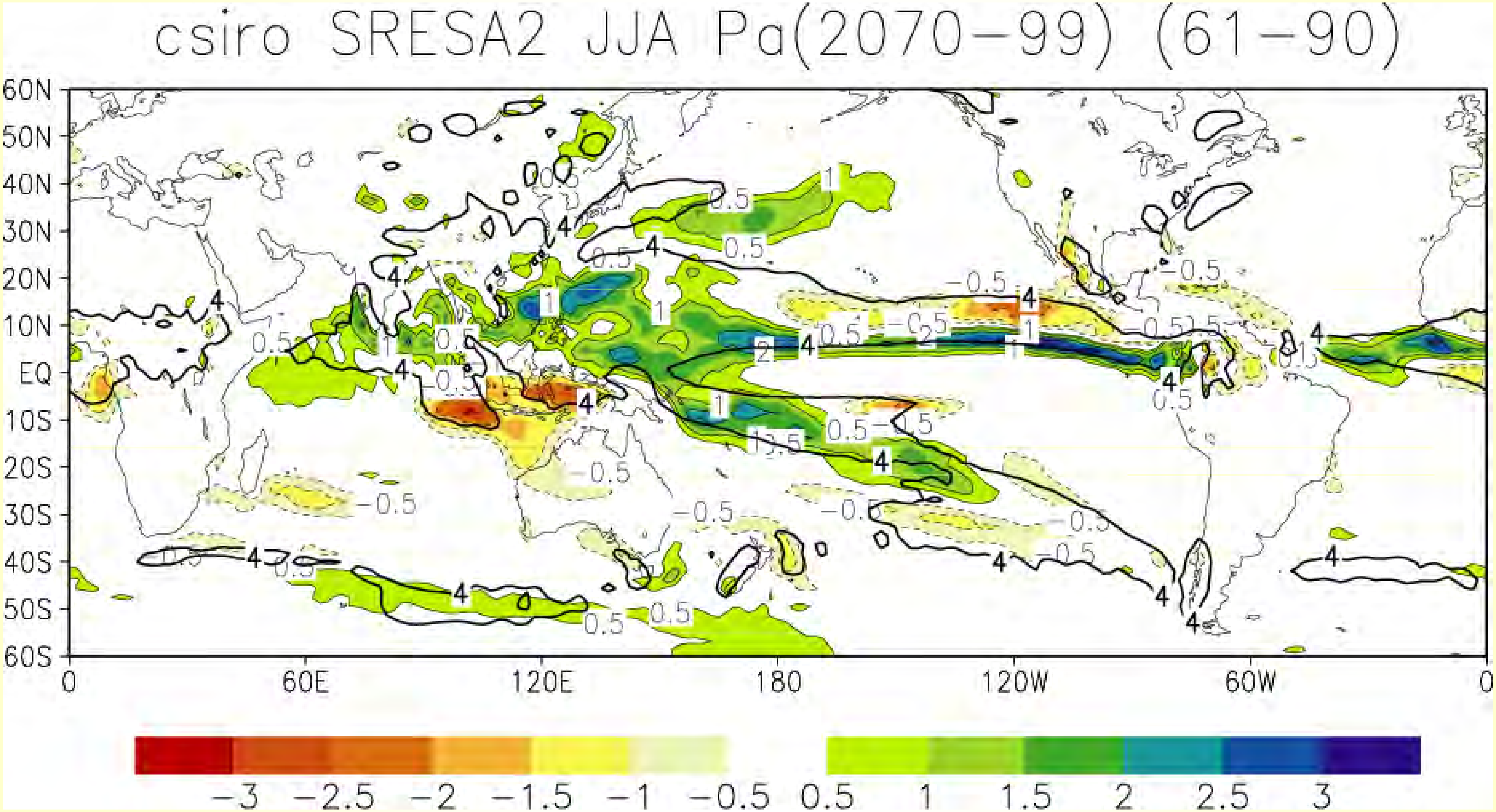
JJA Prec. Anom.



CMIP3

CSIRO_MK3

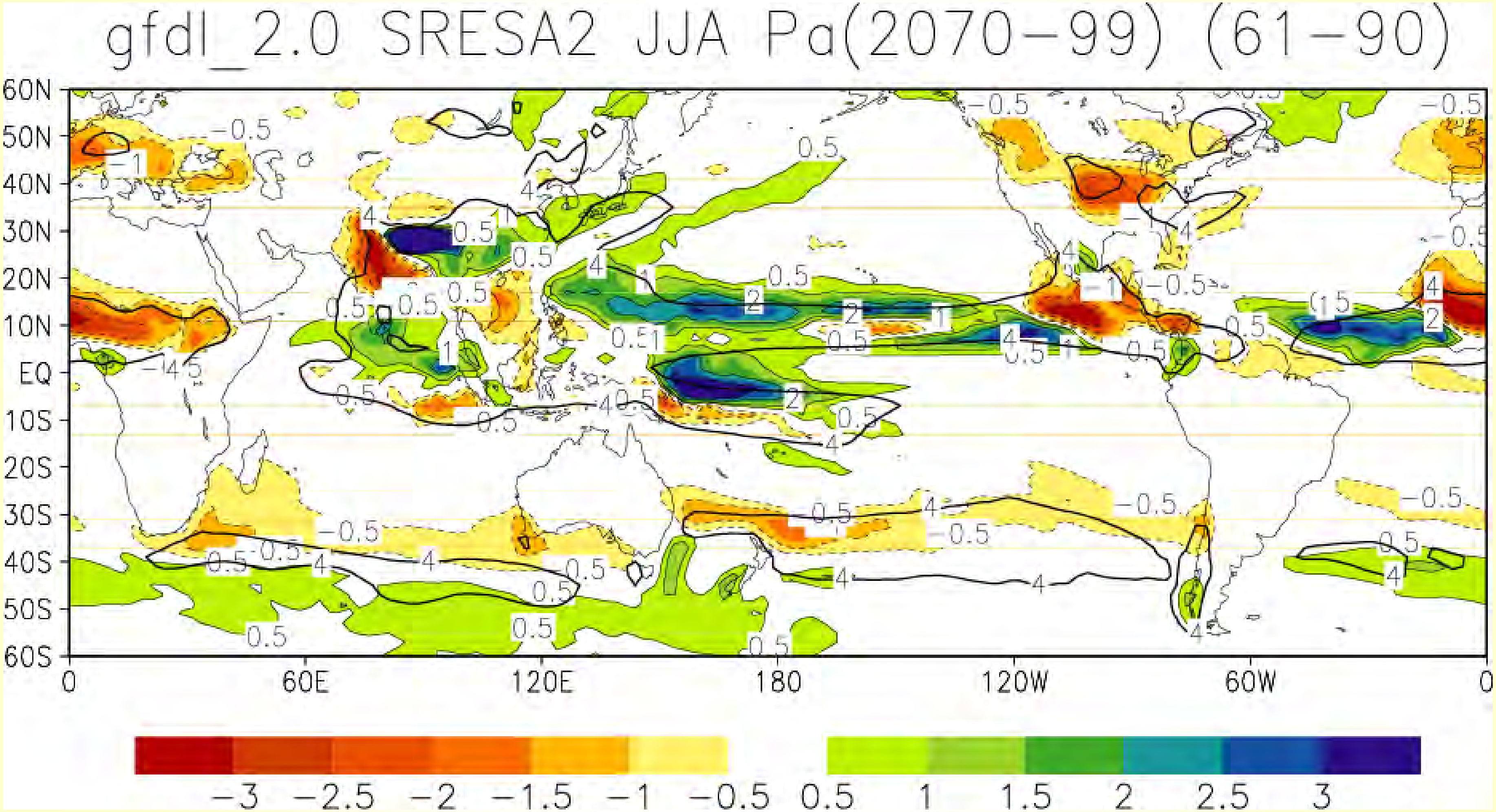
JJA Prec. Anom.



CMIP3

GFDL_CM2.0

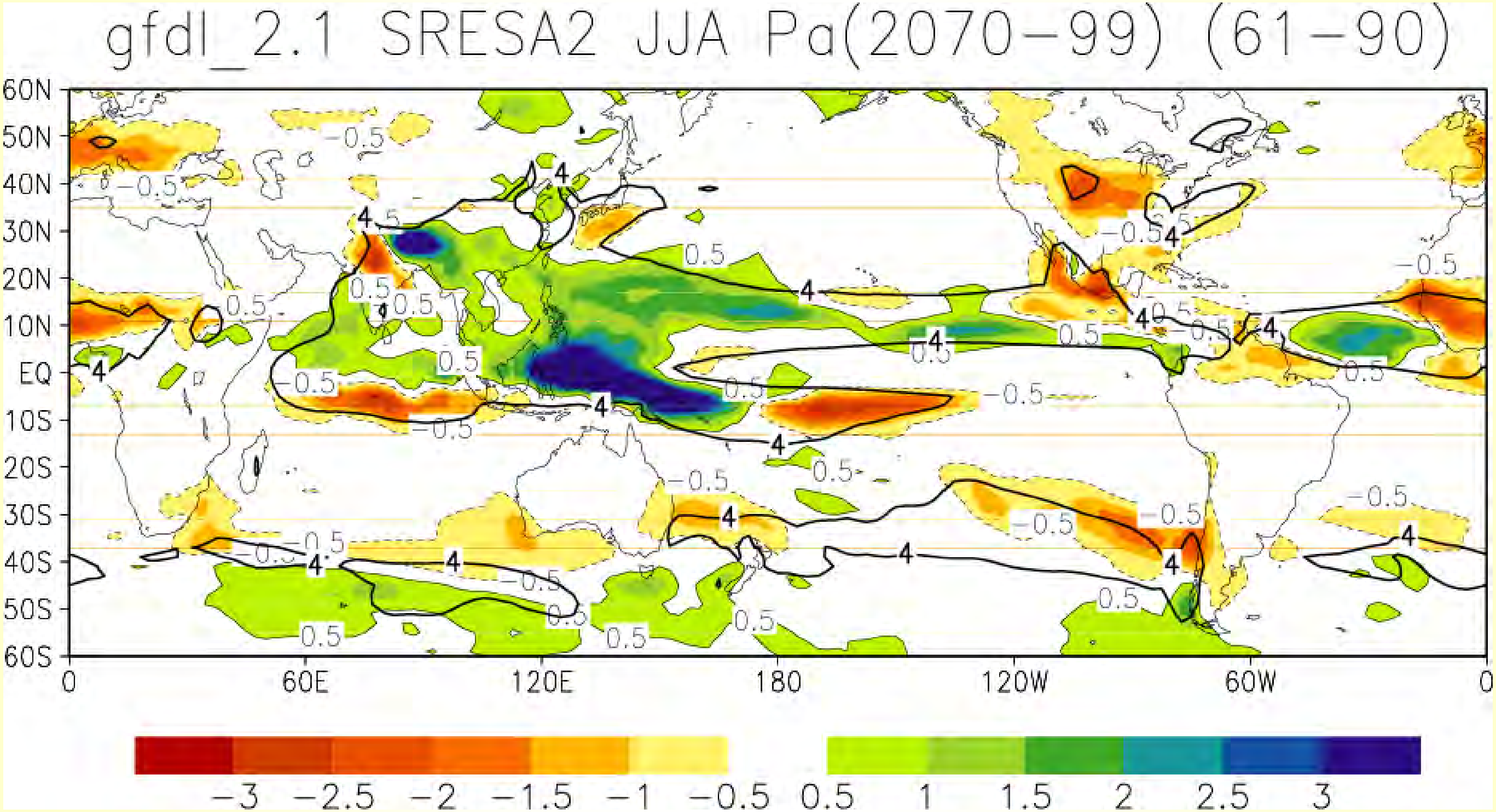
JJA Prec. Anom.



CMIP3

GFDL_CM2.1

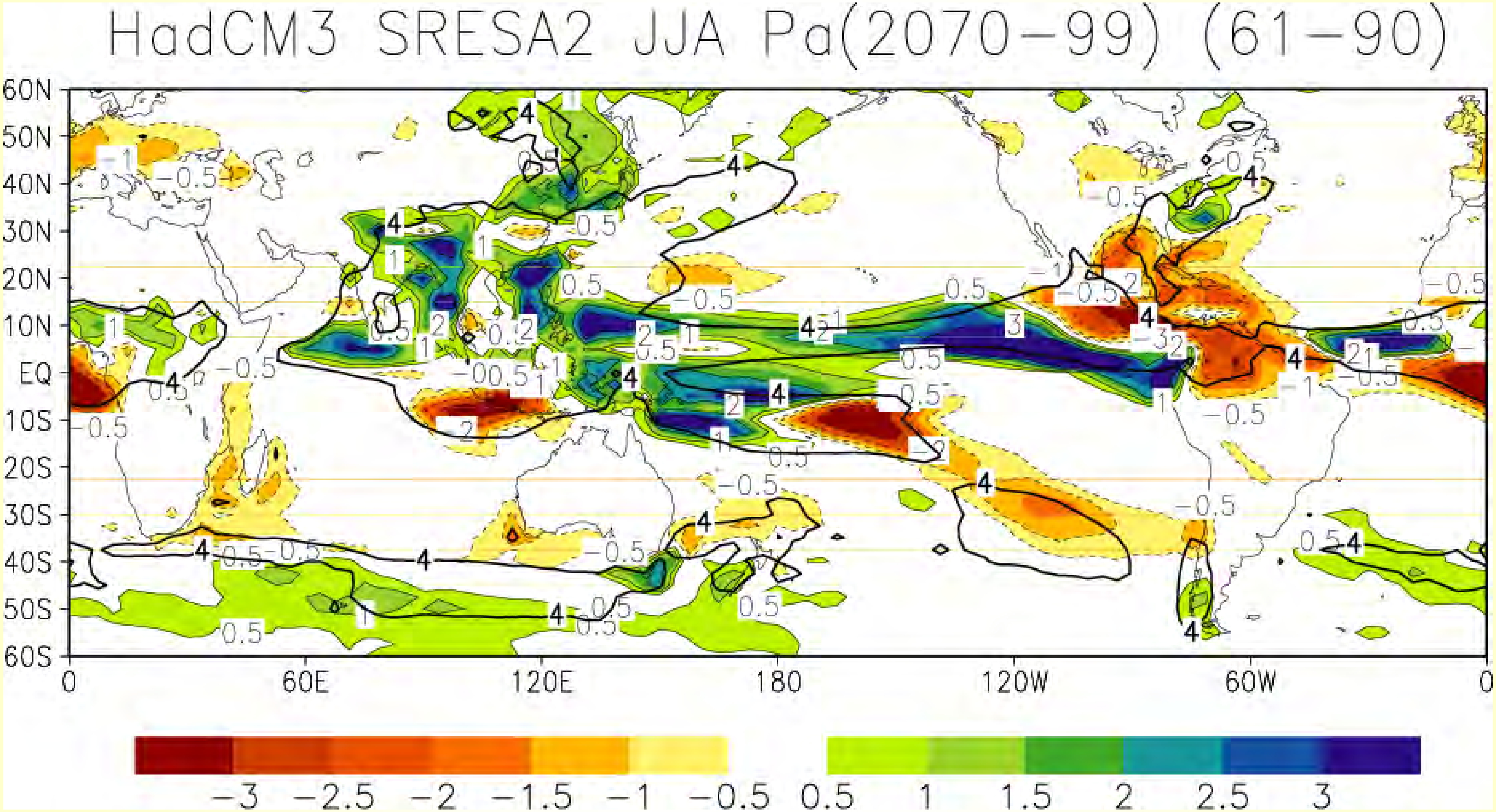
JJA Prec. Anom.



CMIP3

UKMO_HadCM3

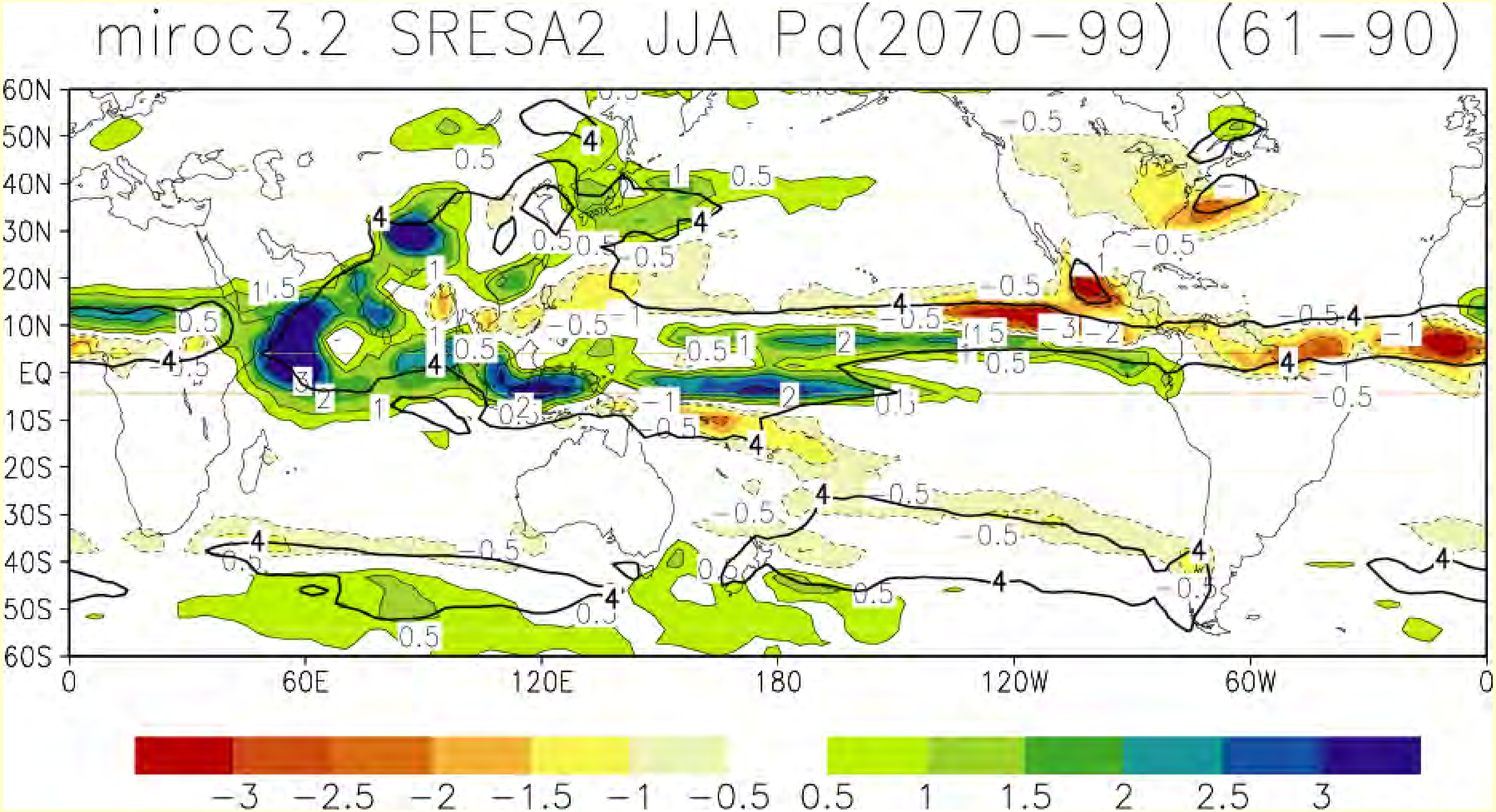
JJA Prec. Anom.



CMIP3

MIROC_3.2

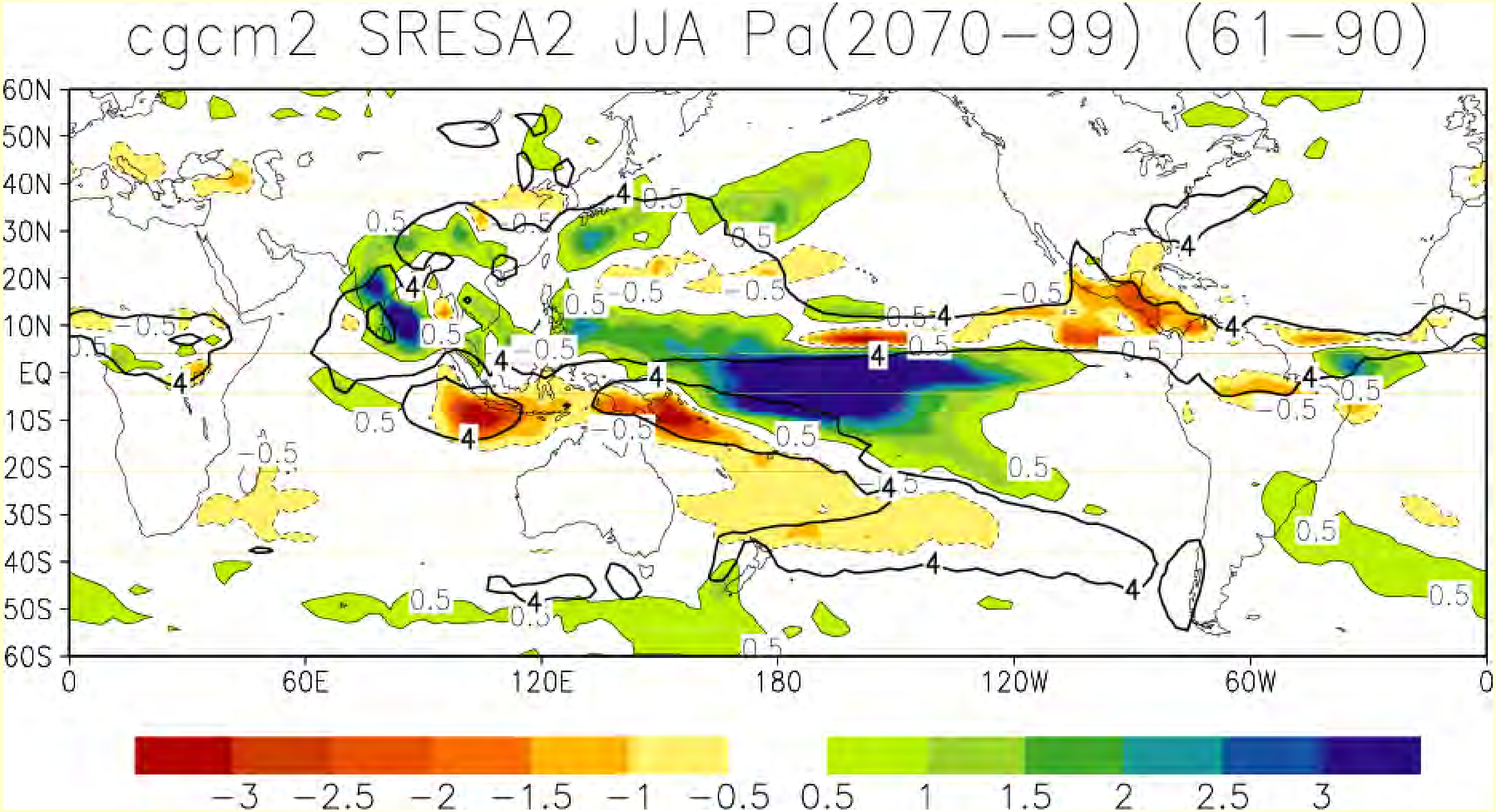
JJA Prec. Anom.



CMIP3

MRI_CGCM2

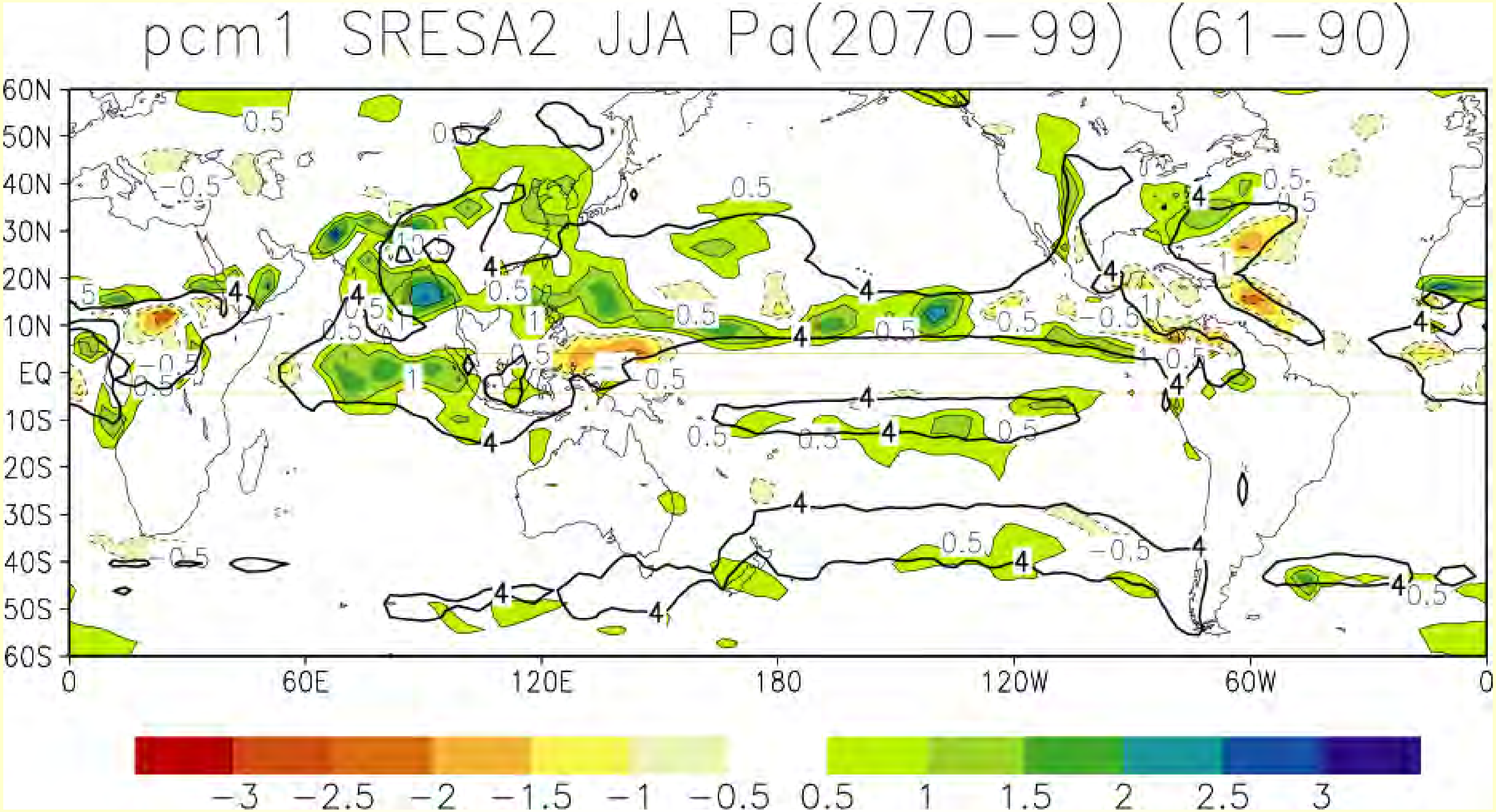
JJA Prec. Anom.



CMIP3

NCAR_PCM1

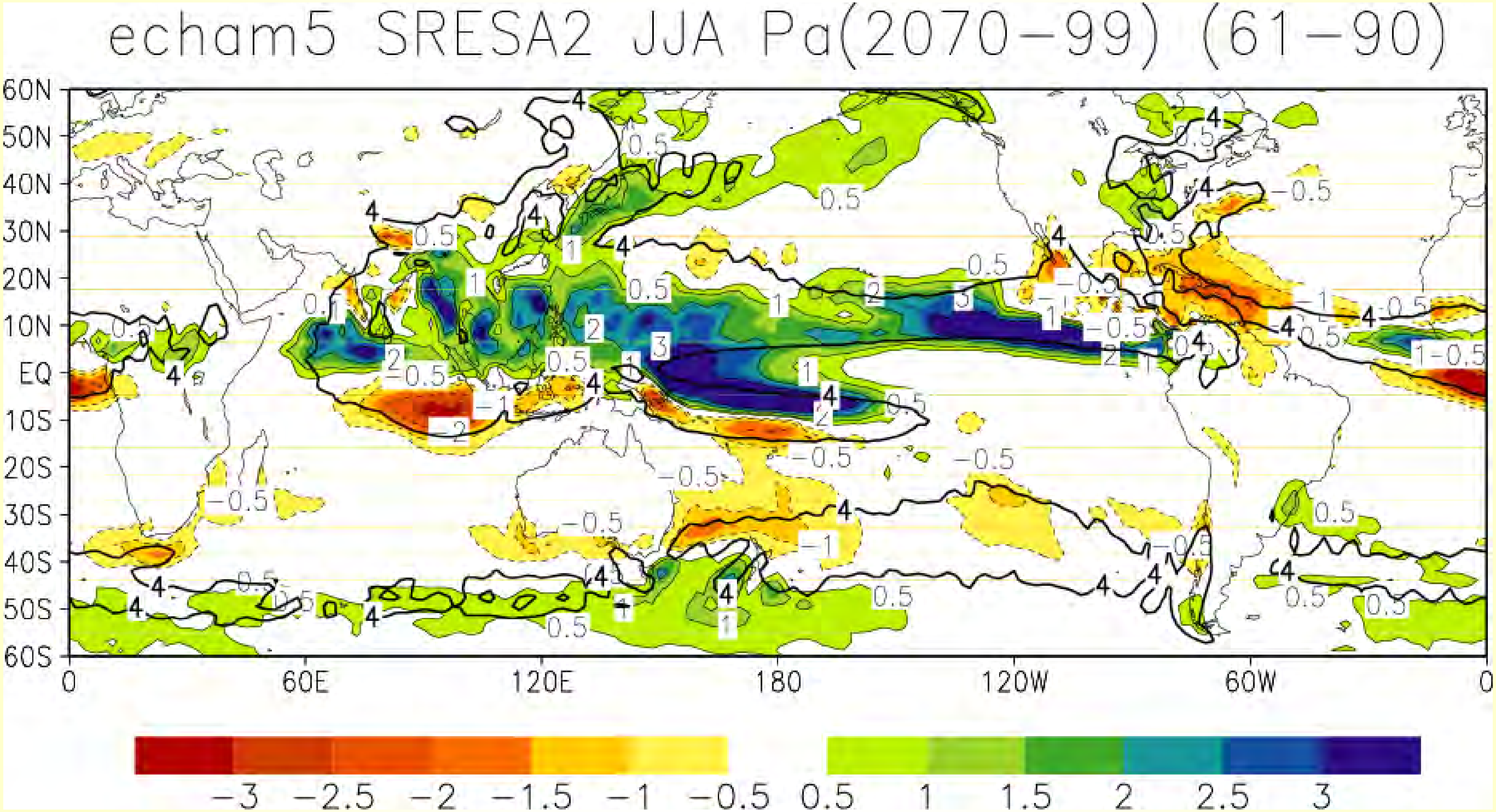
JJA Prec. Anom.



CMIP3

MPI_ECHAM5

JJA Prec. Anom.

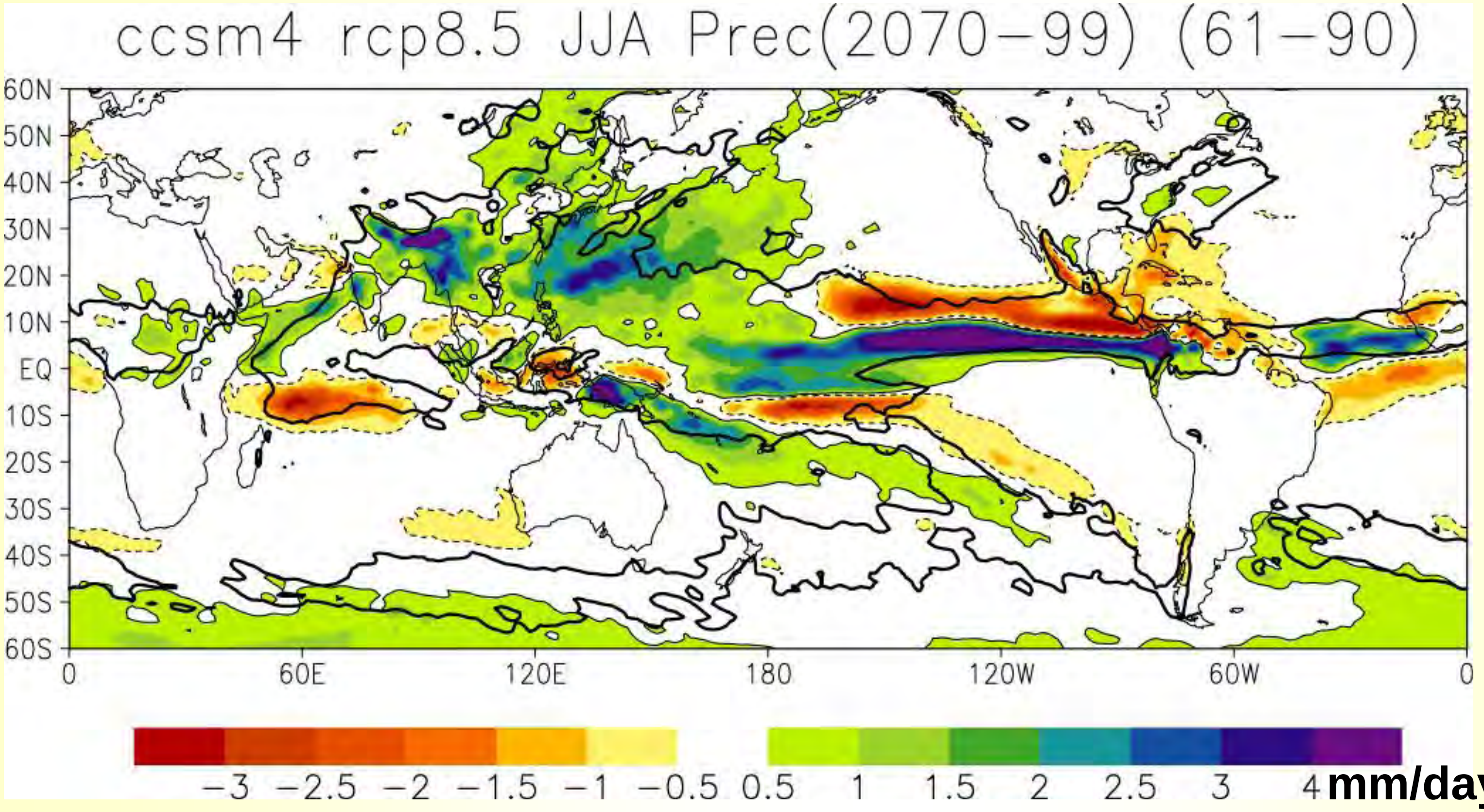


CMIP3

CMIP5/IPCC 5th Assessment report models

- **Representative Concentration Pathway RCP 8.5 (akin to CMIP3 A2 scenario) for greenhouse gases, aerosol forcing**

Precipitation change: HadCM3, Dec.-Feb., 2070-2099 avg minus 1961-90 avg.



4 mm/day model climatology black contour for reference

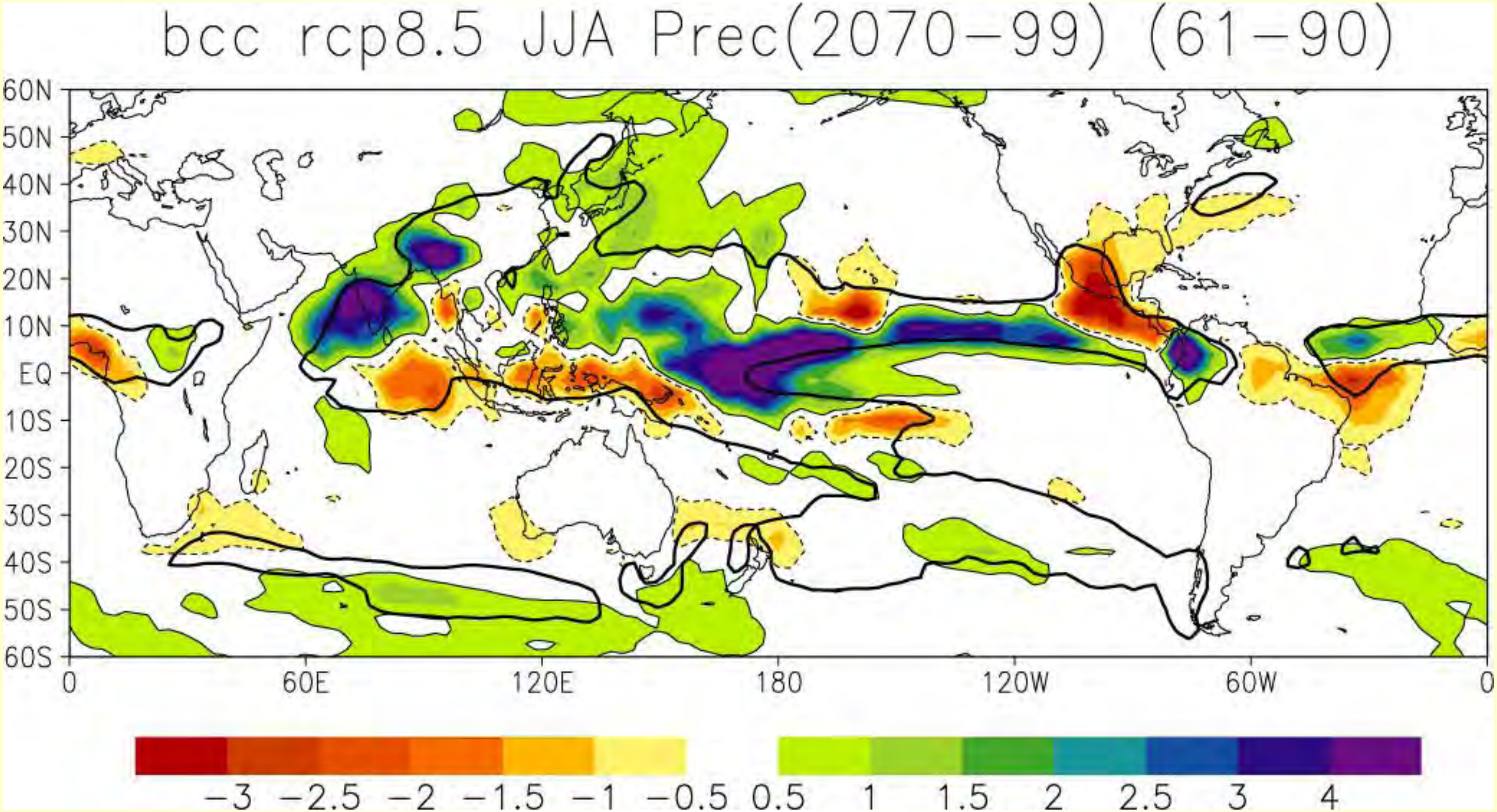
Analysis: J. Meyerson

NCAR Community Climate System Model

CMIP5

BCC-ESM1-1

JJA Prec. Anom.

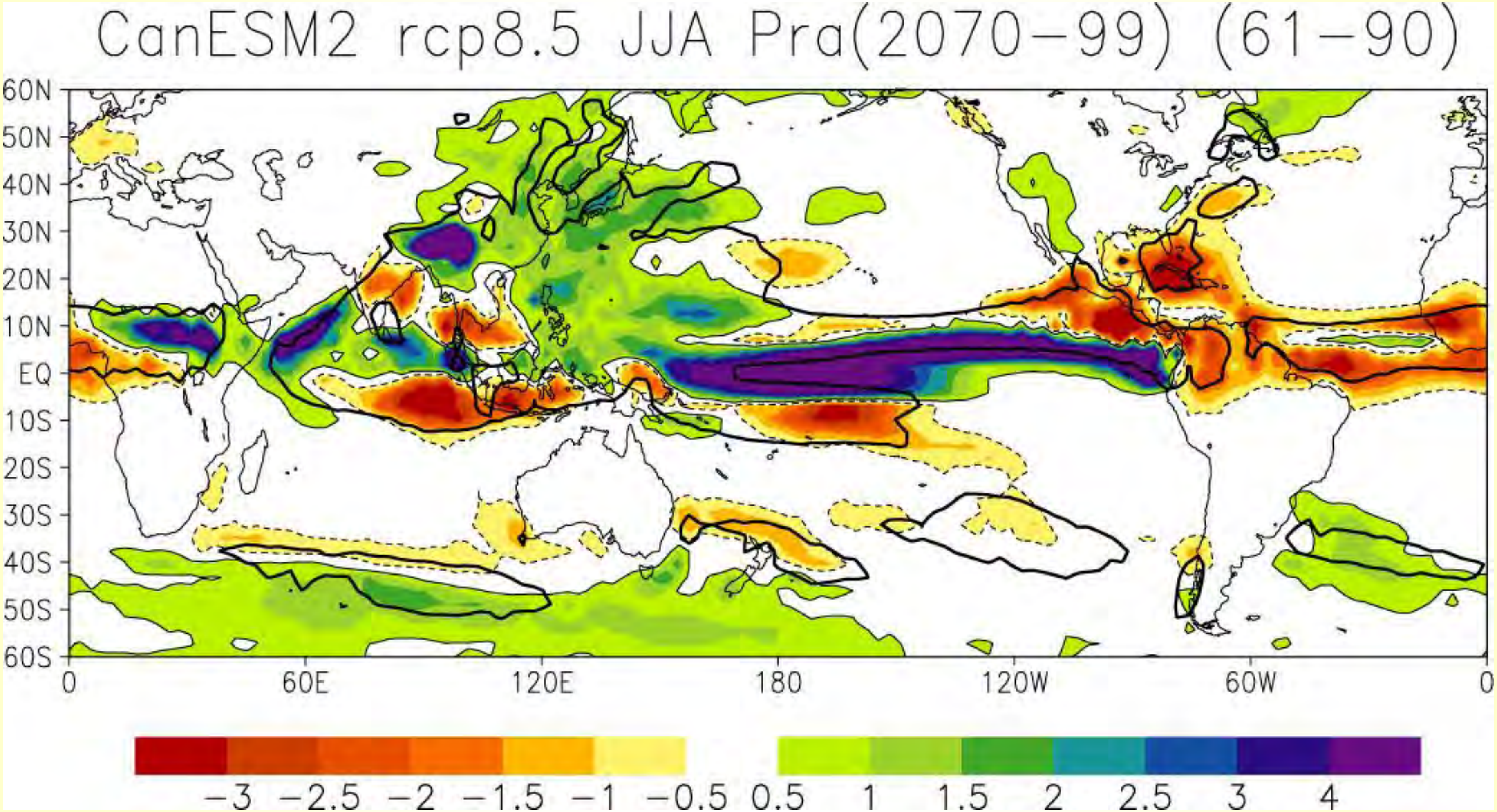


Beijing Climate Center, China

CMIP5

CanESM2

JJA Prec. Anom.

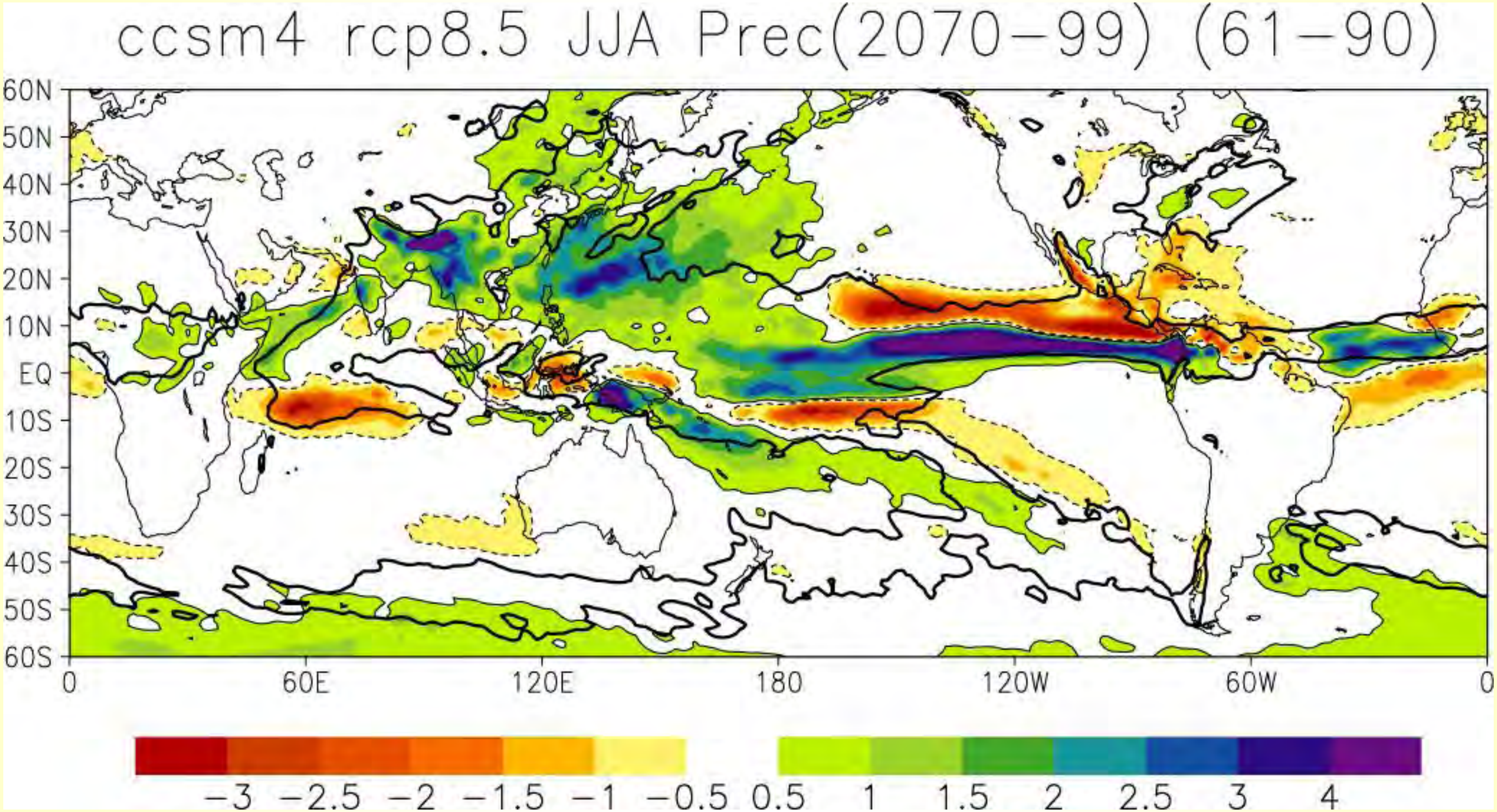


Canadian Center for Climate Modelling and Analysis, Canada.

CMIP5

CCSM4

JJA Prec. Anom.

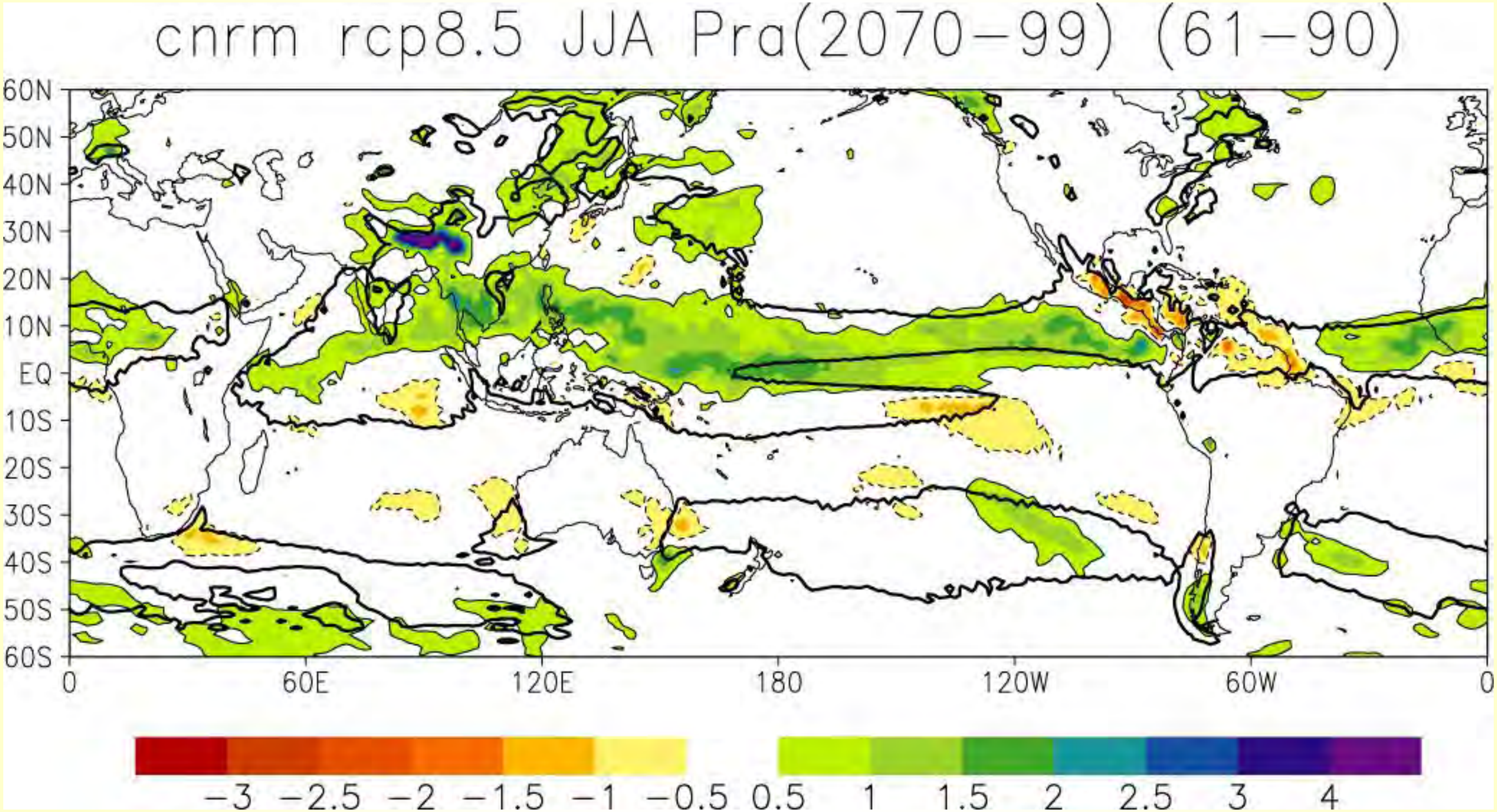


NCAR Community Climate System Model

CMIP5

CNRM-CM5

JJA Prec. Anom.

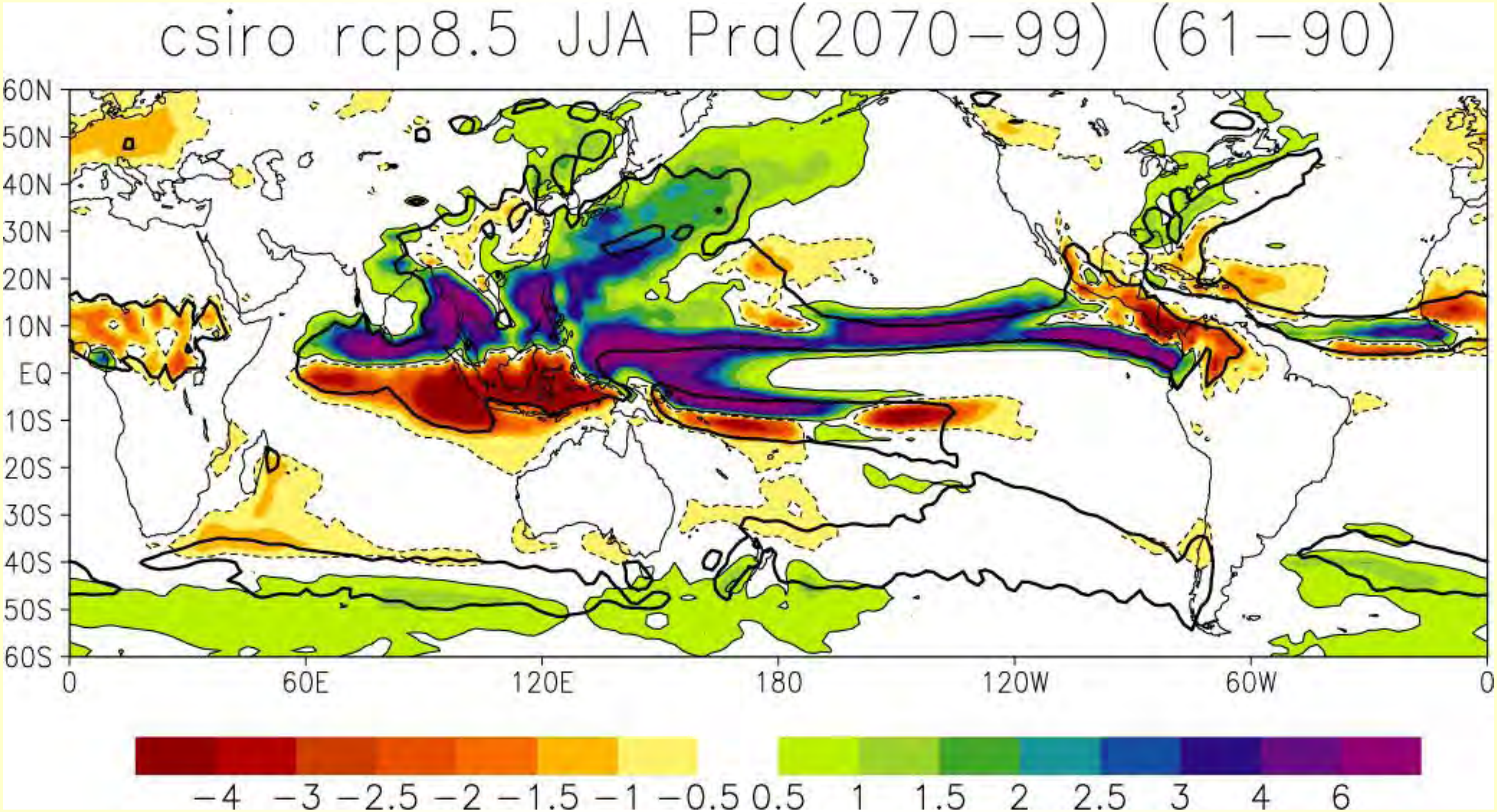


Centre National de Recherches Mereorologiques/ Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France.

CMIP5

CSIRO-MK3

JJA Prec. Anom.

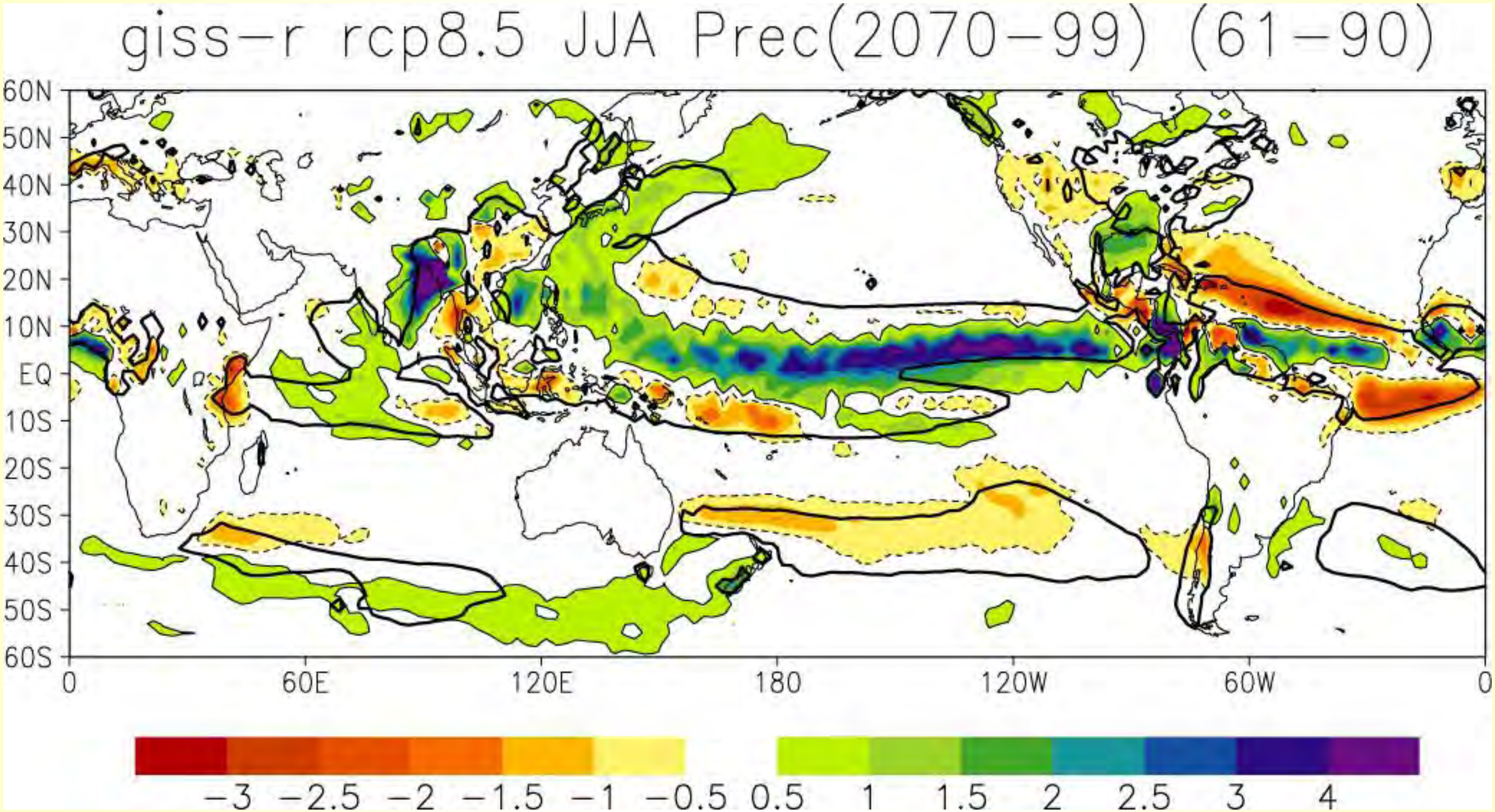


Commonwealth Scientific and Industrial Research Organization, Aus.

CMIP5

GISS-E2-R

JJA Prec. Anom.

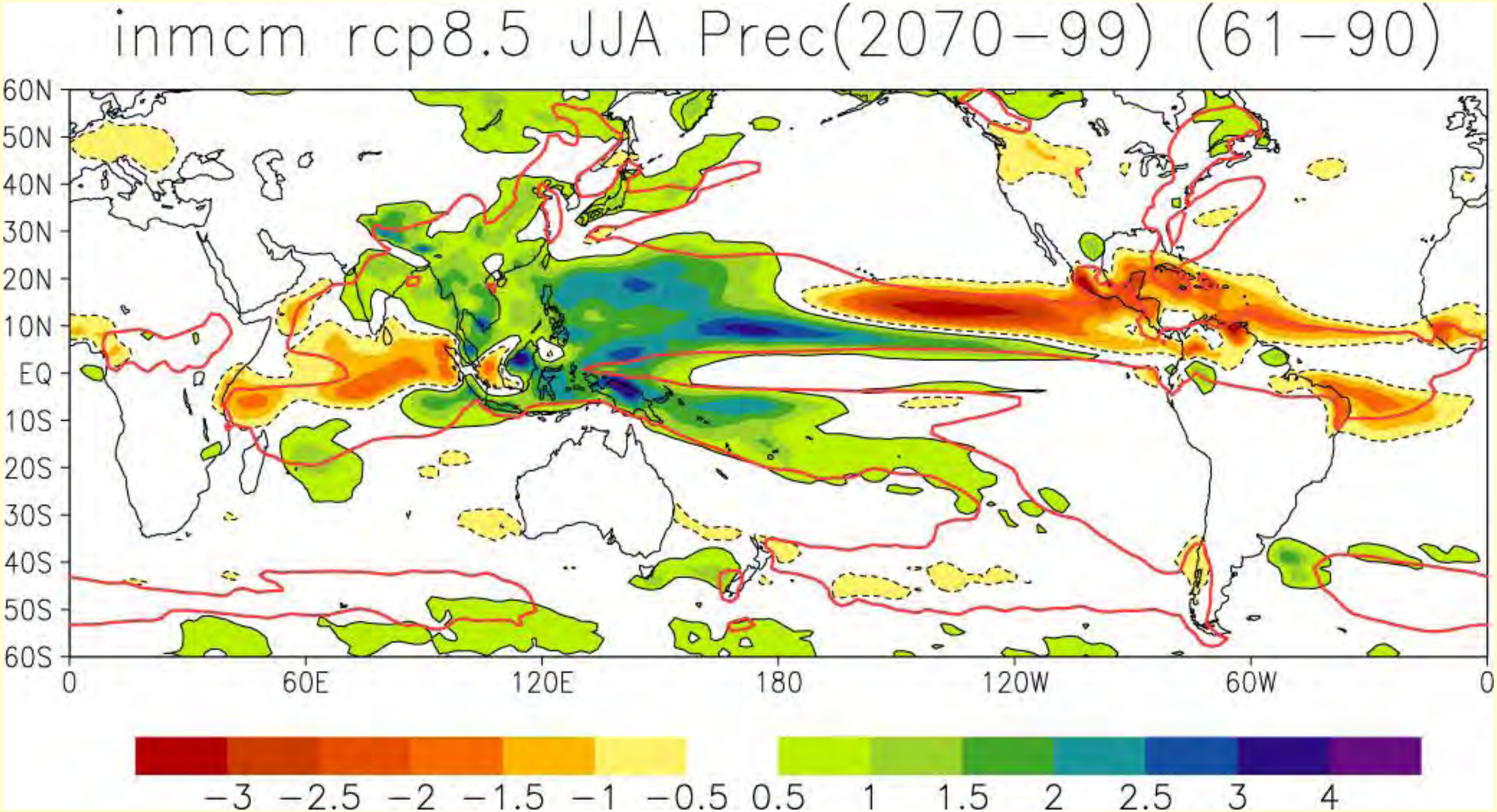


Goddard Institute for Space Studies

CMIP5

INNMCM4

JJA Prec. Anom.

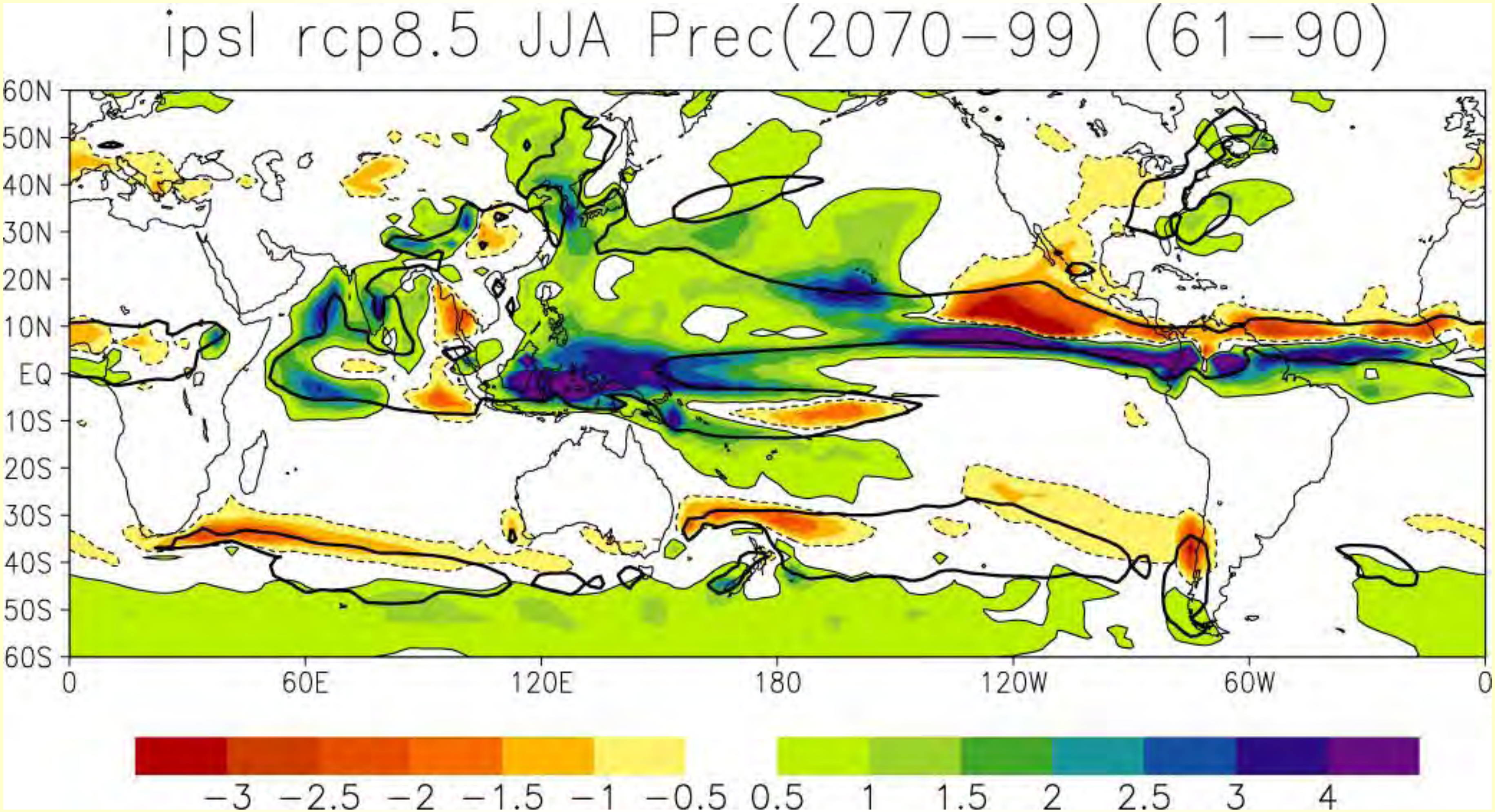


Institute for Numerical Mathematics, Russia.

CMIP5

IPSL-CM5A

JJA Prec. Anom.

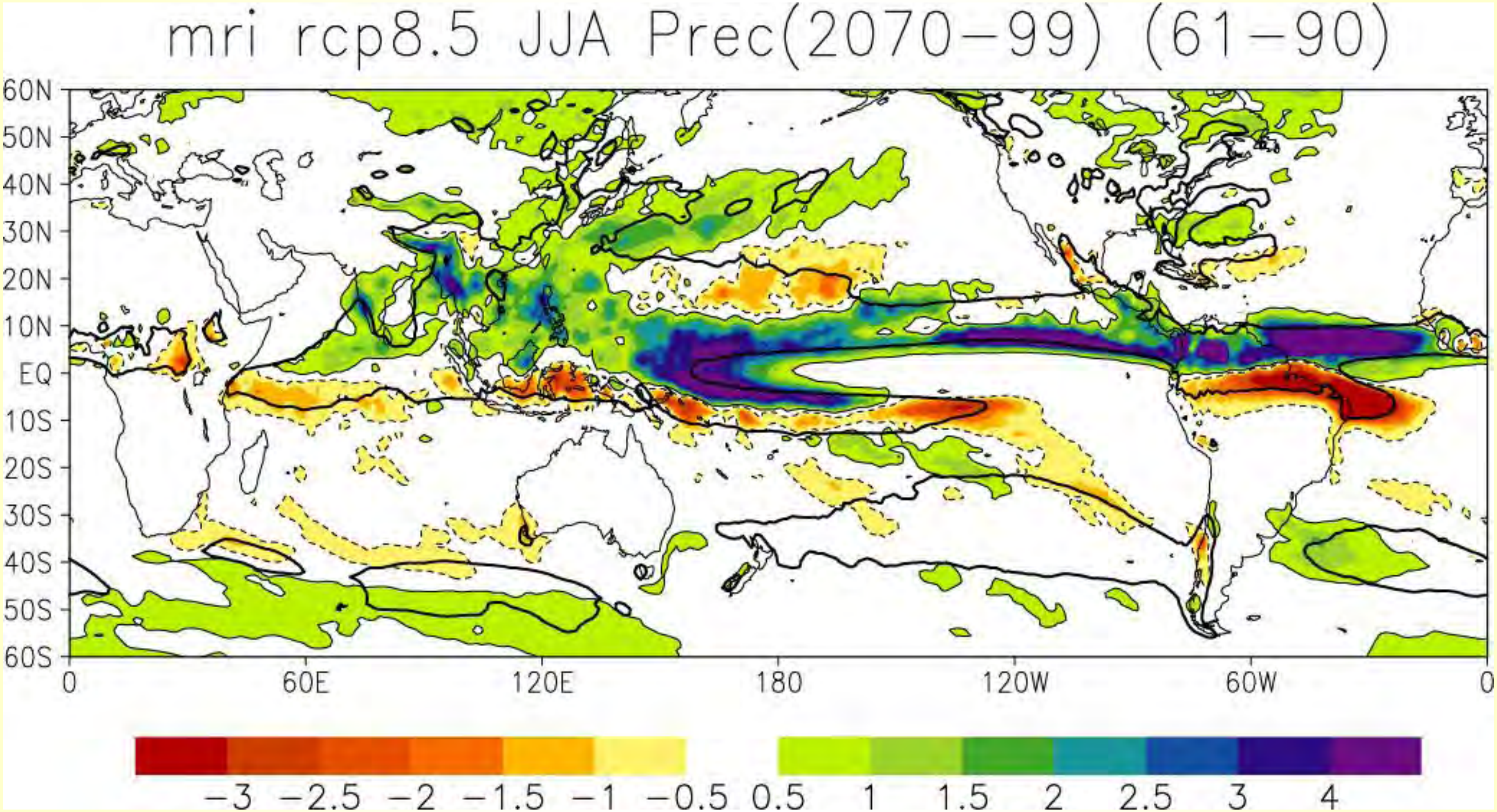


Institut Pierre Simon Laplace, France.

CMIP5

MRI-CGCM3

JJA Prec. Anom.

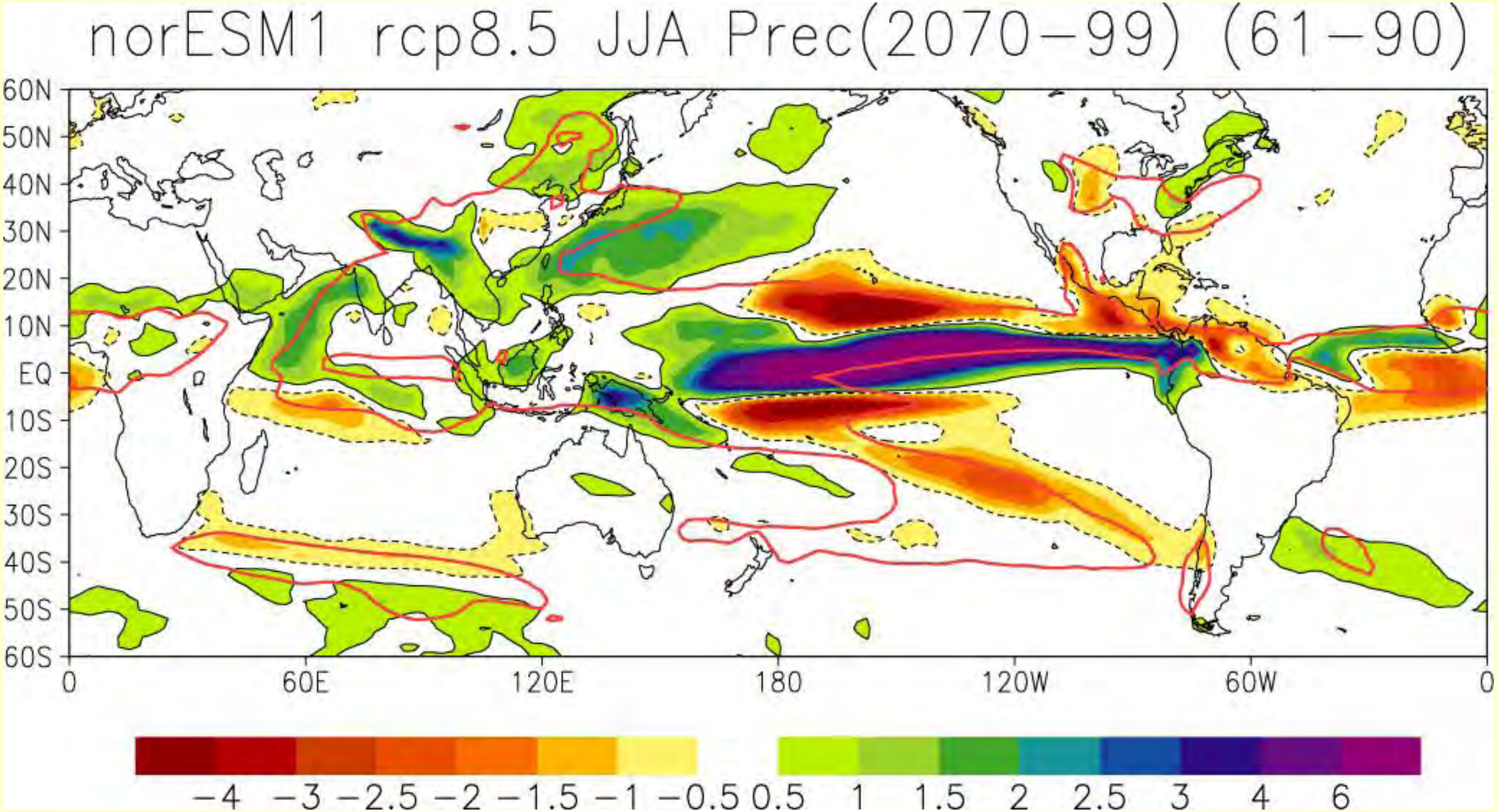


Meteorological Research Institute, Japan

CMIP5

NORESM1-M

JJA Prec. Anom.



Norwegian Climate Center, Norway

CMIP5

Mechanisms & constraints from moisture/energy budgets

Moisture budget for perturbations

$$P' = -\langle q' \nabla \cdot \bar{v} \rangle - \langle \bar{v} \cdot \nabla q' \rangle - \langle \bar{q} \nabla \cdot v' \rangle + E' + \ldots$$

Precip   Rich-get-Richer   Upped-ante   Convergence Fb   Evap

0. At global scale neglect transport $P' \approx E'$, set by surface energy balance $\Rightarrow$ small increase (e.g., Allen & Ingram 2002,…)

0.1 Warmer temperatures & Clausius-Clapeyron $\Rightarrow$ q' tends to increase [Interplay with convection and dynamics $\Rightarrow \nabla q'$]

$\langle\ \rangle$ = vertical average; q' specific humidity; $'$ denotes changes

Mechanisms & constraints from moisture/energy budgets

Moisture budget for perturbations

$$P' = -\langle q' \nabla\cdot \bar{v} \rangle - \langle \bar{v}\cdot\nabla q' \rangle - \langle \bar{q}\, \nabla\cdot v' \rangle + E' + \ldots$$

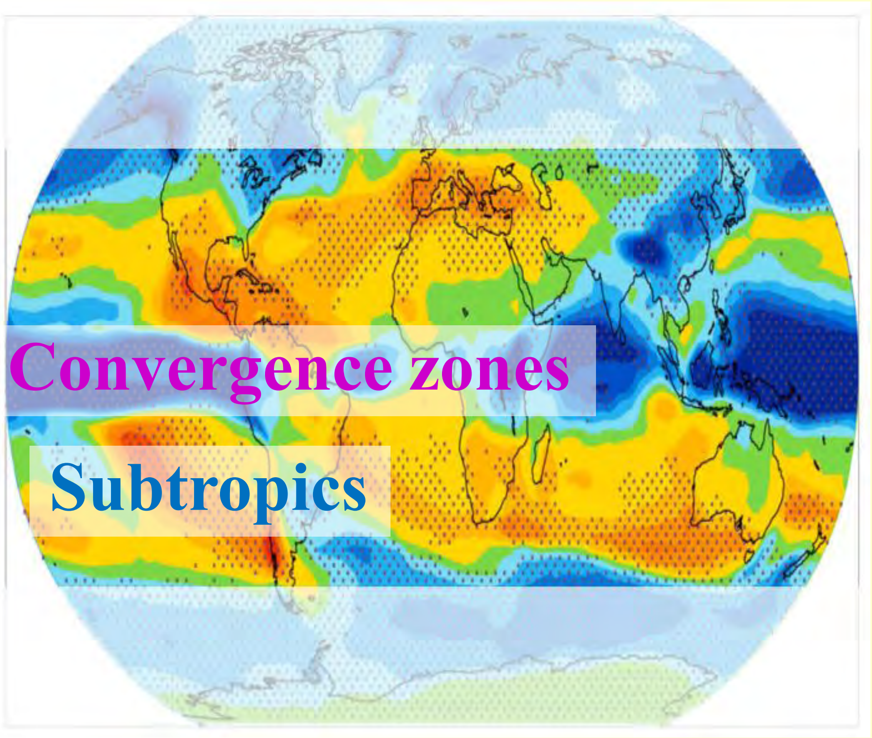
Precip — Rich-get-Richer — Upped-ante — Convergence Fb — Evap

"Rich-get-richer mechanism*"

Subtropics: low-level divergence

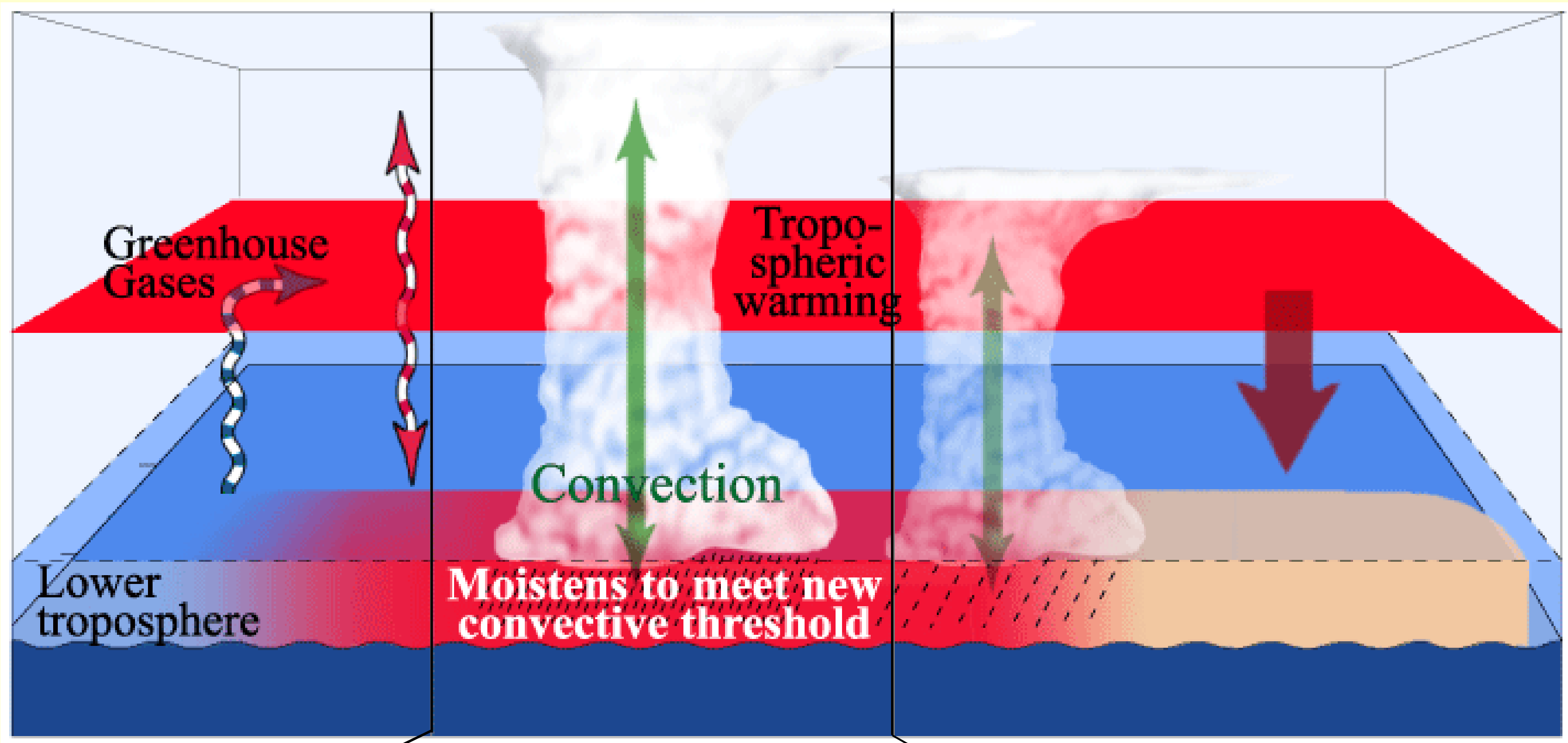
so q' increase ⇒ Precip decrease

Convergence zones: vice versa



*(a.k.a. thermodynamic component):

The Rich-get-richer mechanism



Center of convergence zone: incr. moisture convergence ⇒ incr. precip

Descent region: incr. moisture divergence; less often meets conv. threshold

Chou & Neelin, 2004, Held & Soden 2006, Chou et al 2008

Mechanisms & constraints from moisture/energy budgets

Moisture budget for perturbations

$$P' \quad = \quad -\langle q' \nabla \cdot \bar{v} \rangle \quad -\langle \bar{v} \cdot \nabla q' \rangle \quad -\langle \bar{q} \nabla \cdot v' \rangle \quad + E' + \ldots$$

Precip | Rich-get-Richer | Upped-ante | Convergence Fb | Evap

[Regional differences] (Upped-ante, Convergence Fb)

a. Atm. energy budget to approx. $\nabla \cdot v'$ (Chou & Neelin 2004)

b. Neglect $\nabla \cdot v'$, (Held and Soden 2006; plausible for large scales)

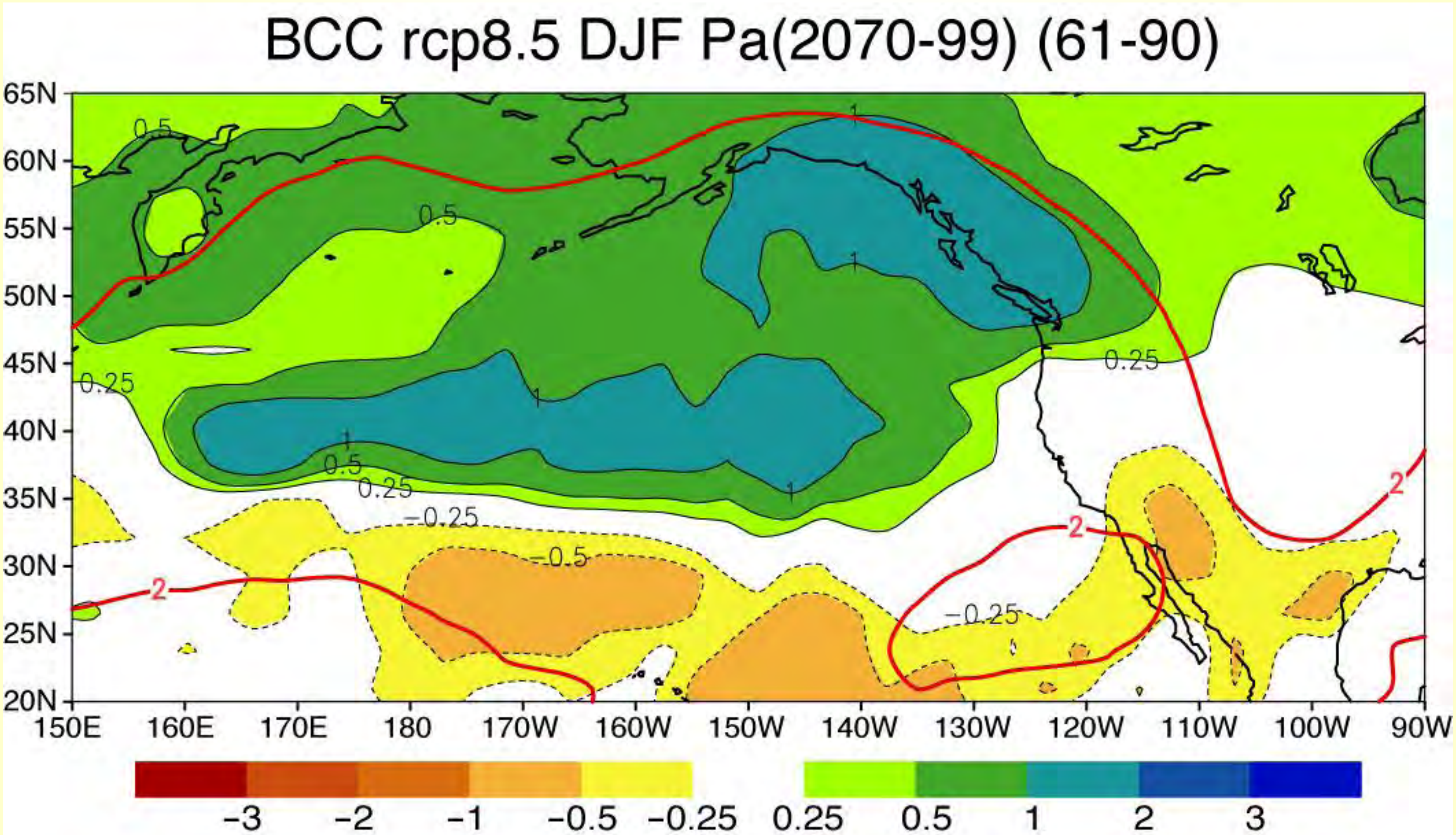
$\nabla \cdot v'$ large at regional scales! $\Rightarrow$ a major factor in uncertainty

$v \cdot \nabla q'$ in particular regions

Averaging over larger scales, e.g., latitude bands; or a an ensemble of models that disagreed on location of strong convergence change can reduce the visibility of the convergence feedback terms

West Coast rainfall change under global warming

DJF Prec. Anom. (2070-99)- (1961-90), RCP 8.5 scenario

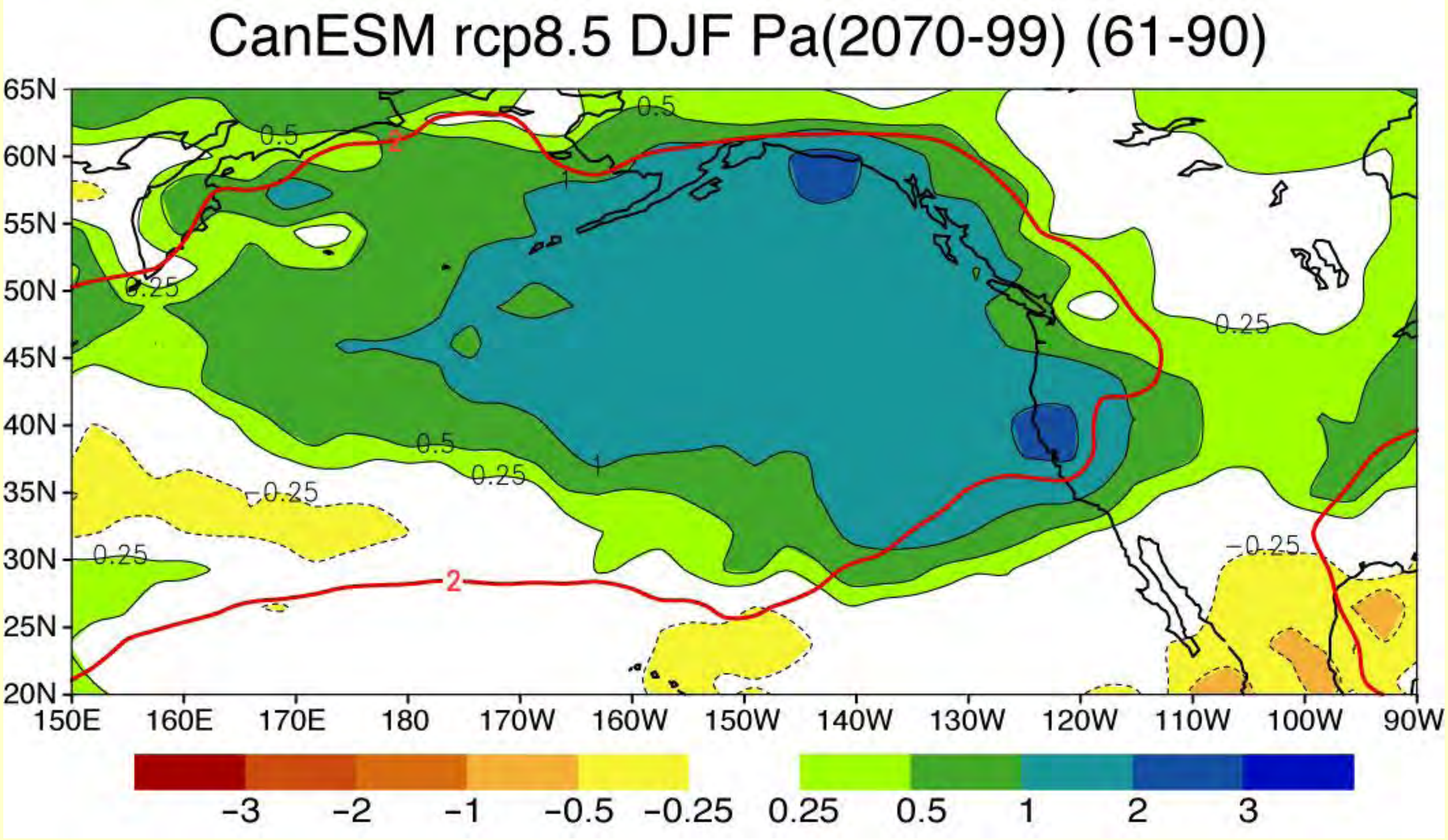


CMIP5

Analysis: J. Meyerson

CanESM2

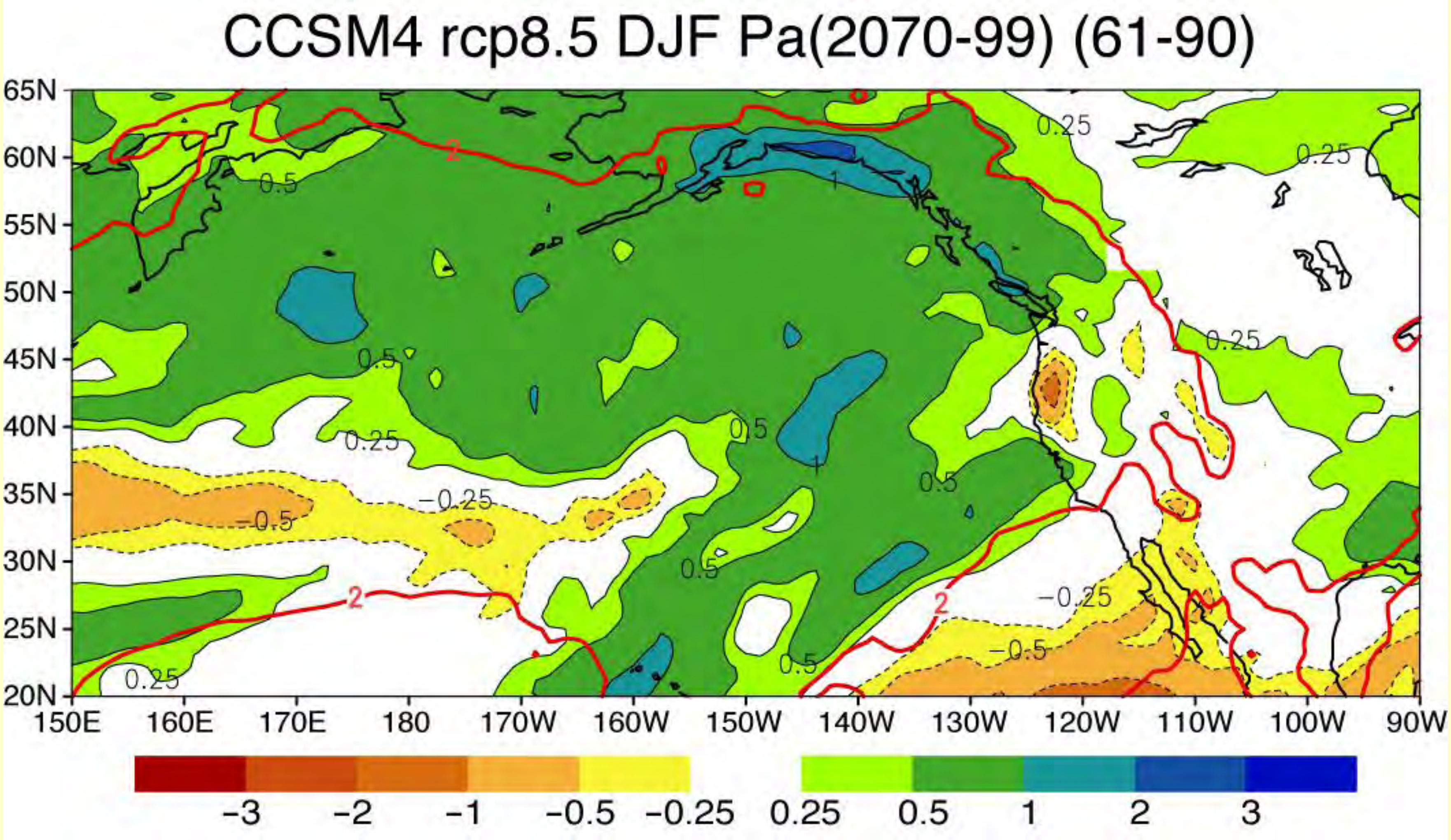
DJF Prec. Anom.



CMIP5

CCSM4

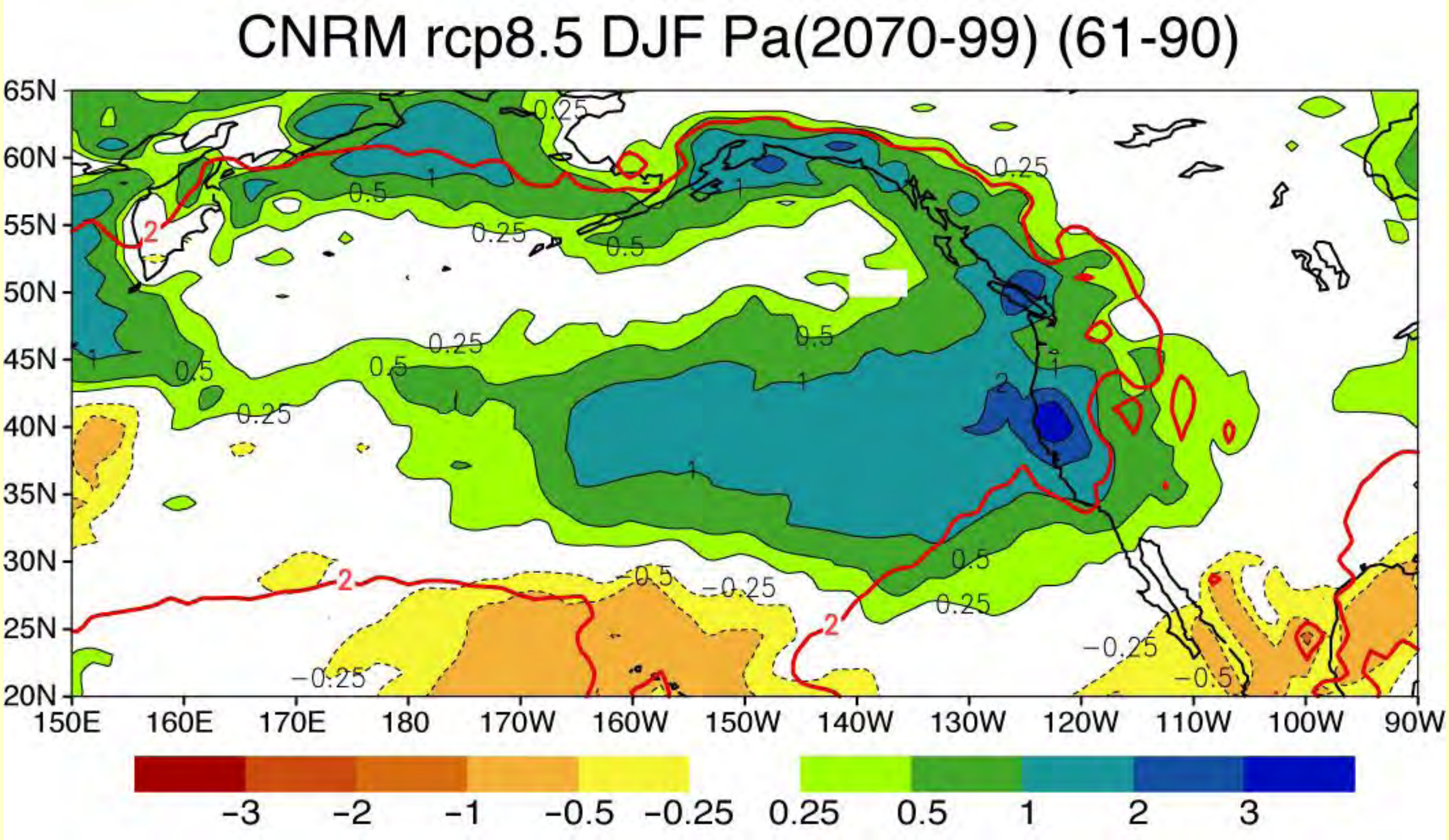
DJF Prec. Anom.



CMIP5

CNRM-CM5

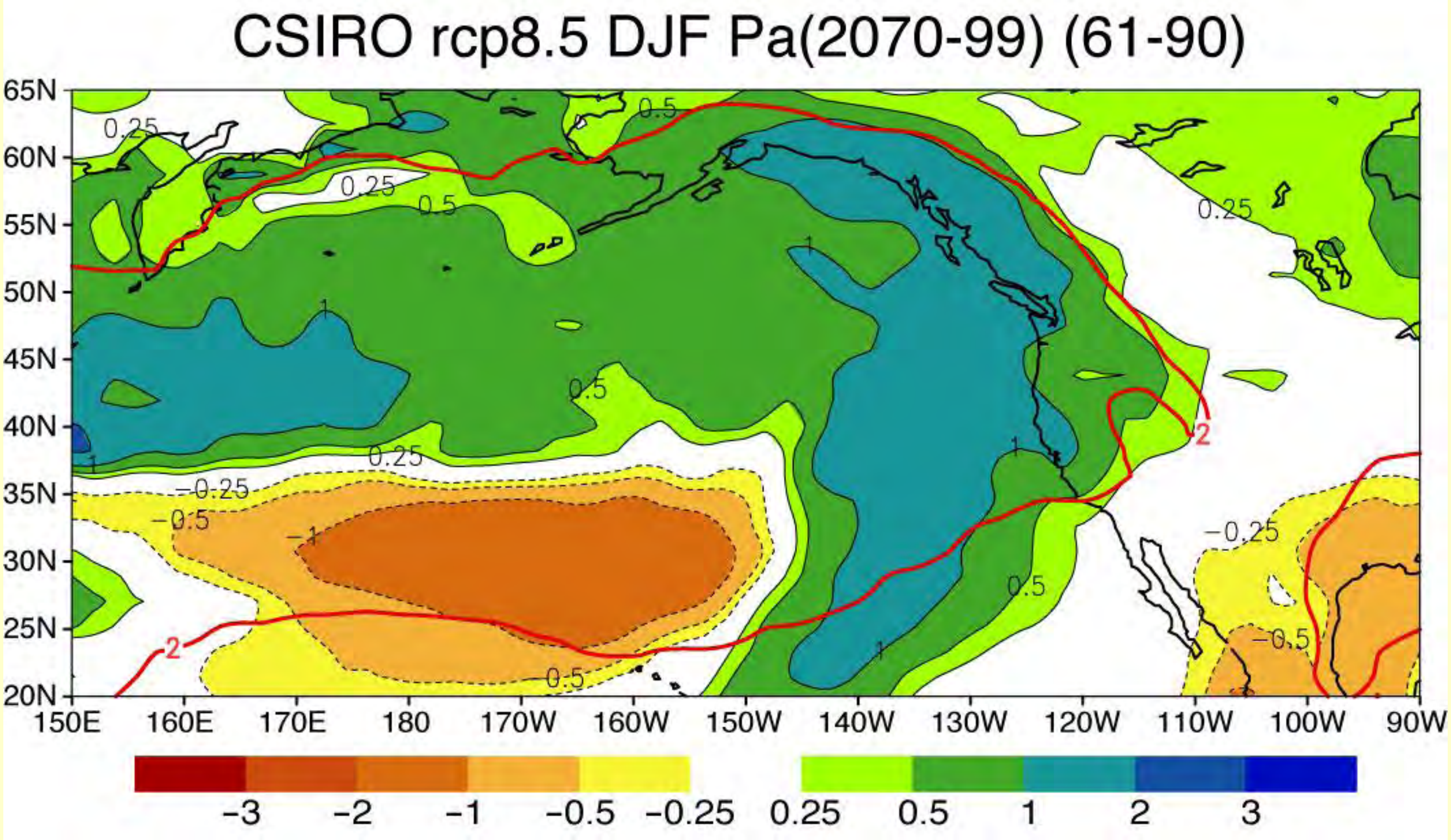
DJF Prec. Anom.



CMIP5

CSIRO-MK3

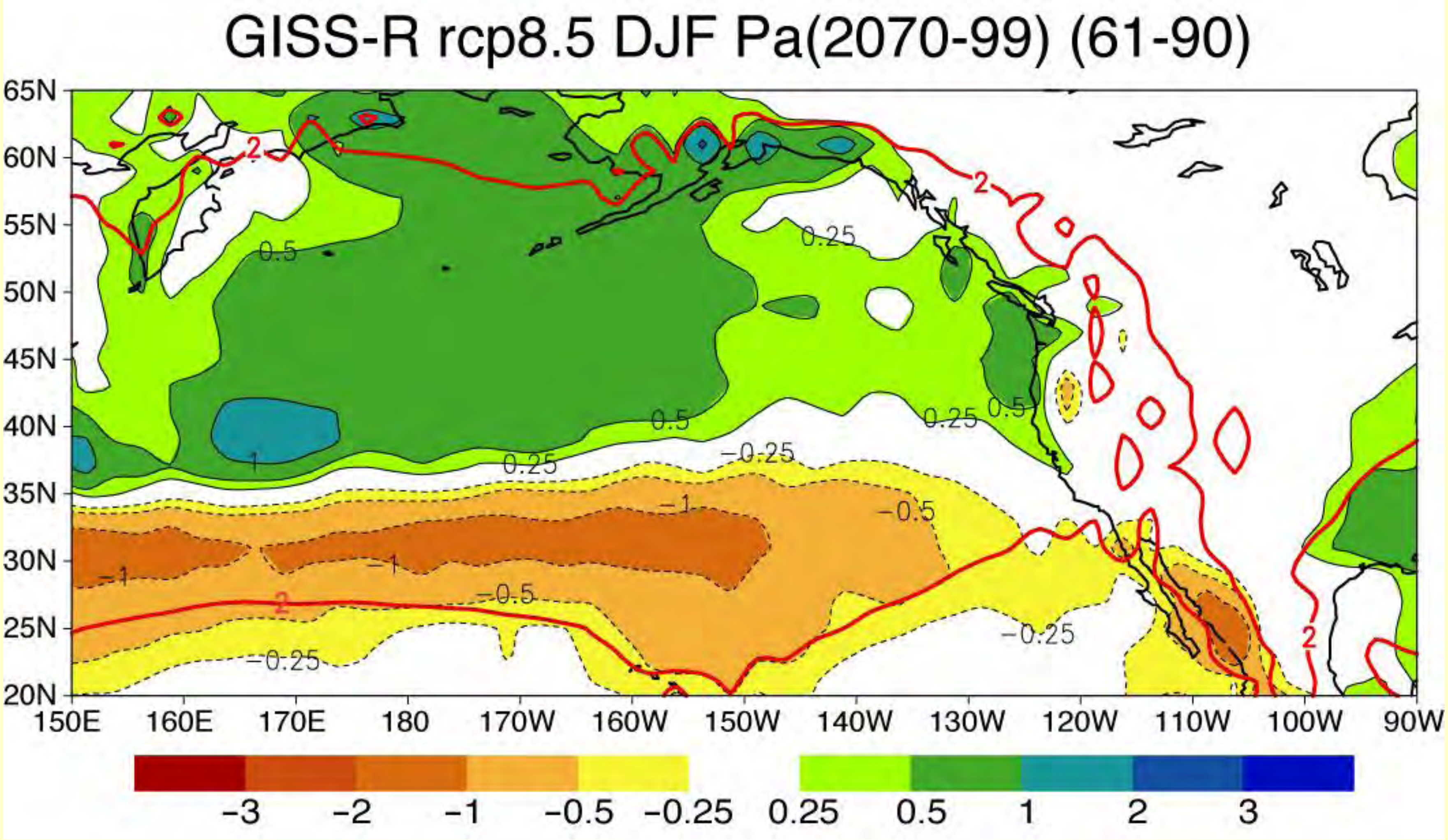
DJF Prec. Anom.



CMIP5

GISS-E2-R

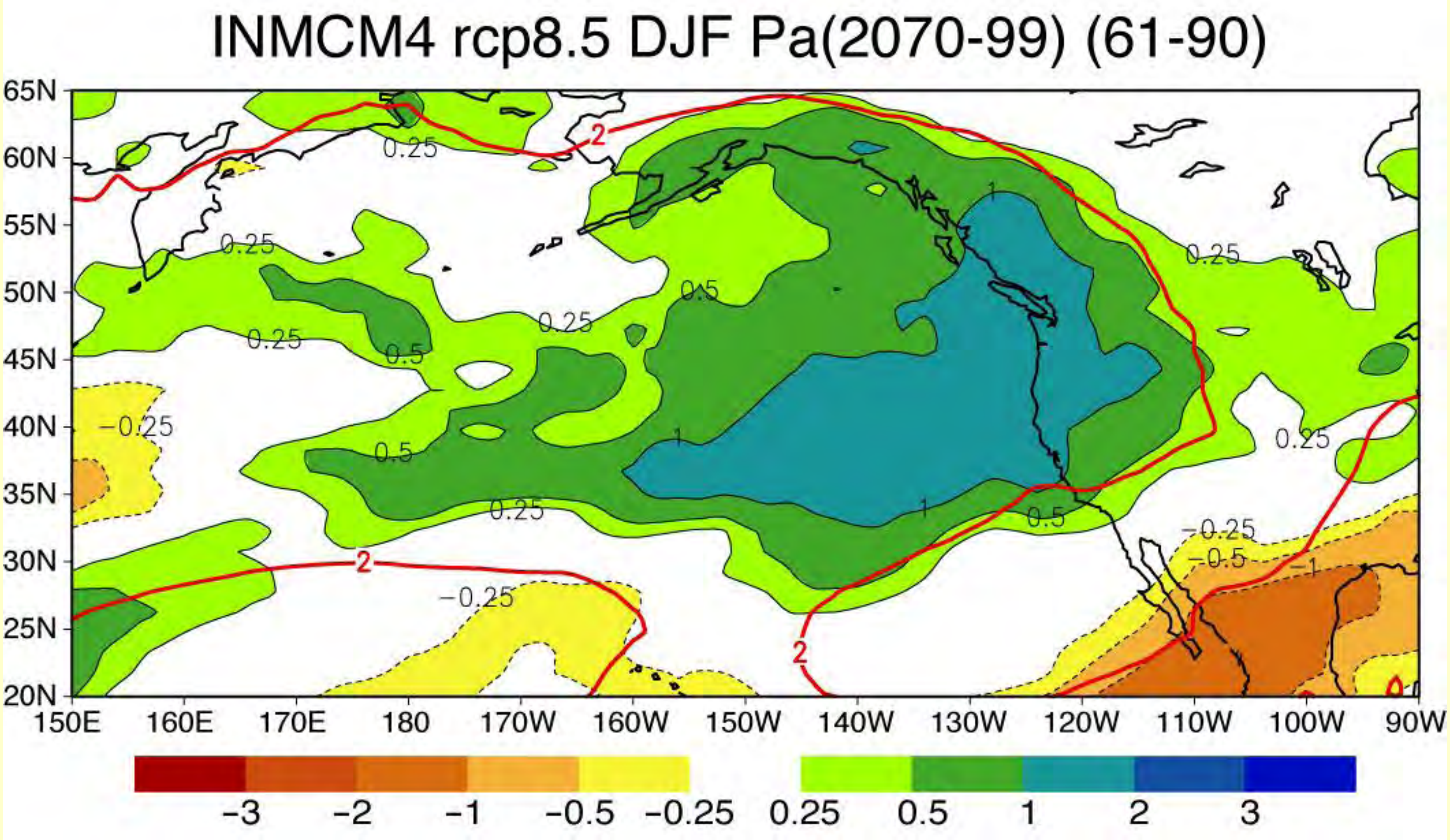
DJF Prec. Anom.



CMIP5

INNMCM4

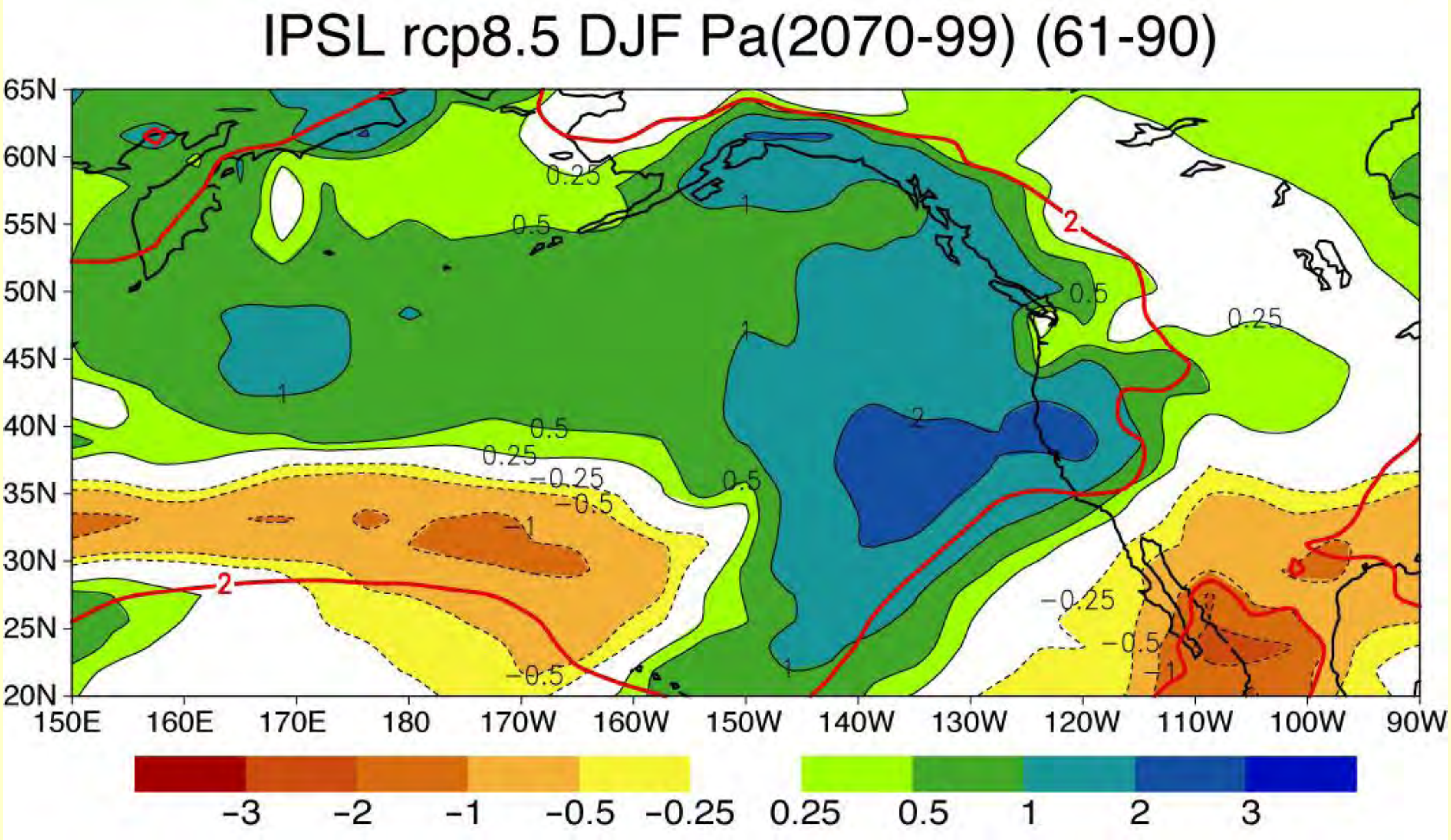
DJF Prec. Anom.



CMIP5

IPSL-CM5A

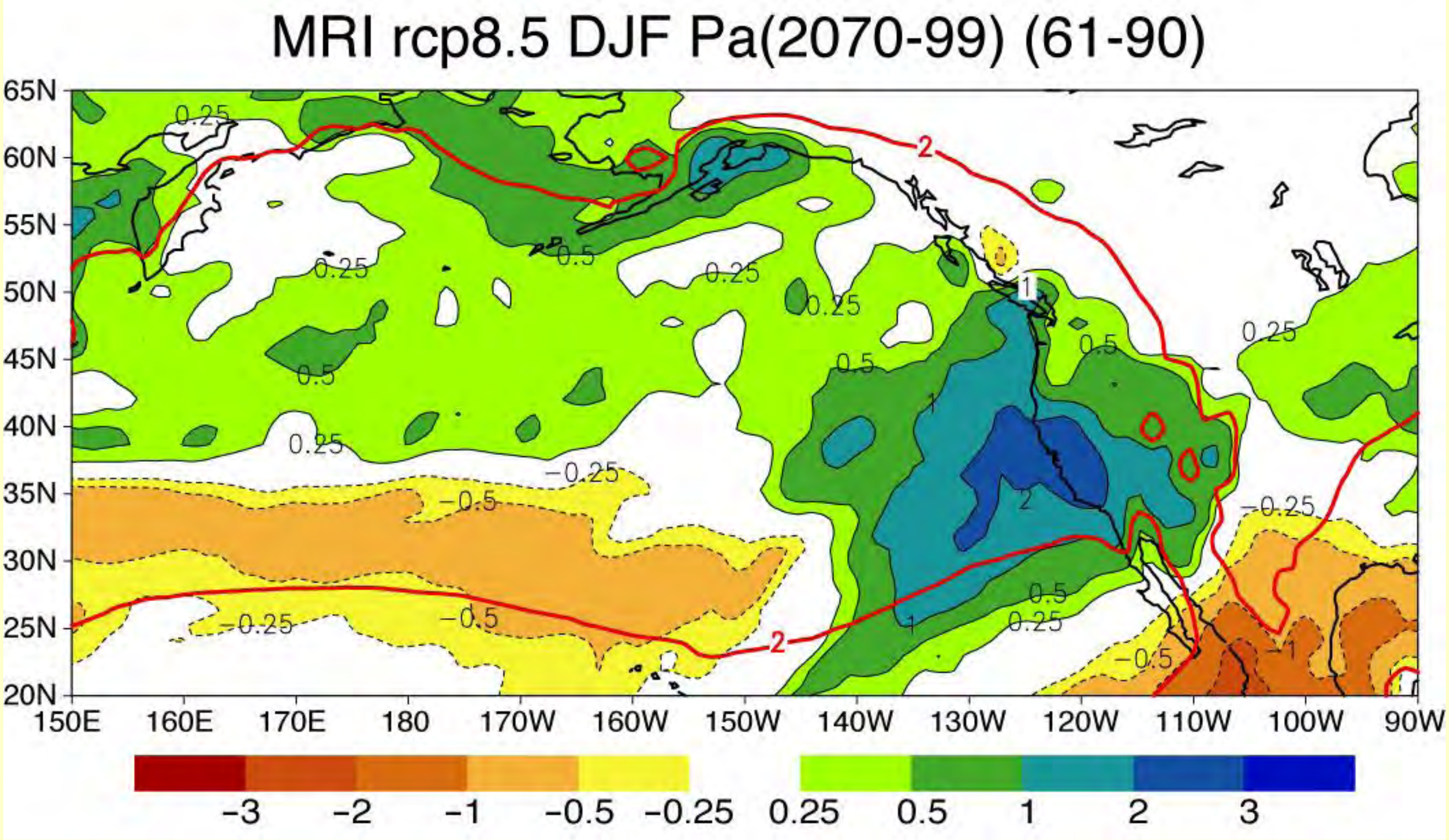
DJF Prec. Anom.



CMIP5

MRI-CGCM3

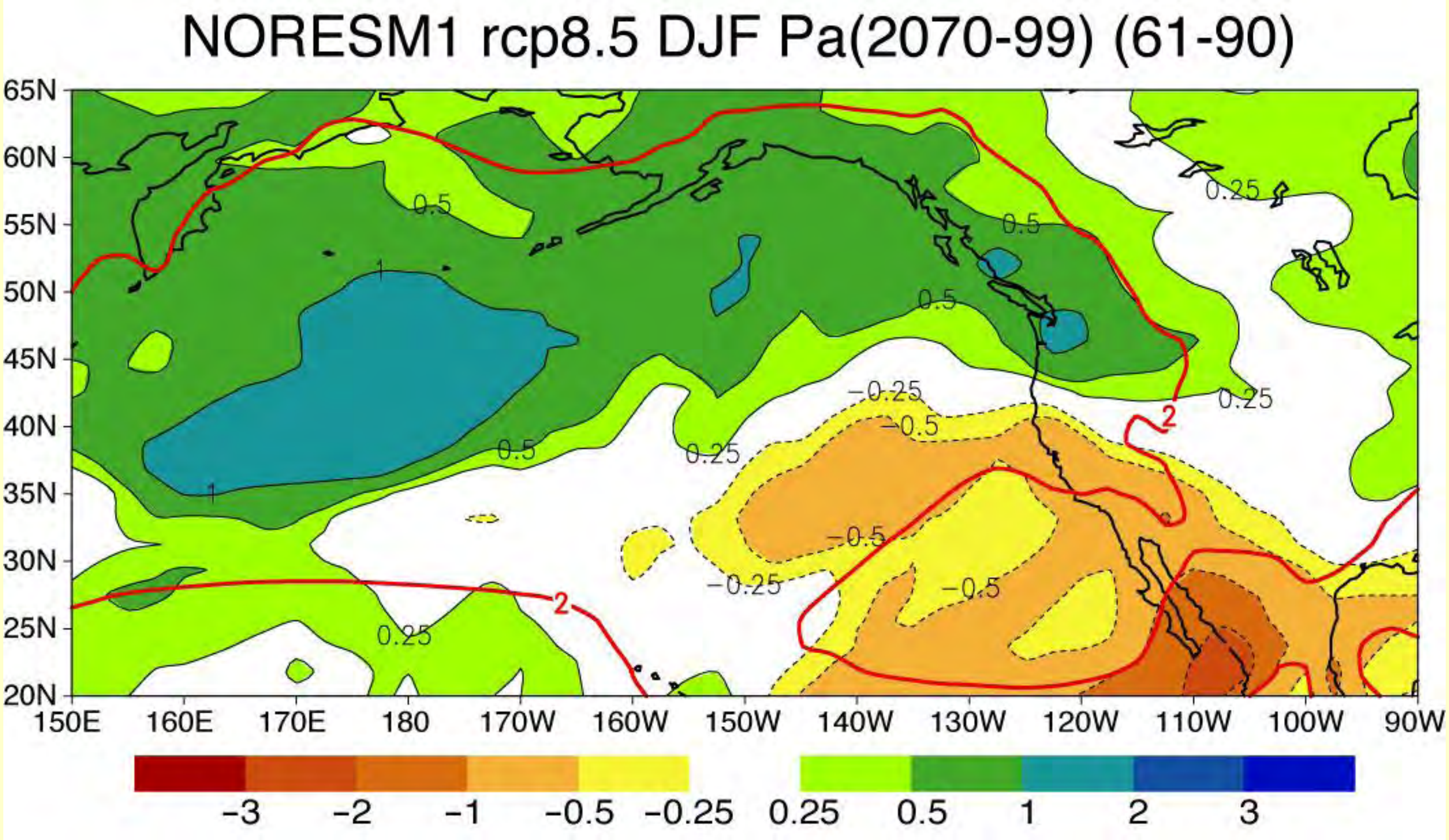
DJF Prec. Anom.



CMIP5

NORESM1-m

DJF Prec. Anom.

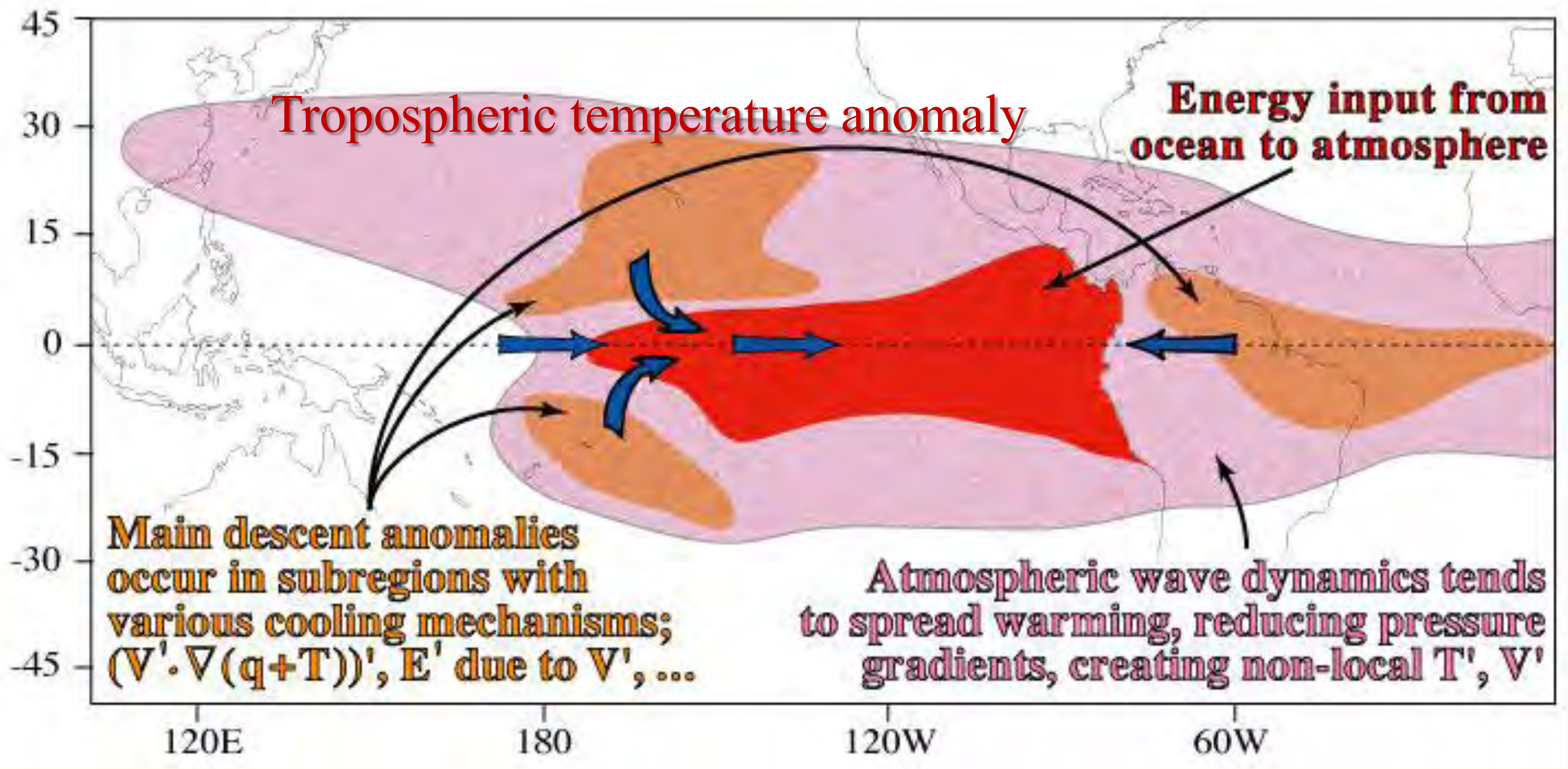


CMIP5

How do the models do for El Niño/Southern Oscillation (ENSO)?

- A phenomenon we can observe
- Important for interannual prediction
- Satellite precipitation retrievals since 1979
- Atmospheric model component runs with observed sea surface temperature (SST) or ocean atmosphere models
- Rank correlation/Regression/compositing of events based on an equatorial Eastern Pacific SST index “Nino3.4”

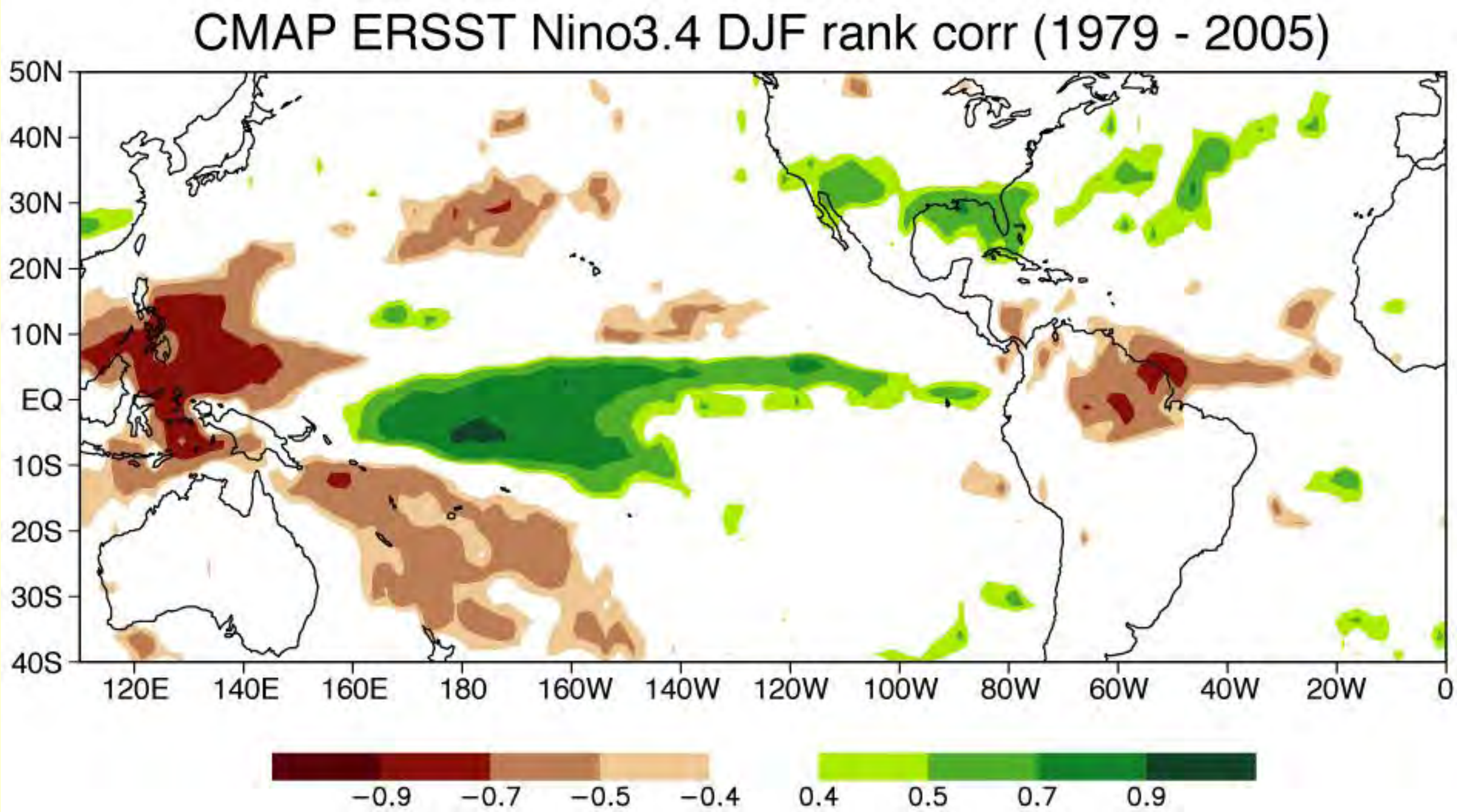
ENSO teleconnections to regional precip. anomalies



Su & Neelin, 2002

See Newell and Weare (1976); Salby & Garcia 1987; Yulaeva & Wallace (1994); Wallace et al. (1998); Chiang and Sobel (2002); Kumar & Hoerling (2003); Su and Neelin 2003; Sperber and Palmer 1996, Giannini et al 2001; Saravanan & Chang, 2000; Joseph & Nigam 2006,…

Observed Nino3.4 rank correlations (Dec.-Feb.) CMAP

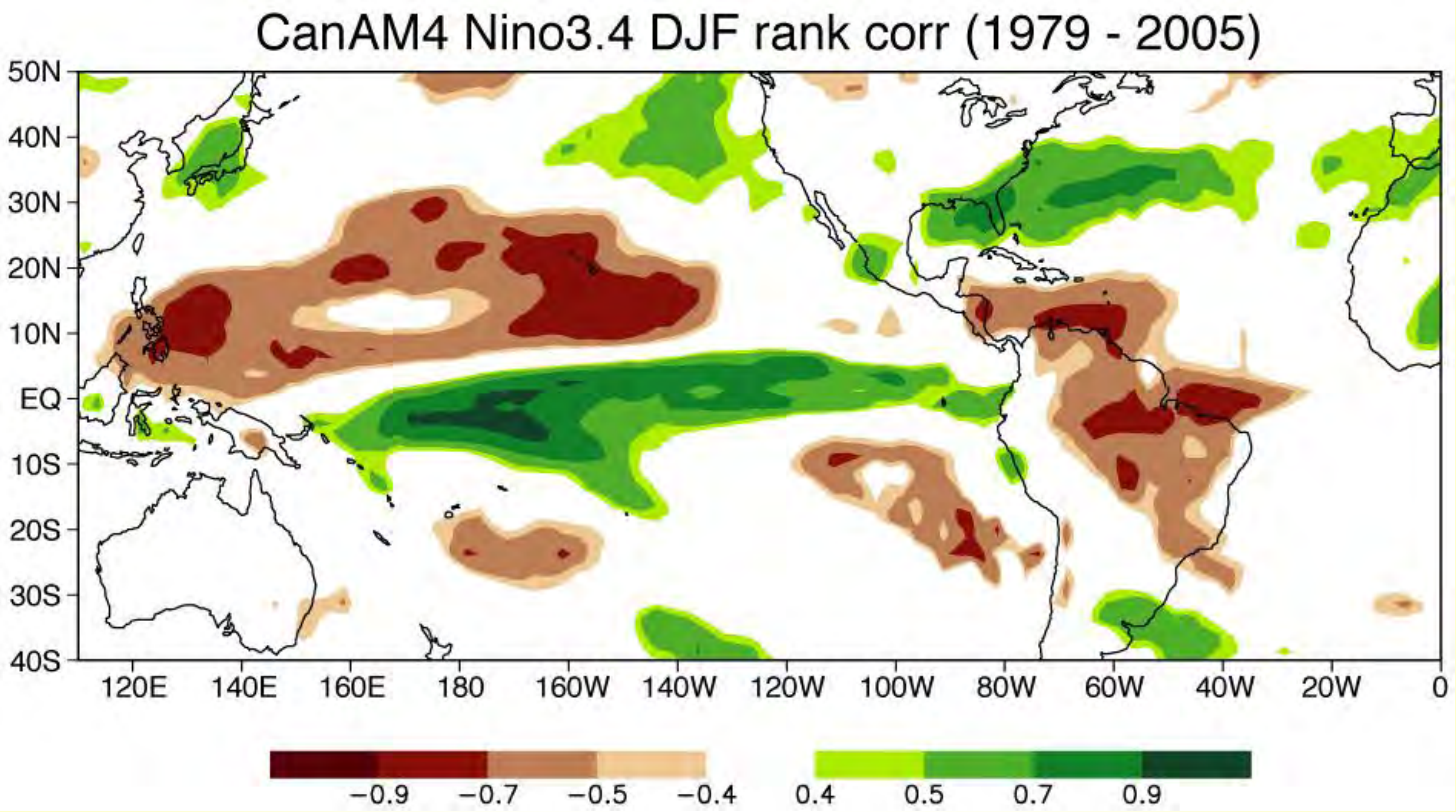


CPC Merged Analysis of Precipitation

Compare to preliminary results from CMIP5 models

Analysis: B. Langenbrunner

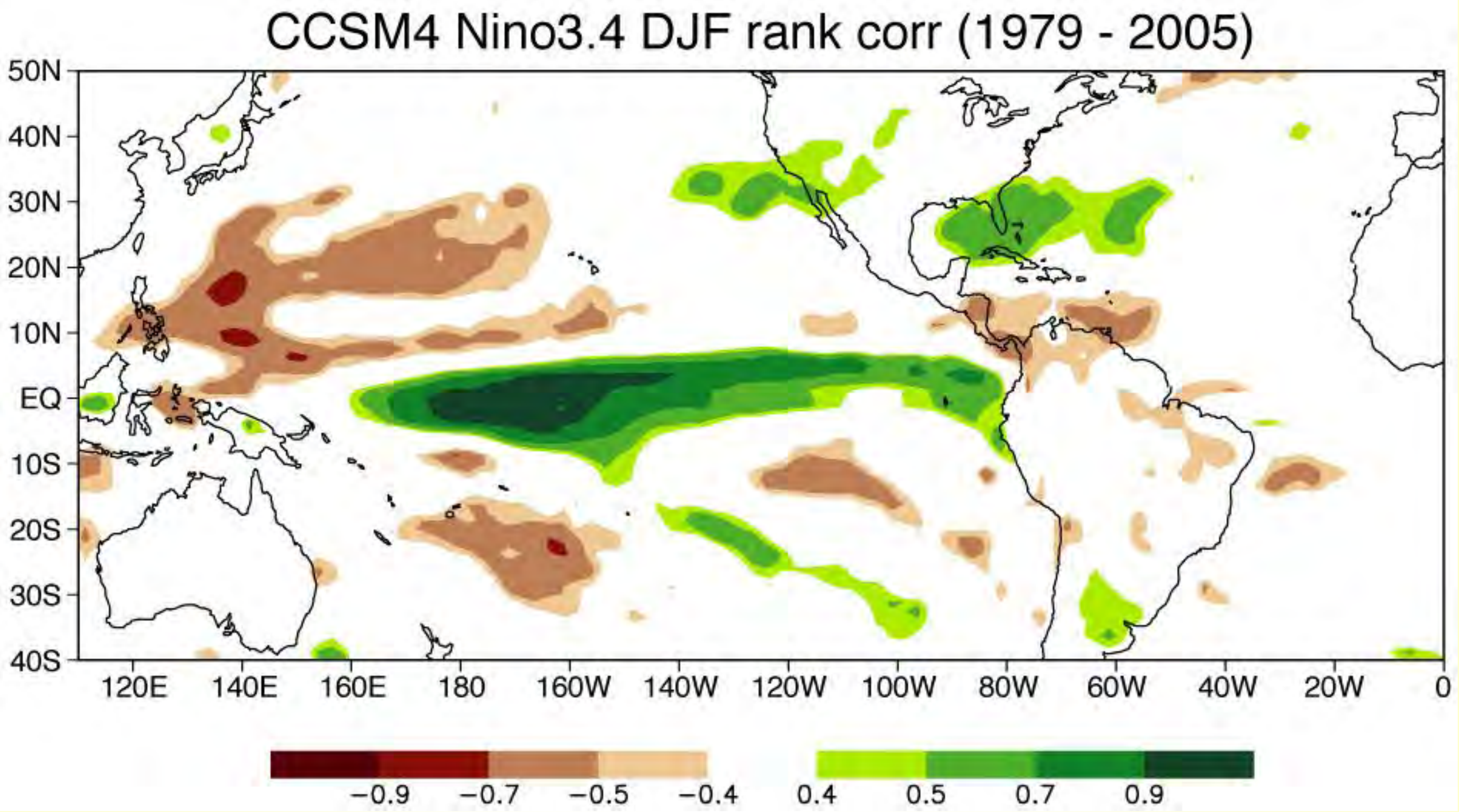
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.)
CanAM4



Canadian Center for Climate Modelling and Analysis, Canada.

CMIP5

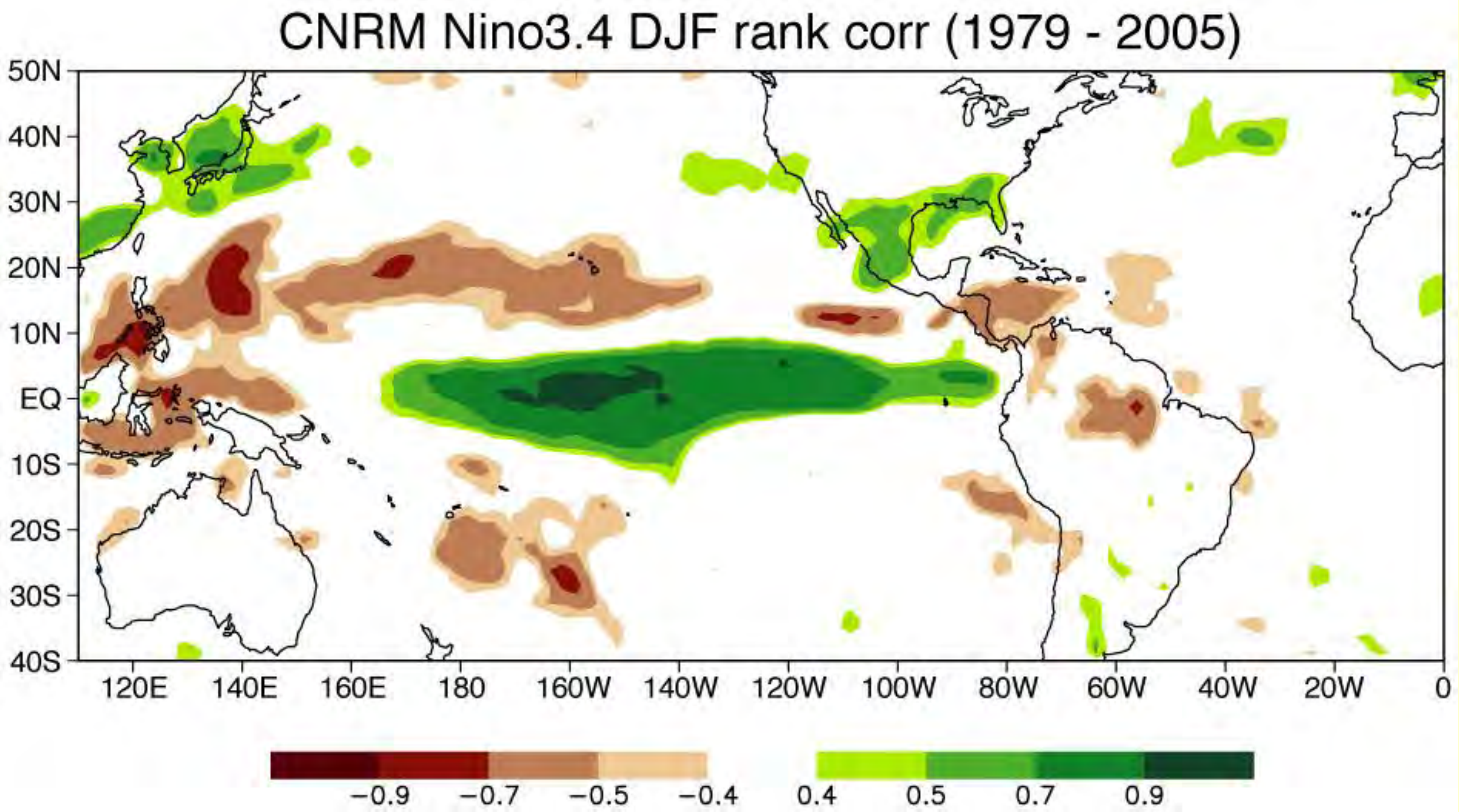
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.)
CCSM4



NCAR Community Climate System Model

CMIP5

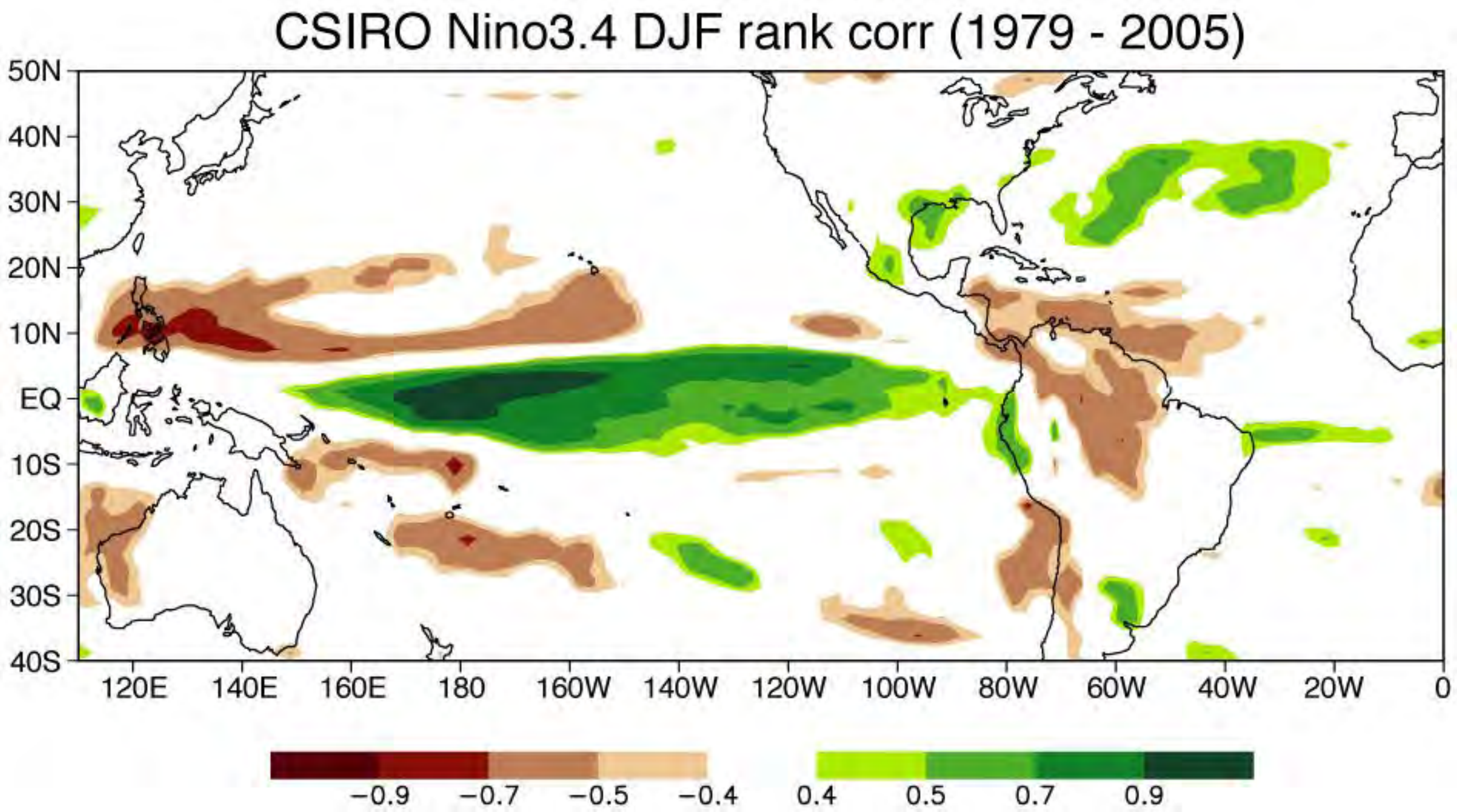
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.) CNRM



Centre National de Recherches Mereorologiques/ Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France.

CMIP5

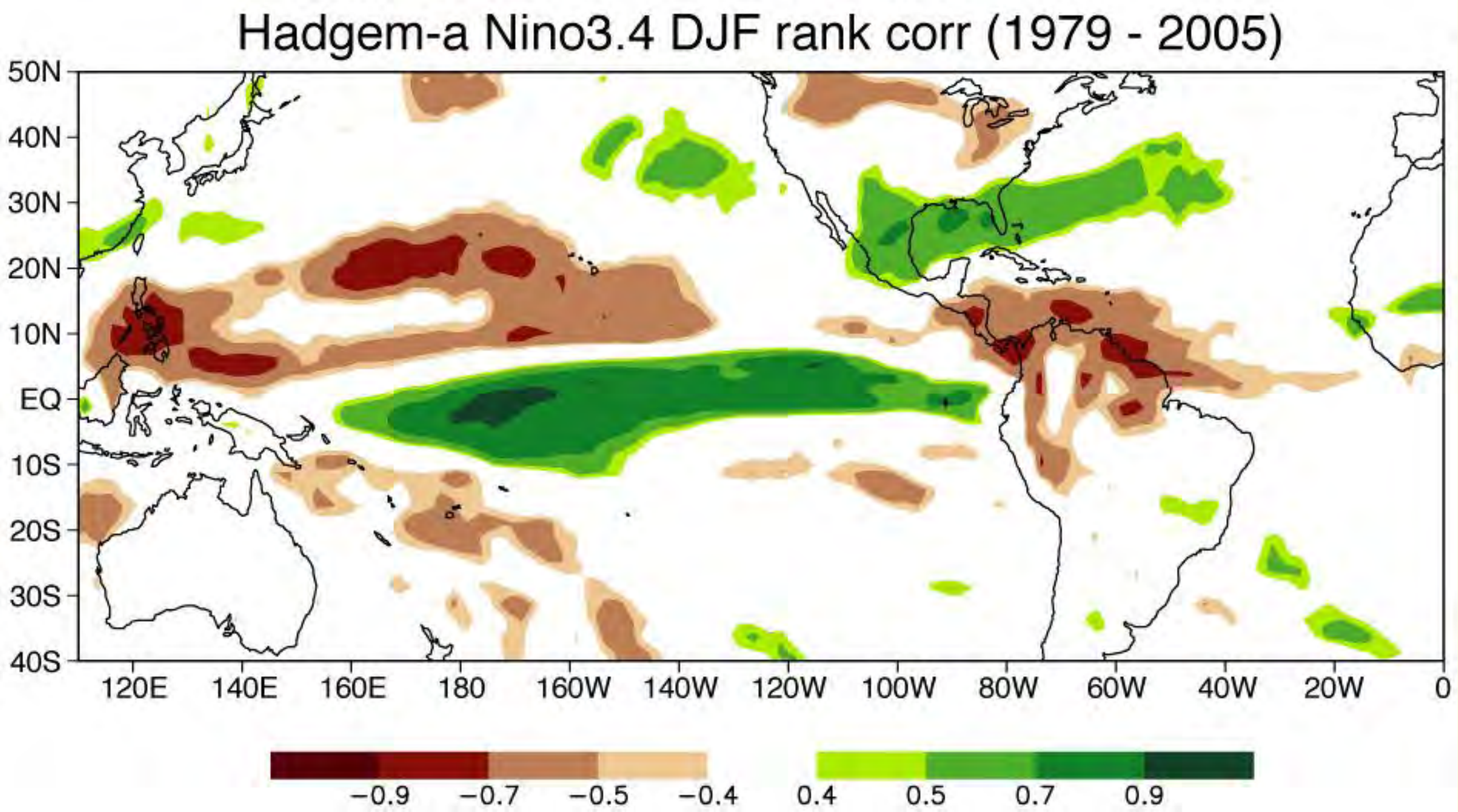
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.) CSIRO



Commonwealth Scientific and Industrial Research Organization, Aus.

CMIP5

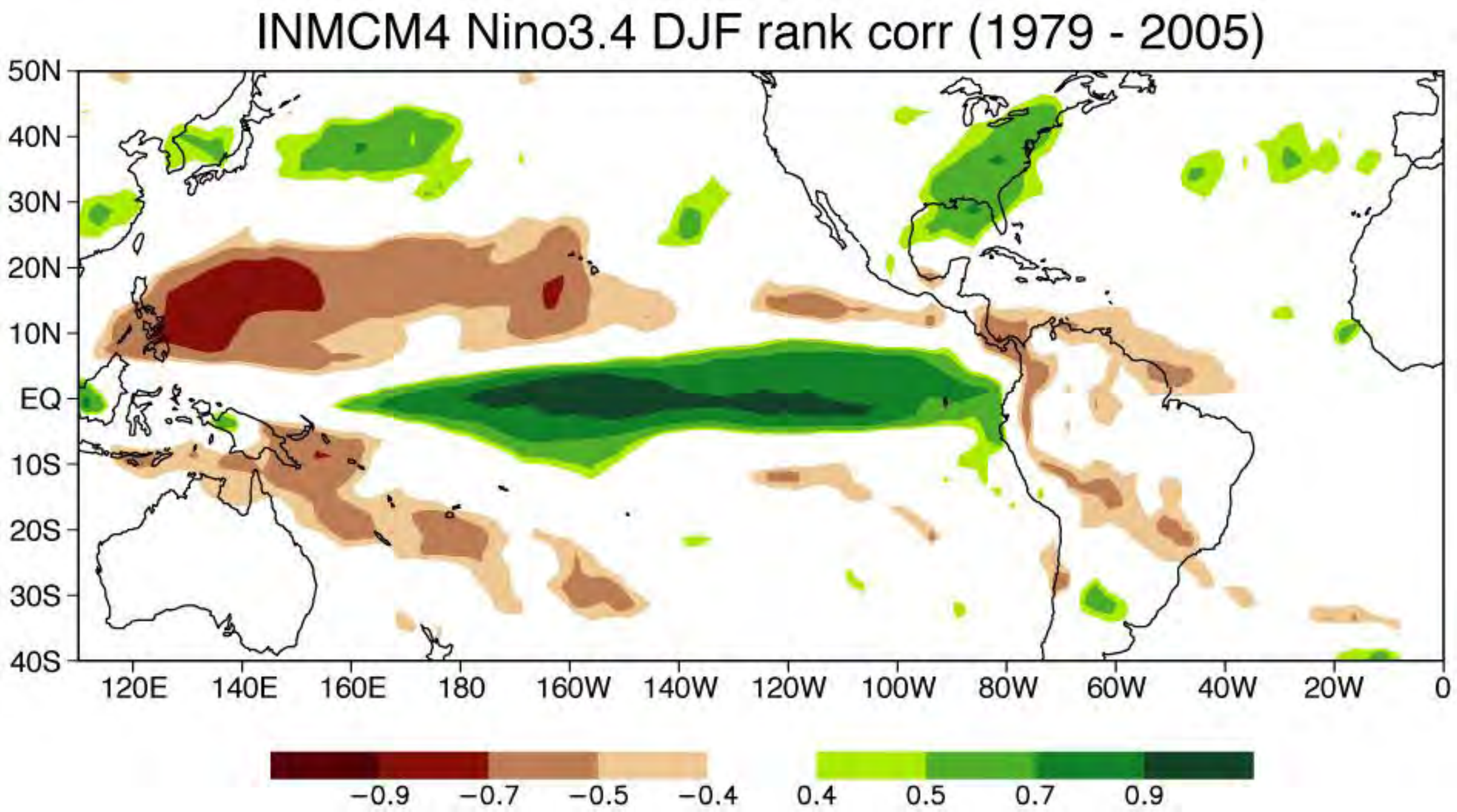
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.) HadGEM-A



Met Office Hadley Centre, UK.

CMIP5

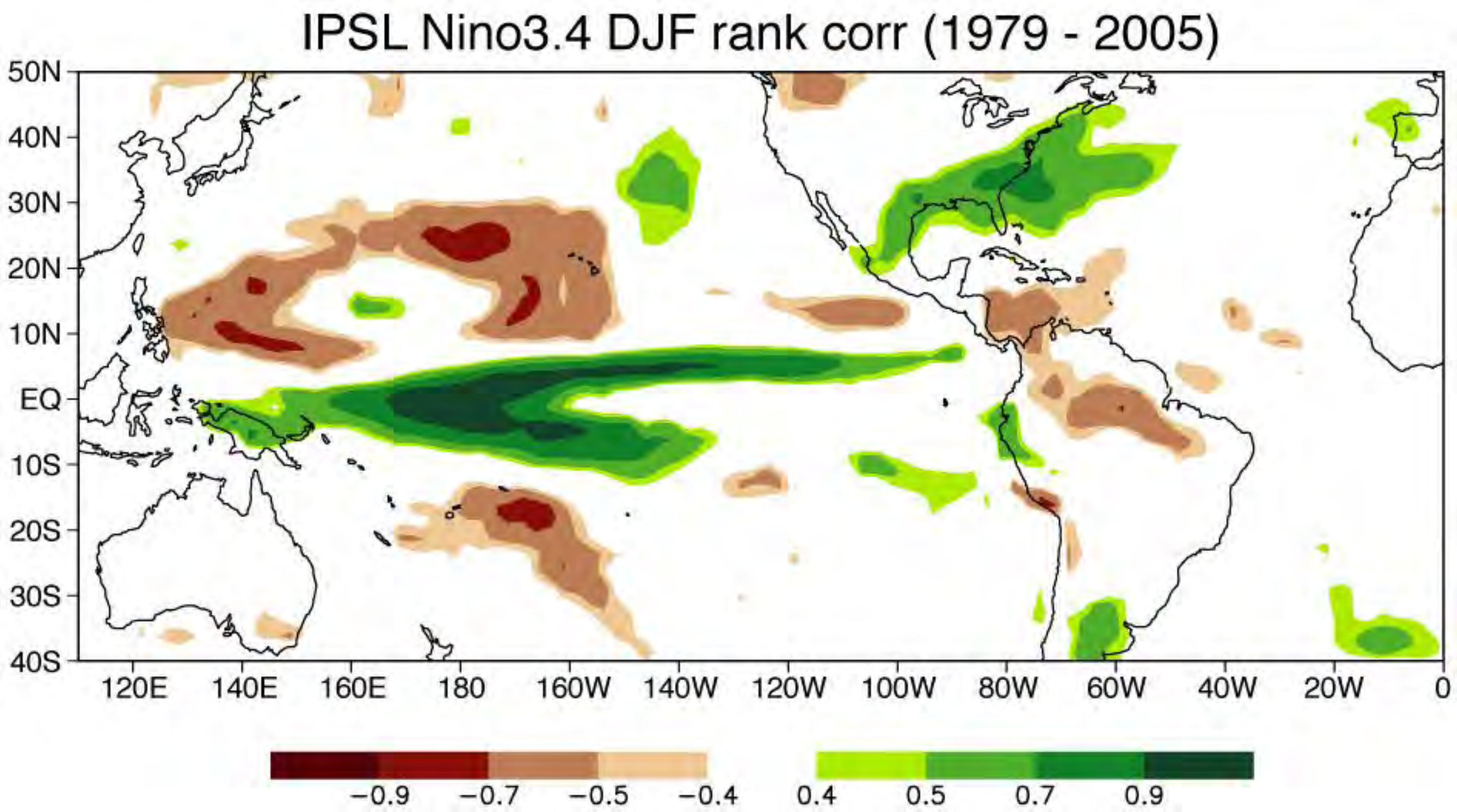
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.)
INMCM4



Institute for Numerical Mathematics, Russia.

CMIP5

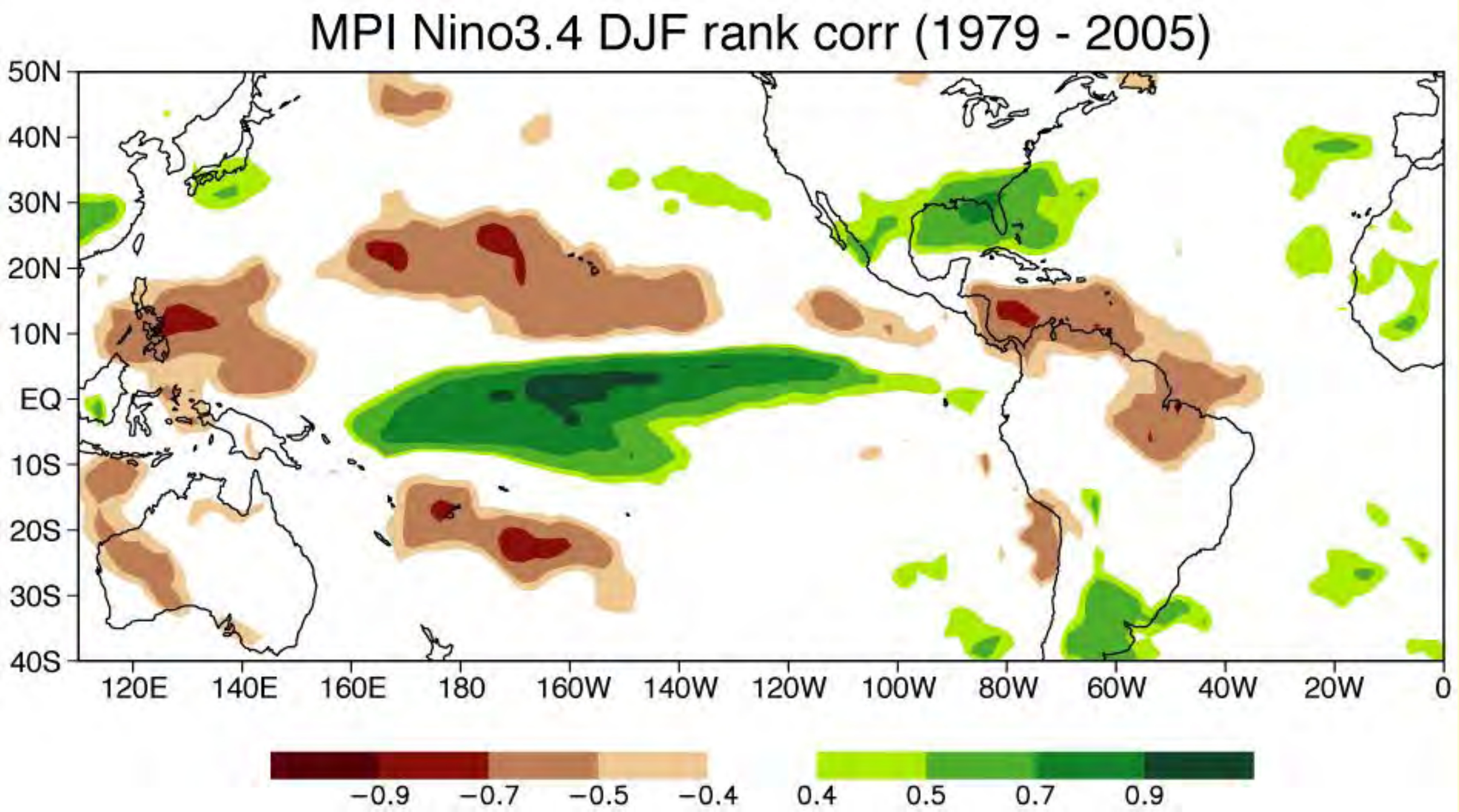
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.) IPSL



Institut Pierre Simon Laplace, France.

CMIP5

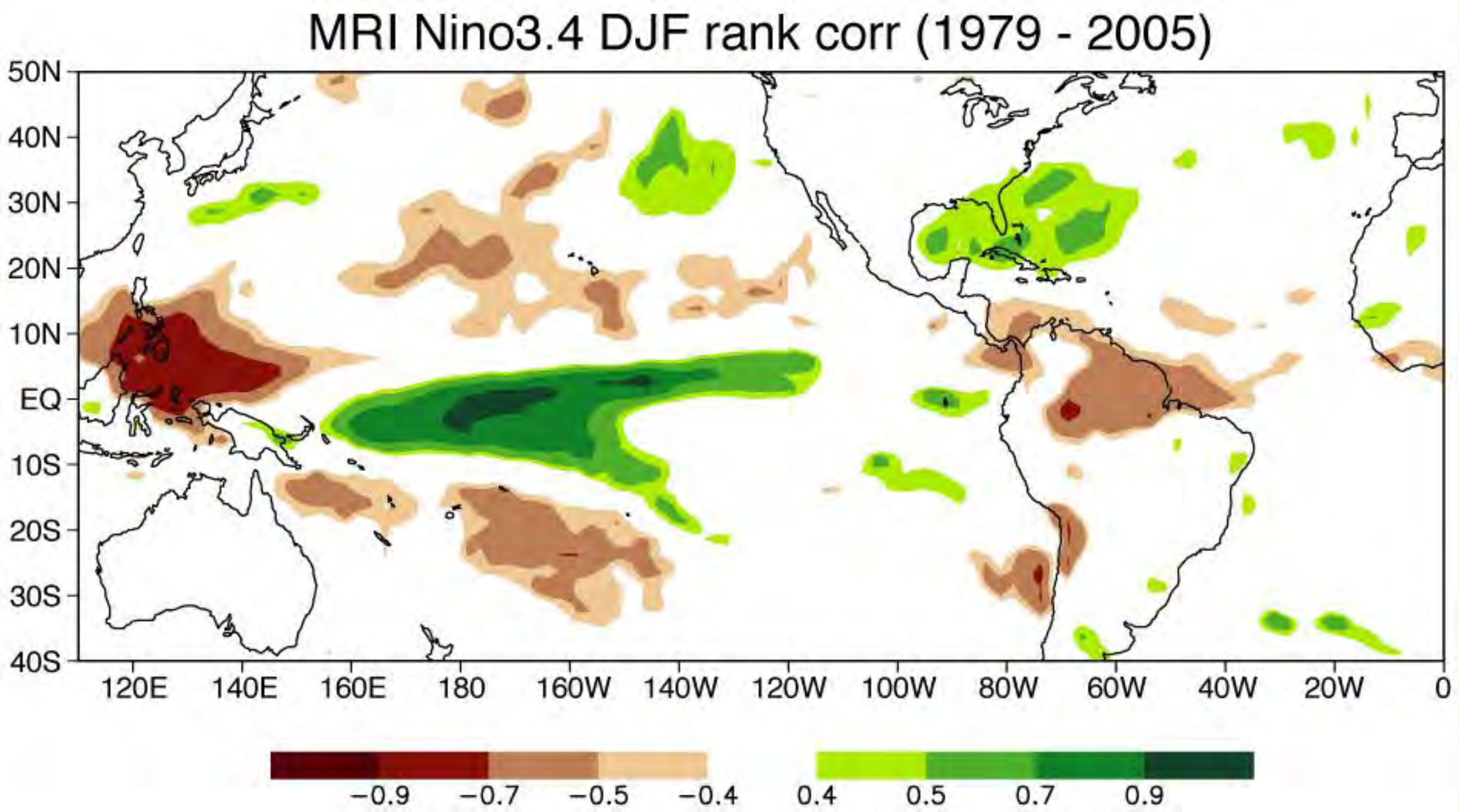
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.) MPI



Max Plank Institute, Germany

CMIP5

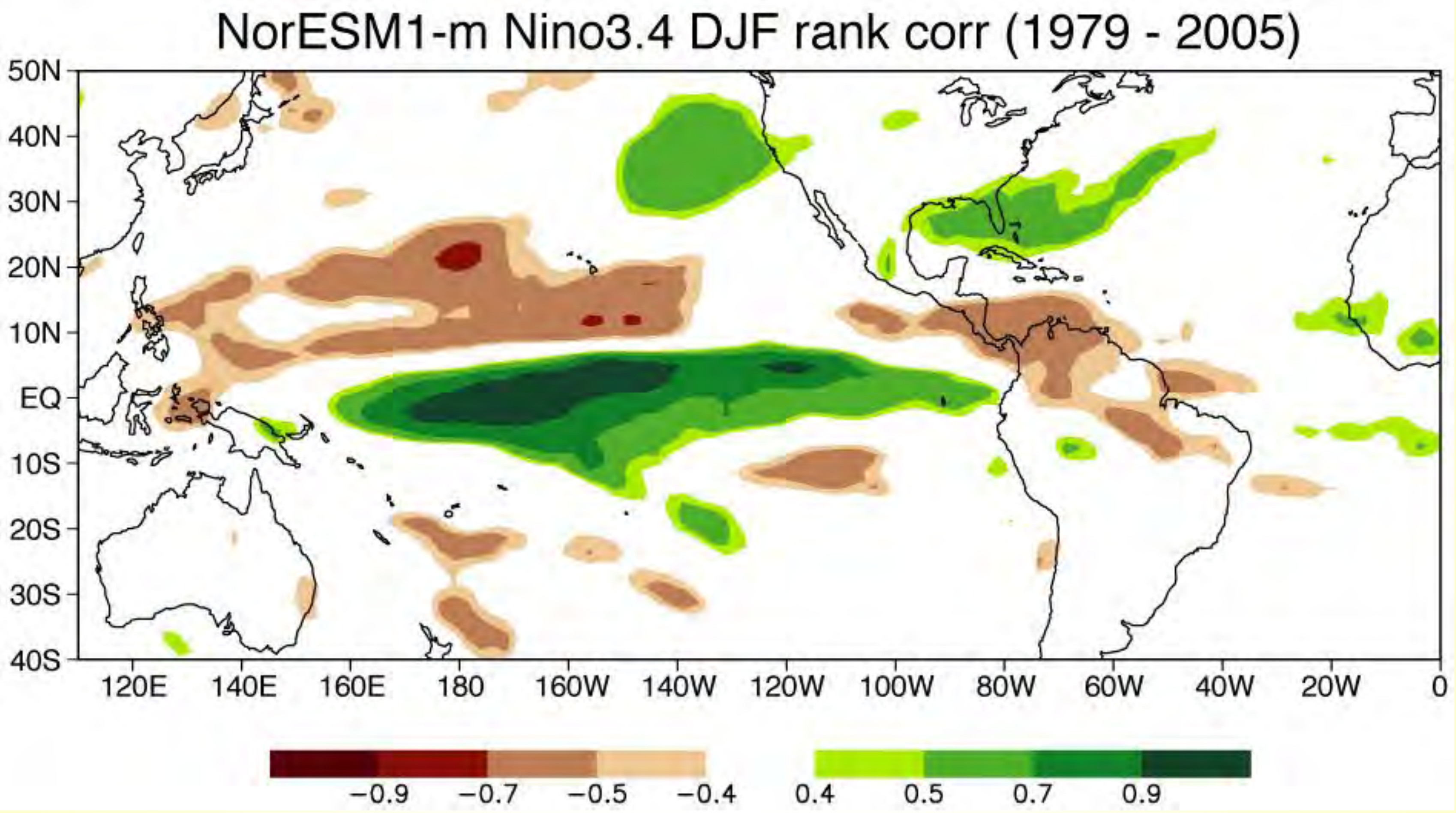
CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.)
MRI



Meteorological Research Institute, Japan

CMIP5

CMIP5 models nino3.4 rank corr. AMIP runs(Dec.-Feb.)
NorESM1-m



Norwegian Climate Center, Norway

Analysis: B. Langenbrunner

CMIP5

What is being done across the field?

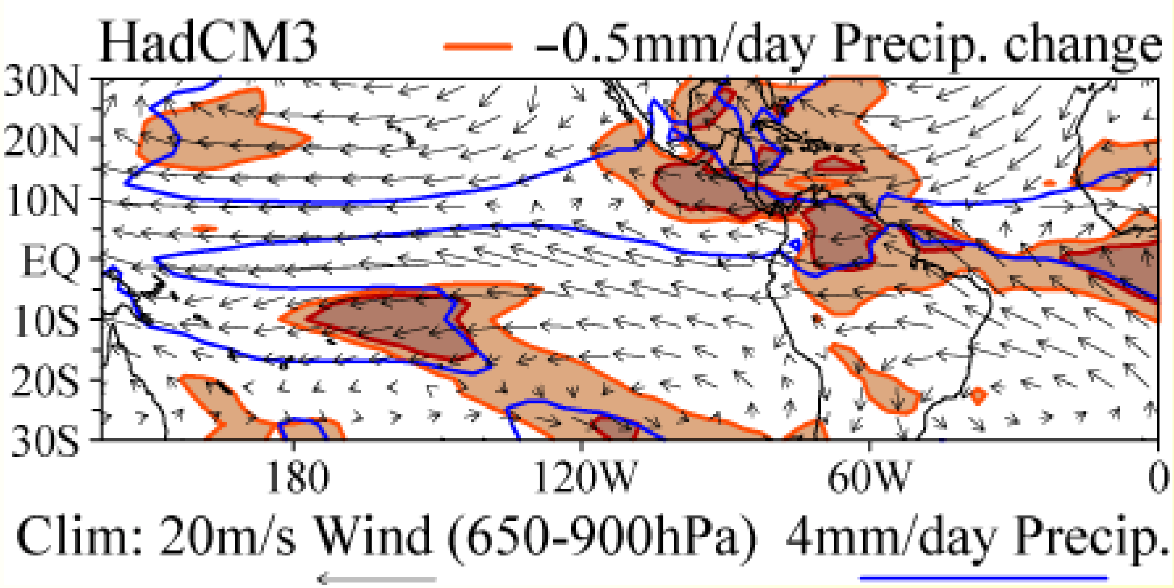
- Higher-resolution models… (no guarantee)
- Regional models (boundary conditions from global models)
- Multimodel ensemble means and general (vs. regional) statements
- Large satellite data sets, field campaigns, monitoring at Atmospheric Radiation Measurement sites….
- Need to digest in ways that better constrain parameterizations* of moist convection at short time scales
- Understanding of parameter sensitivity/uncertainty quantification; practical means of optimizing models with available data
- Alternatives to point by point multi-model ensemble mean

*Parameterization: representation of bulk effects of small-scale phenomenon as a function of grid-scale variables

Hypothesis for disagreement on regional scale:

- models have similar processes for precip increases and decreases but the geographic location is sensitive

…to differences in model clim. of wind, precip; convective closure (e.g. threshold)…



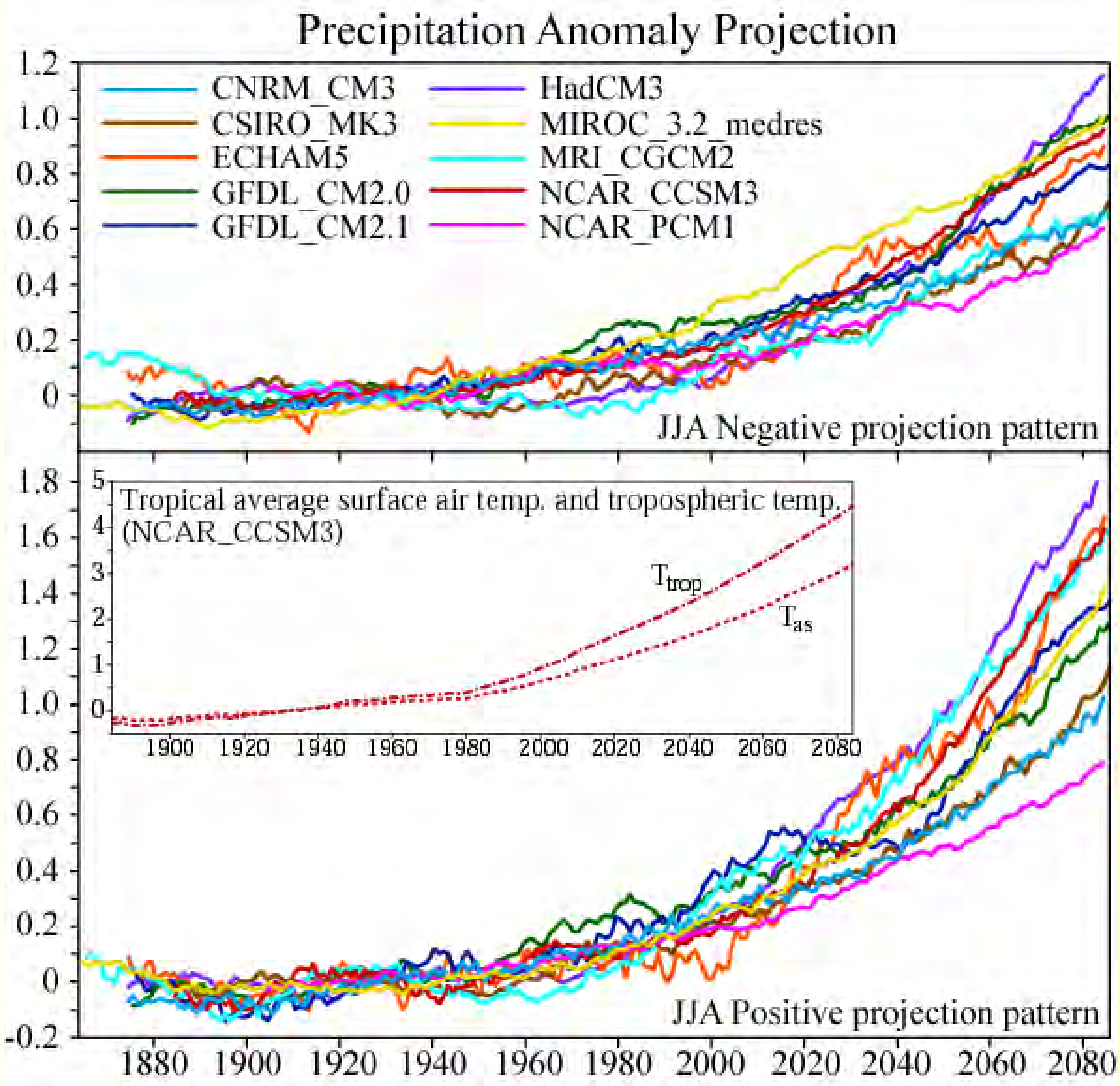
- agreement on amplitude measure*
- suggests strong regional changes are likely that are not reflected in multi-model averages.

*e.g., spatial projection of precip change on each model's own characteristic pattern

Despite disagreement on precise location, seek measures of extent of precip change that are more predictable

E.g., amplitude of precip incr/decr pattern shows better agreement

Projection of Jun-Aug (30yr running mean) precip pattern onto normalized positive & negative late-century pattern for each model

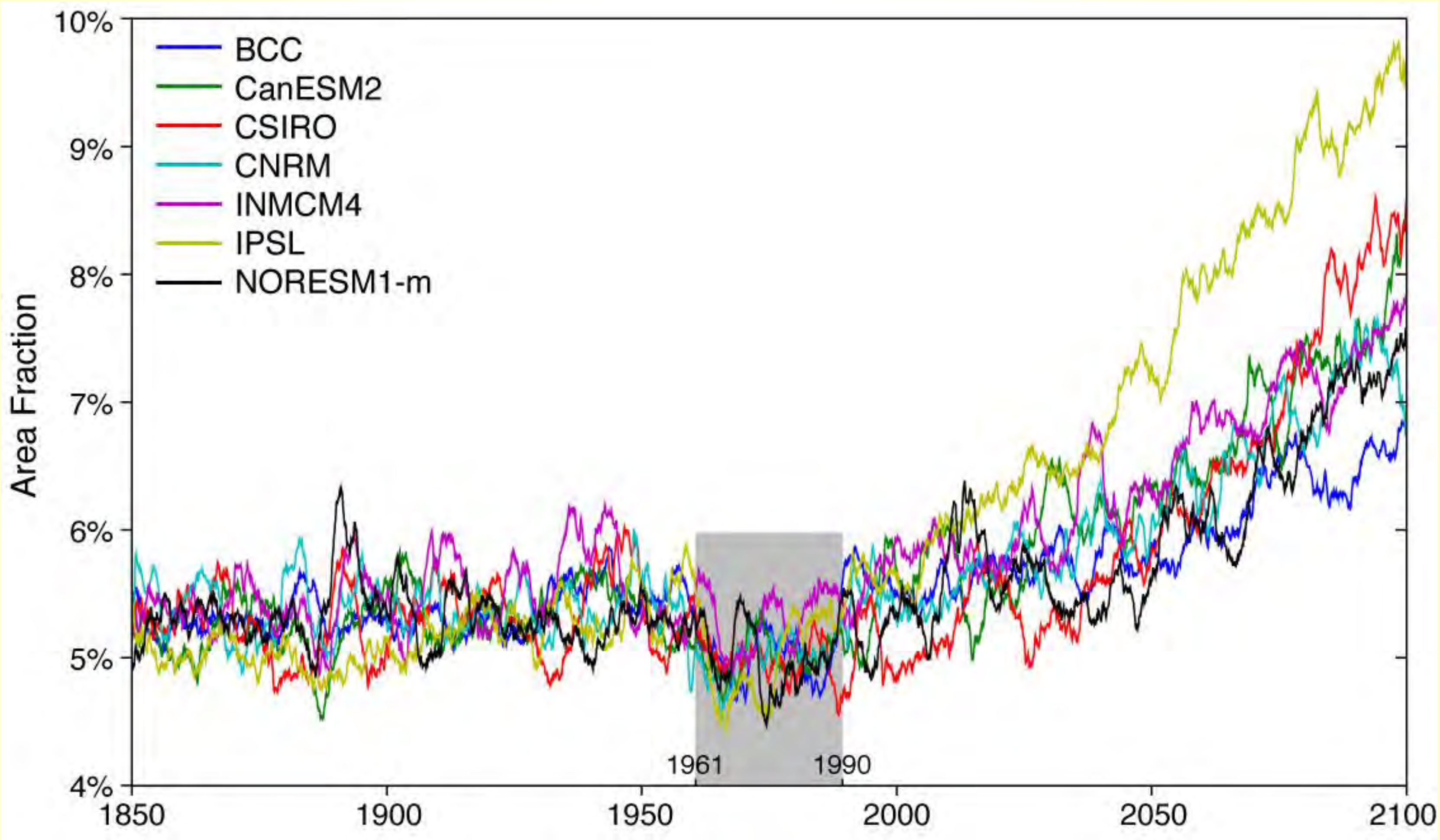


Neelin, Munnich, Su, Meyerson and Holloway , 2006, *PNAS*

CMIP3

Integrated measures of regional precip. change cont'd

Fraction of the globe with annual precipitation that would be in highest 5% (~20 year wet spell) during base period (1961-1990) for each model

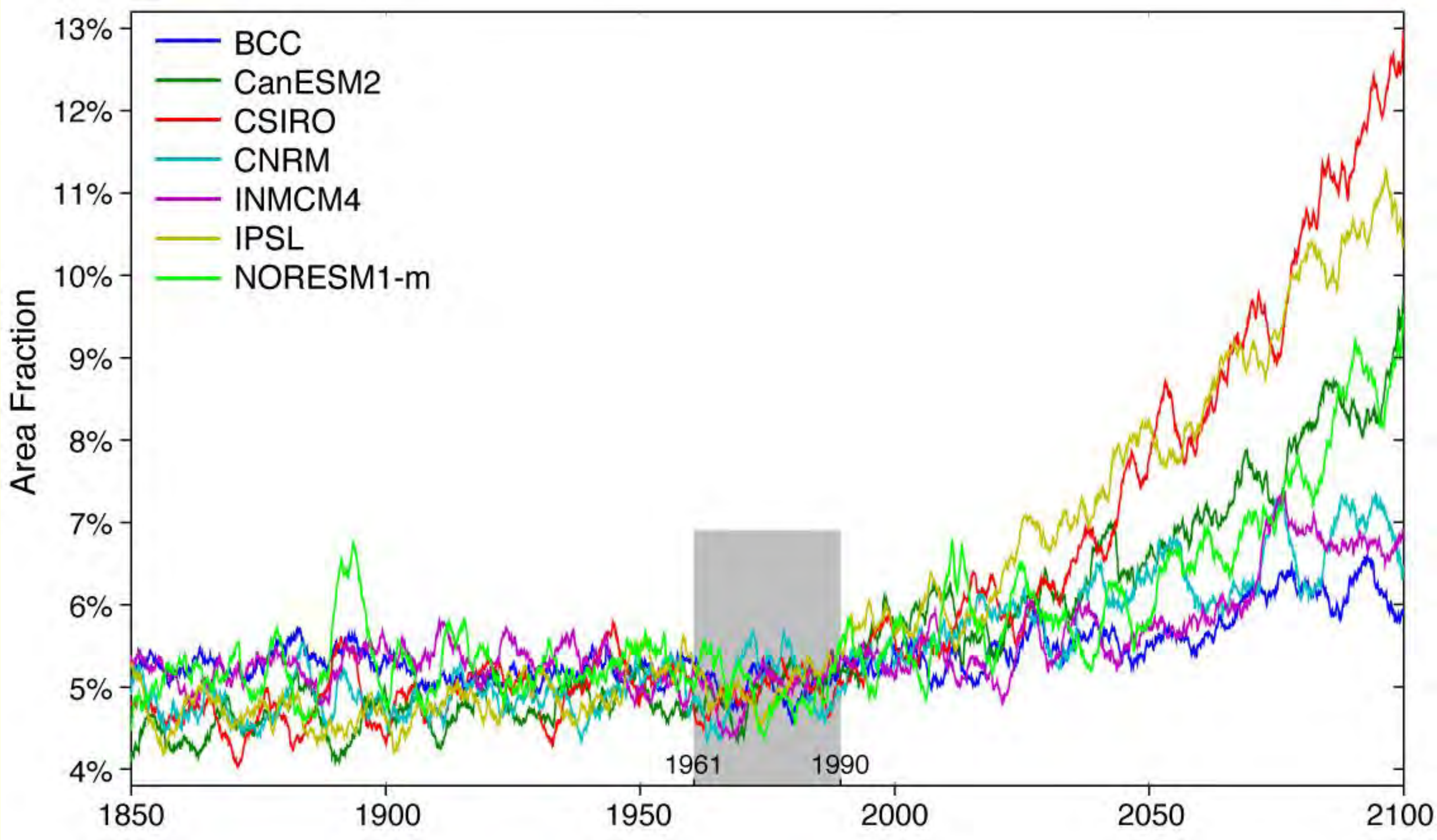


CMIP5

Analysis: B. Langenbrunner ; five year running mean shown for graphical clarity

Integrated measures of regional precip. change cont'd

Fraction of the globe with annual precipitation that would be in lowest 5% (~20 year drought) during base period (1961-1990) for each model



Analysis: B. Langenbrunner ; five year running mean shown for graphical clarity

CMIP5

Are there fundamental considerations in climate model sensitivity that techniques borrowed from optimization methods can help with?

- **Precipitation parameter sensitivity a critical limitation to confidence levels in regional scale projections---arguably more important for impacts this century than climate sensitivity for global average temperature**
- **How nonlinear is this sensitivity? E.g., convection has sharp threshold for onset, but climate avgs over many instances**
- **Can we infer implications for the model improvement process and the use of multi-model ensemble averages to estimate projected precipitation changes?**

Neelin, Bracco, Luo, McWilliams, Meyerson, 2010, *PNAS*.

Precipitation sensitivity cont'd

- **Interest in systematic parameter sensitivity (esp. global avg climate sensitivity) and optimization in climate models**
  (Severijns & Hazeleger 2005 *Clim. Dyn.*, Stainforth et al. 2005 *Nat.*, Jones et al. 2005 *Clim. Dyn.*, Knight et al. 2007 *PNAS*, Kunz et al. 2007 *Clim. Dyn.*, Jackson et al. 2008 *J. Clim.*, Rougier et al. 2009 *J. Clim.*,…)
- **# parameters *N* can easily be *>10*; *a priori* feasible range**
- **Brute force sampling at density *s* gives order s^N problem, but e.g. ~N^2 depending on nature of parameter dependence.**

Rough/smooth? High-order nonlin? Irreducible imprecision?

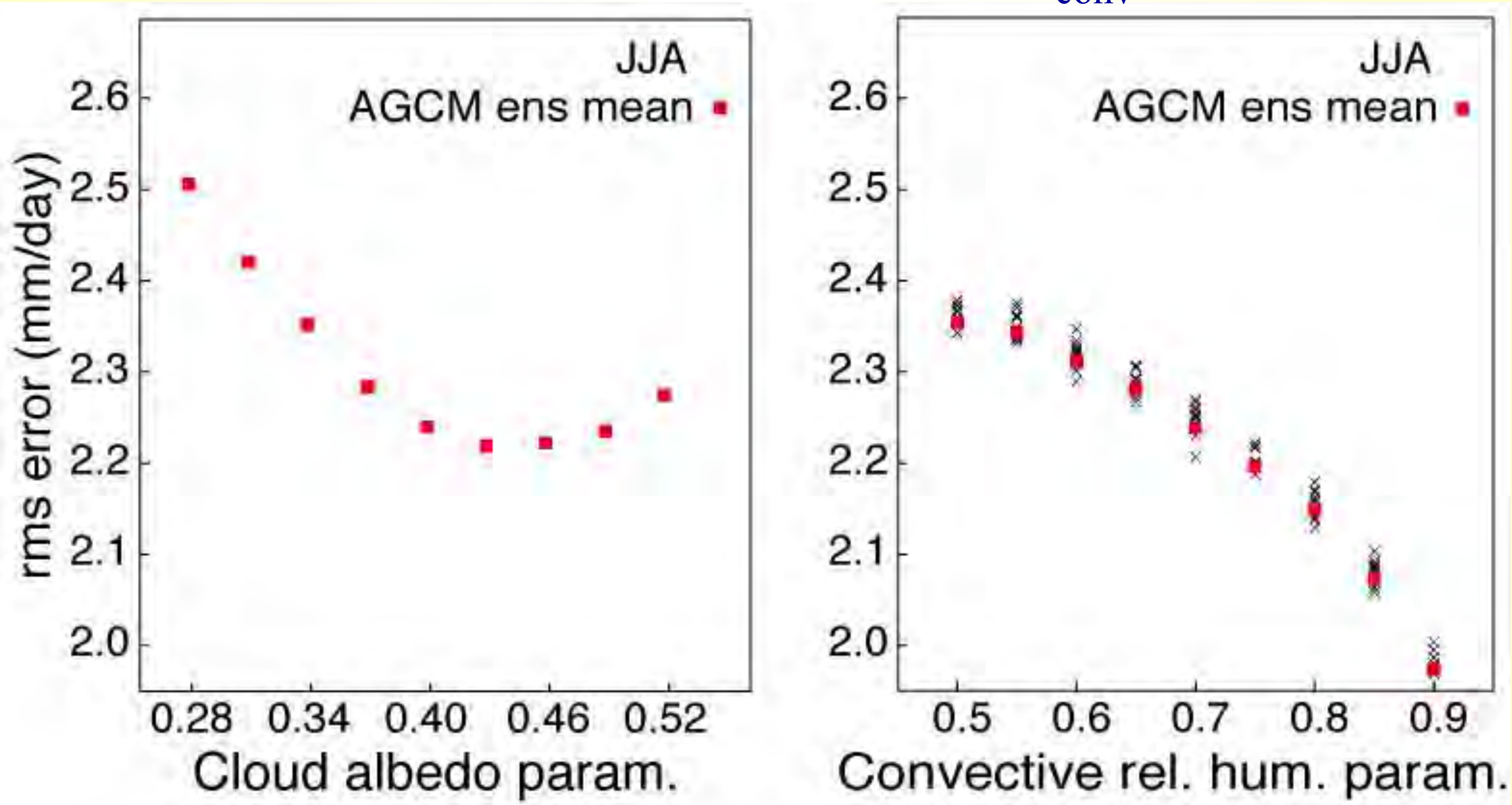
- **Here examined in the ICTP climate model**

*International Centre for Theoretical Physics atmospheric general circulation model: ICTP AGCM; Molteni F., 2003, Climate Dyn.; Bracco et al. 2004, Climate Dyn.)

- Eight Sigma-levels, spectral triangular truncation T30 ~3.75 x 3.75-degree

Parameter dependence of RMS error* of June-Aug. precip as a function of cloud albedo, convective rel. hum., RH_{conv}

AGCM ensemble mean over 10*25-year runs, (with observed sea surface temp.).
Vertical size of symbol=2*standard error of ensemble mean
Individual ensemble members shown for RH_{conv}



Neelin, Bracco, Luo, McWilliams, Meyerson, 2010, *PNAS*.

*(vs. NCEP reanalysis)

Metamodel fit to param. dependence of AGCM fields

Try **quadratic metamodel** on space of N **parameters μ_i** for **field φ**

$$\tilde{\varphi} = \varphi_{std} + \sum_{i}^{N} a_i \mu_i + \sum_{i=1}^{N} \sum_{j=1}^{N} b_{ij} \mu_i \mu_j$$

Simple but important: linear coefficient $a_i(x,t)$ & quadratic coefficient $b_{ij}(x,t)$ are spatial & seasonal fields

•e.g. of **entry-level strategy for "computationally-expensive black-box functions"** (cf. review by Shan & Wang, 2010, Struct. Multidisc. Optim.)

•φ can be a climatological field, anomaly regression, or other statistic from model output. Adopt multi-objective approach (for each field).

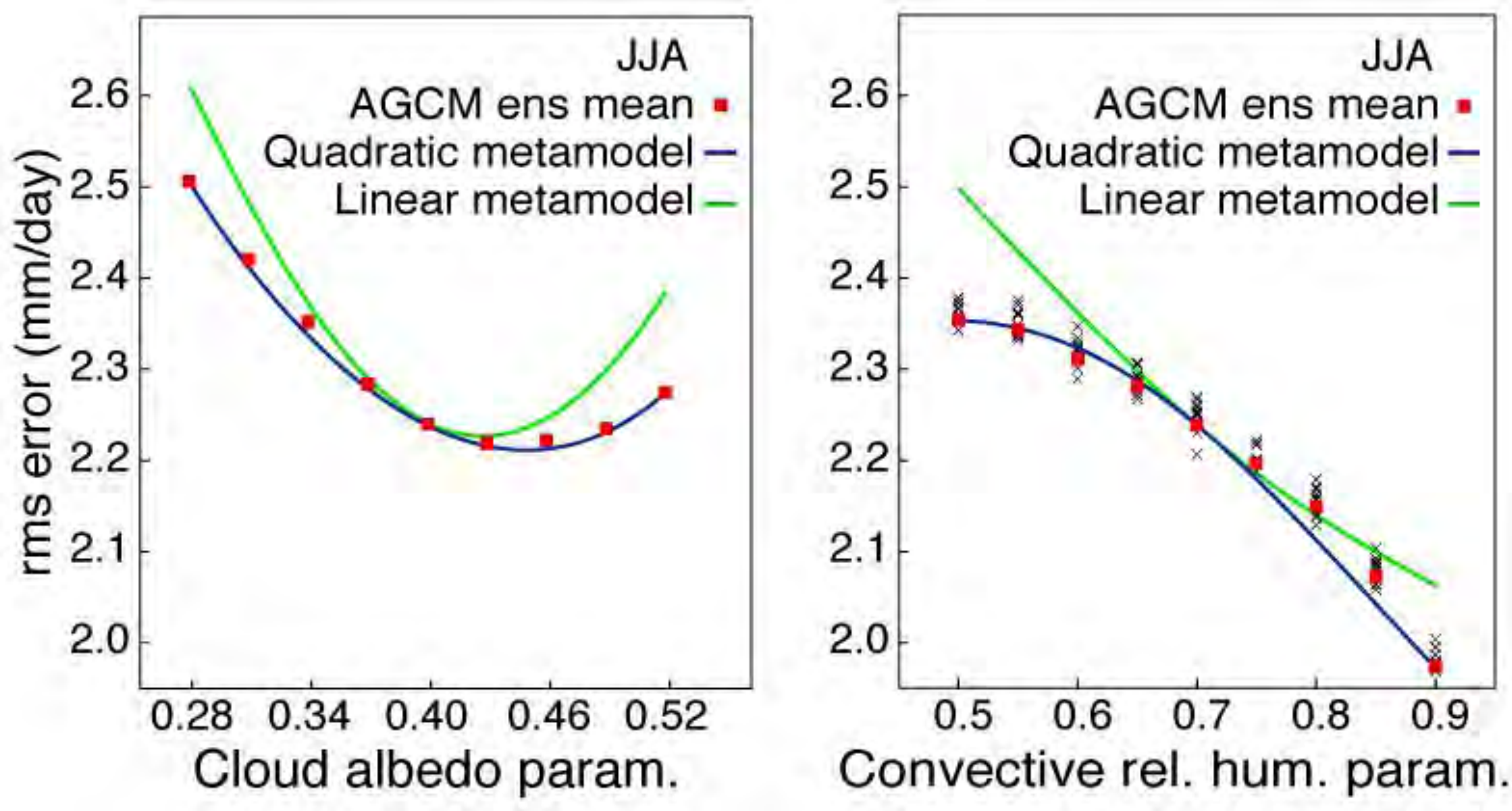
•Then construct objective function, e.g., rms error $\left\langle \left[\tilde{\varphi}(\mu_i) - \bar{\varphi} \right]^2 \right\rangle^{1/2}$ (or sq. error, spatial correlation…) with ⟨⟩ typically a spatial mean, φ_{obs} observed, φ_{std} the GCM for standard parameters

•First fit: $a_i(x,t)$, $b_{ii}(x,t)$ from the **2N** endpoints of the μ_i ranges (order N integrations even if add redundant points).

•For off-diagonal $b_{ij}=b_{ji}$: order N^2 (at least $N(N-1)/2$ simulations).

RMS error of June-Aug. precipitation (vs. NCEP) as a function of cloud albedo, convective RH

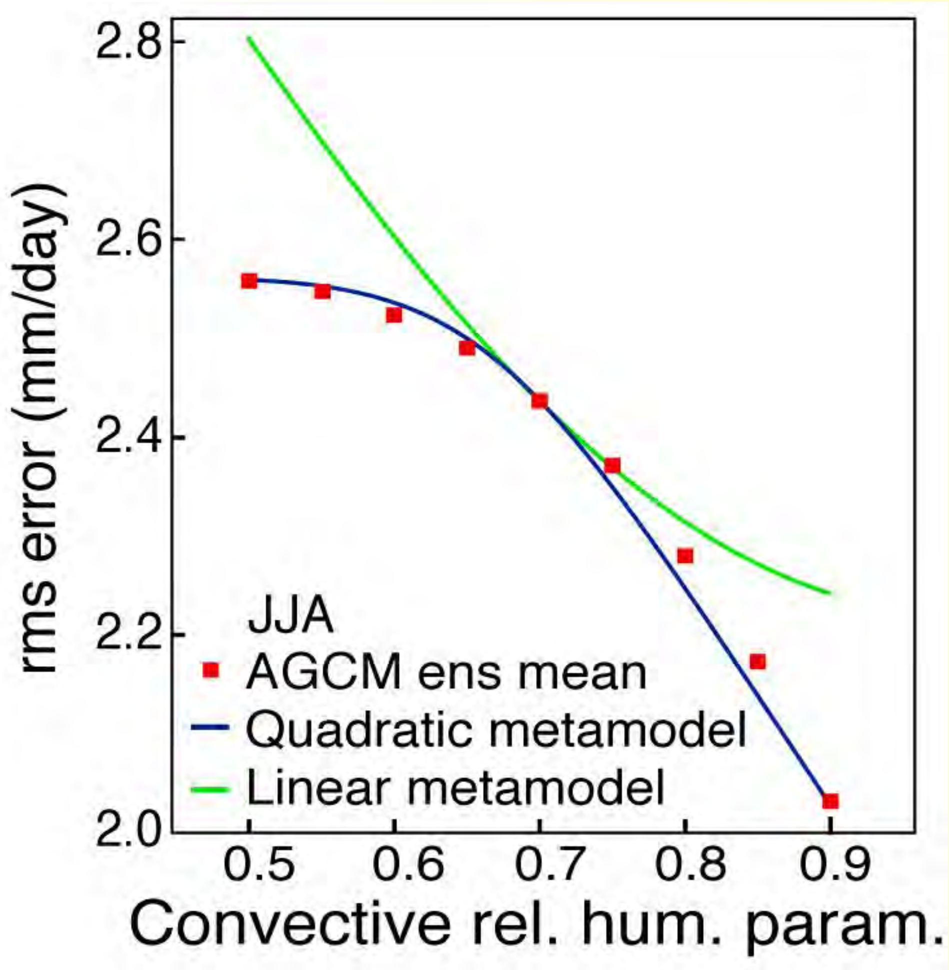
AGCM ensemble average versus linear and quadratic metamodels. Note negative curvature for relative humidity, due to ~quadratic nonlinearity in spatial field. No interior minimum ⇒ boundary solution in constrained optimization problem



Neelin et al. 2010.

RMS error of June-Aug. precipitation (vs. reanalysis) as a function of convective RH but AGCM coupled to a mixed-layer (ML) ocean (preindustrial CO_2)

•Same properties in coupled model
AGCM-ML average (250 yrs) versus linear and quadratic metamodel. Negative curvature for relative humidity (assoc. with ~quadratic nonlinearity in param. dependence of spatial fields) as in specified SST case.
Vertical size of symbol=2*standard error



Neelin, Bracco, Luo, McWilliams, Meyerson 2010, *PNAS*.

Role of high dimensional fields in improvement challenges

Common experience: One region improves but another gets worse!

Illustrate with case* of objective function *f*, **(e.g. RMS precip error)** with standard case error φ_{err}

$$\partial_{\mu_i} f = g_i + A_{ii}\mu_i = 0$$

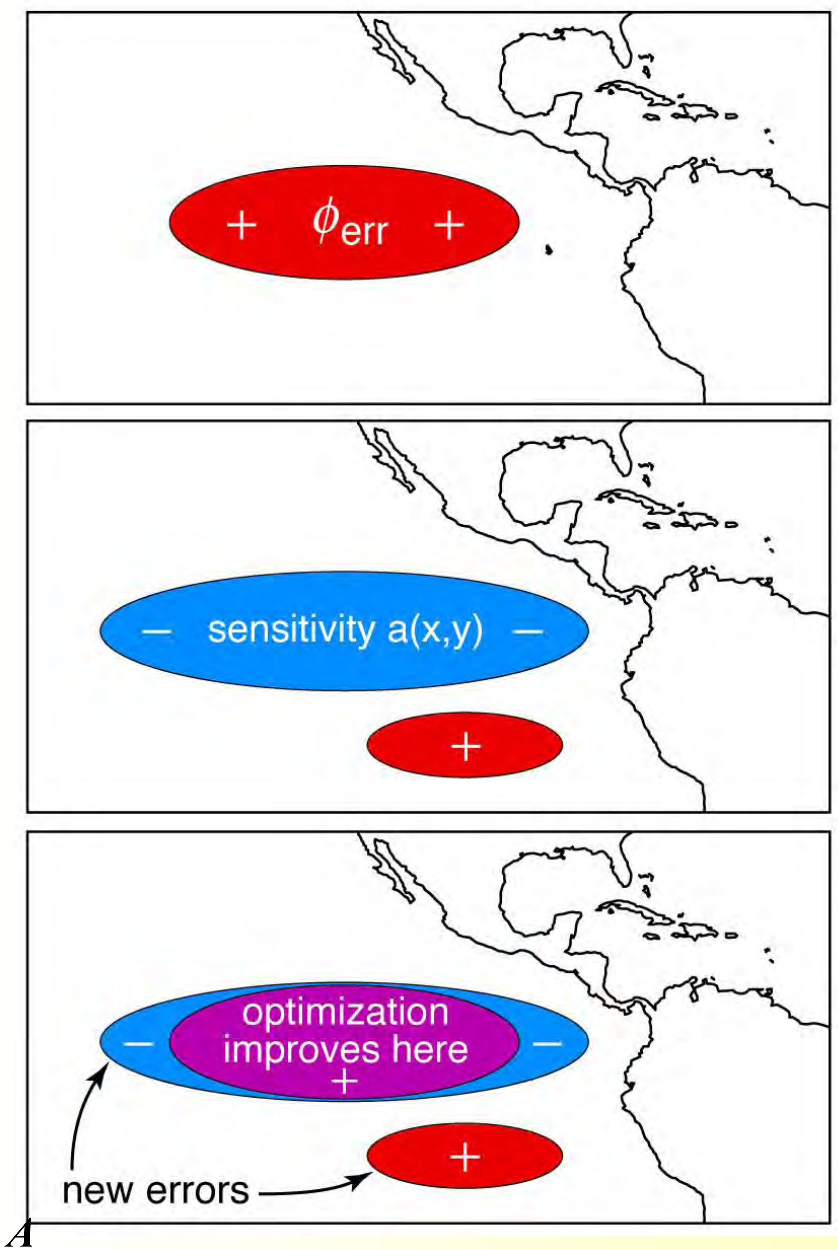
$$g_i = 2\langle a_i \varphi_{err}\rangle,$$

$$A_{ii} = 2(\langle a_i^2\rangle + 2\langle b_{ii}\,\Delta\varphi\rangle)$$

$\langle\rangle$ spatial average, metamodel linear coeff a_i, quadratic b_{ij}. For simplicity neglect b_{ij} in curvature.

$$\Rightarrow \mu_i = -\langle a_i \varphi_{err}\rangle / \langle a_i^2\rangle$$

If sensitivity a_i had same spatial pattern as the standard case error $\varphi_{err}=\varphi_{std}-\varphi_{obs}$, this would cancel the error. Instead, compromise between reducing φ_{err} and introducing new error.



*case of interior minimum for diagonally dominant Hessian *A*

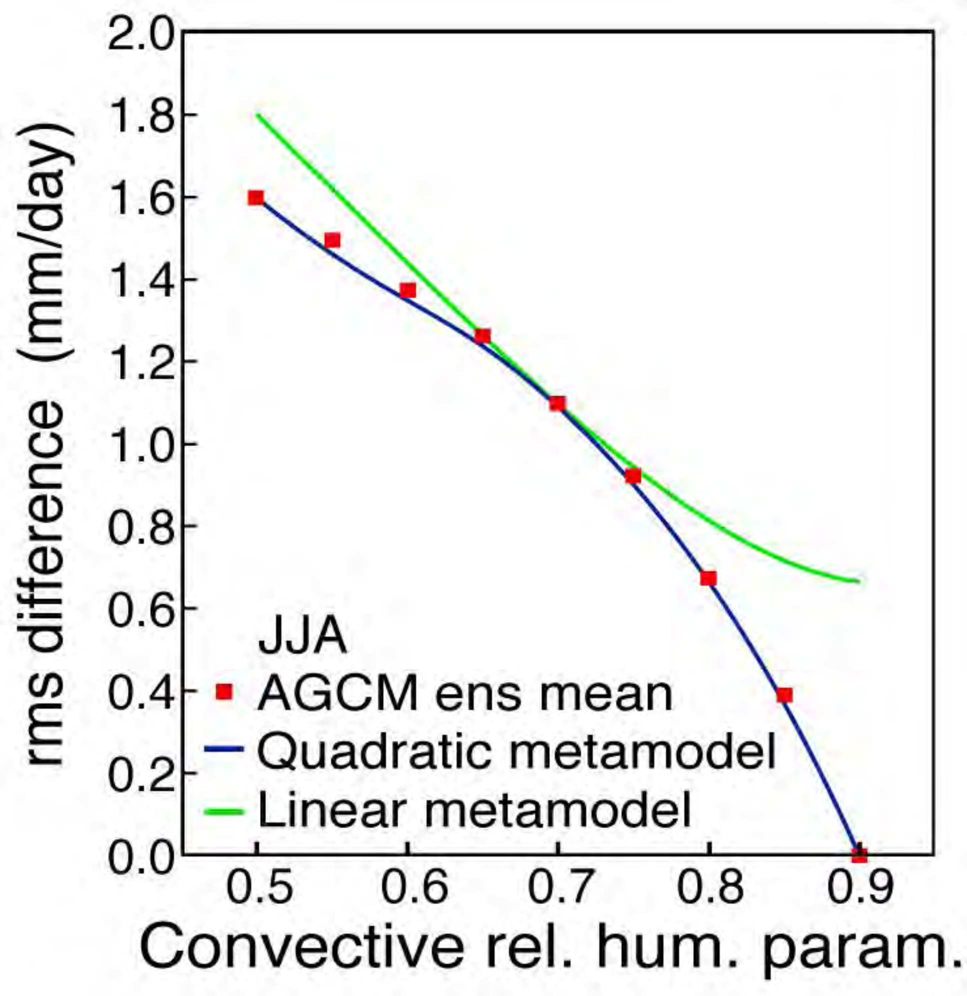
Parameter dependence for precipitation (etc) changes under global warming: Implications for multi-model ensemble average

- Does sensitivity across the feasible parameter domain provide a prototype for differences among models?
- If so, multi-model ensemble average ~ random sampling
- If parameter dependence is linear, and distribution of sample points is unbiased with respect to "true" parameter value multi-model ensemble average should work well
- parameter directions with (1) strong nonlinearity or (2) boundary optima (suggesting sampling across feasible range likely biased) can limit usefulness of multi-model ensemble average; e.g., convective rel. humidity param.

RMS difference (vs. Rh_{conv}=0.9) of June-Aug. precipitation change as a function of convective RH for AGCM-ML $2xCO_2$ minus preindustrial CO_2

AGCM ensemble average versus linear and quadratic fit. Note negative curvature for relative humidity, due to quadratic effects.

Global warming precipitation change parameter dependence



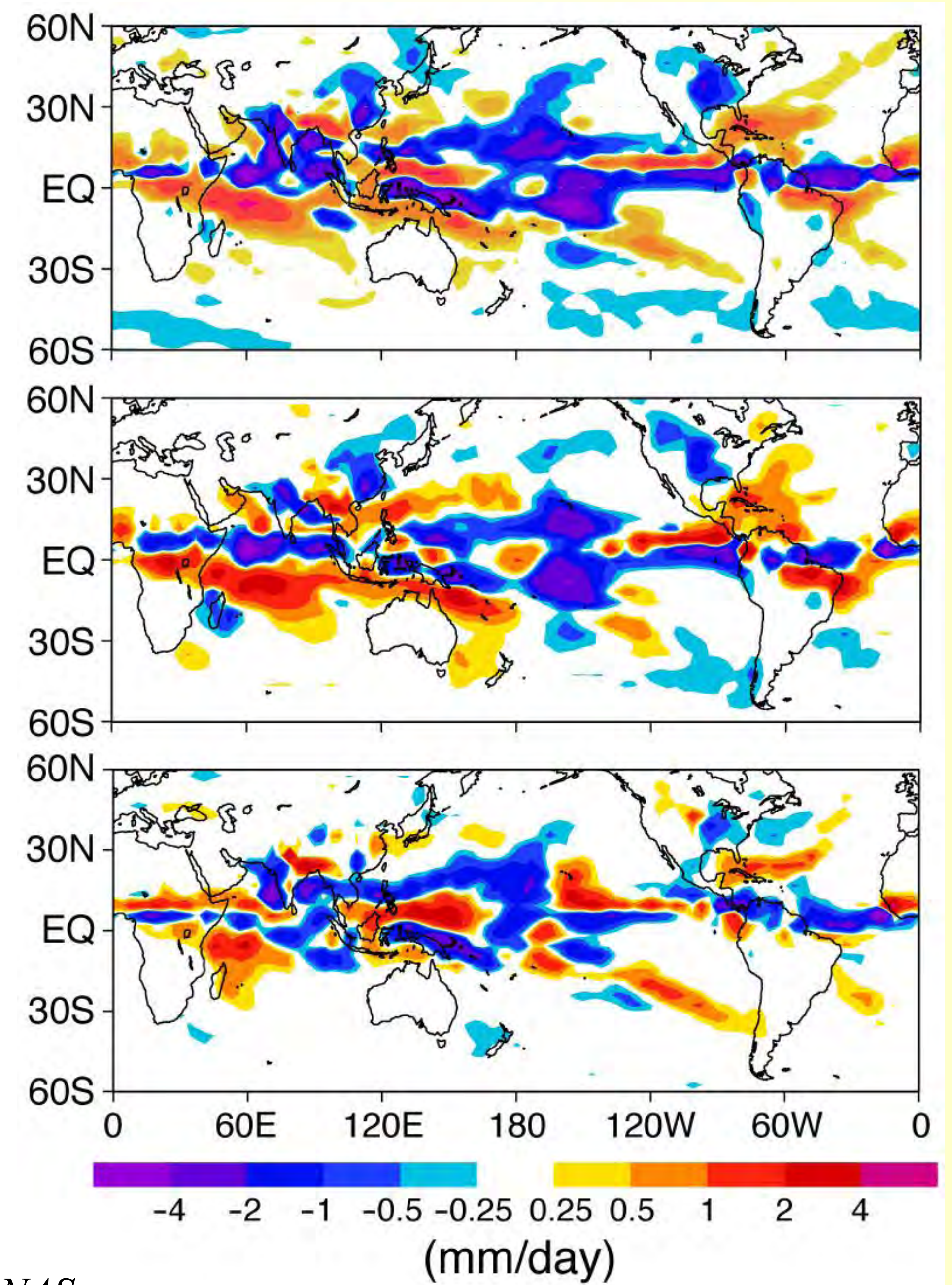
Neelin, Bracco, Luo, McWilliams, Meyerson 2010, *PNAS*.

Global warming precipitation change parameter sensitivity

Ensemble-mean JJA precipitation (as a departure from the annual mean) for Conv. rel. hum. param μ_{max} relative to the standard case for AGCM coupled to a mixed-layer ocean: change for $2xCO_2$ minus pre-industrial.

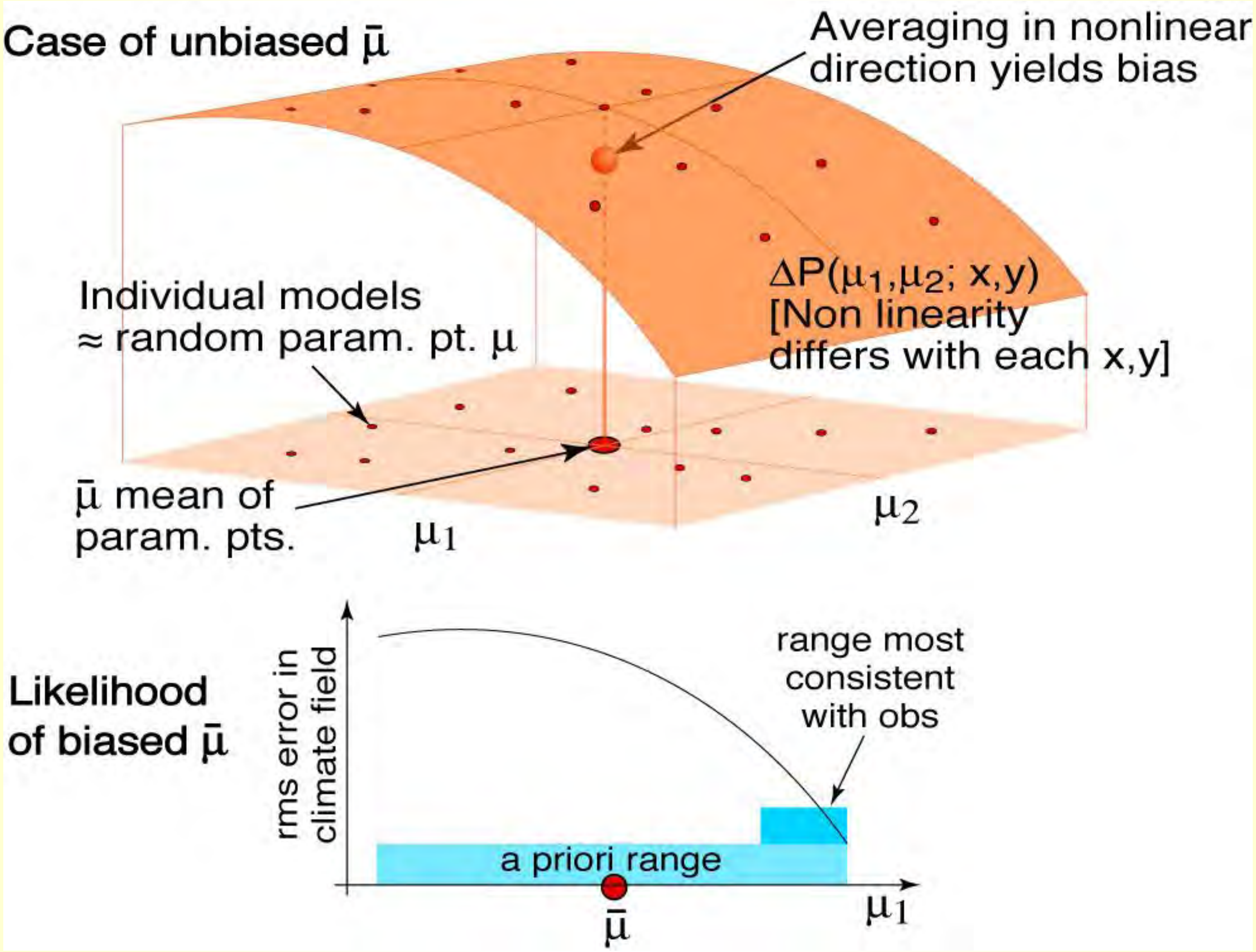
Linear contribution

Nonlinear contribution



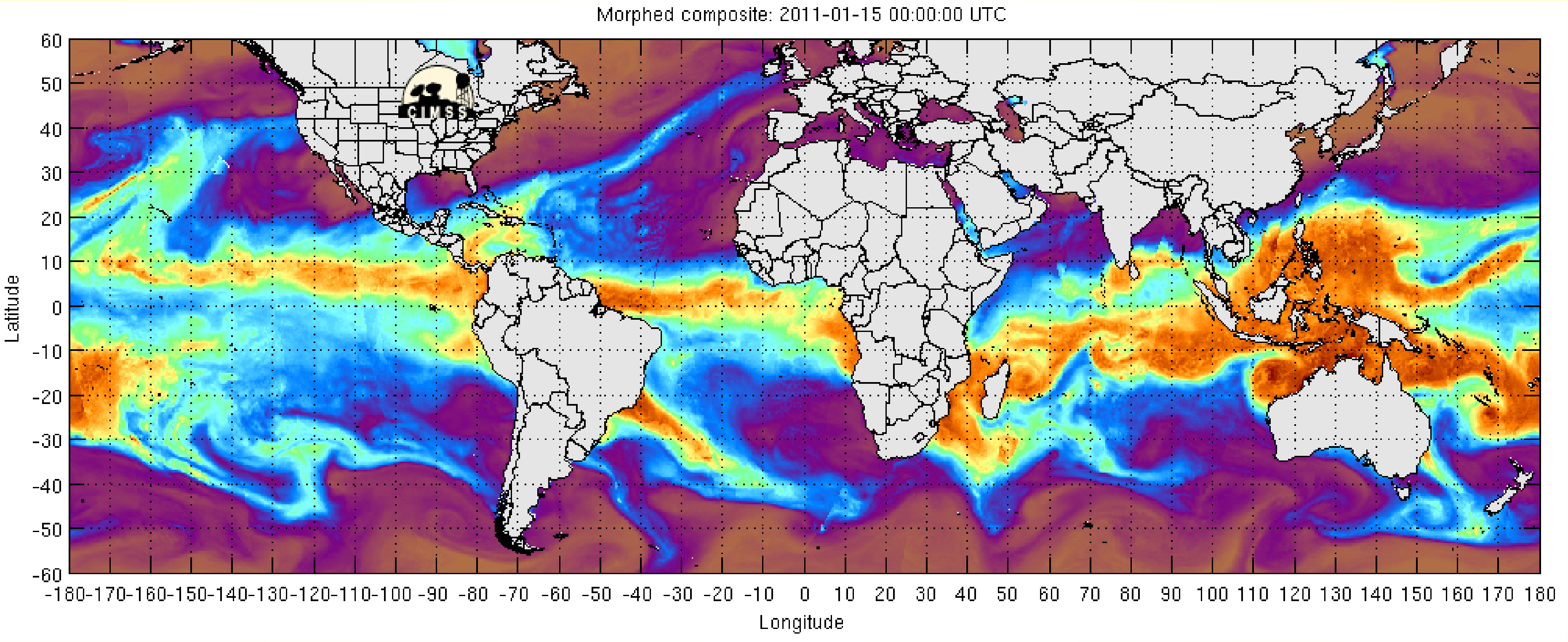
Neelin, Bracco, Luo, McWilliams, Meyerson 2010, *PNAS*.

Implications for multi-model ensemble average



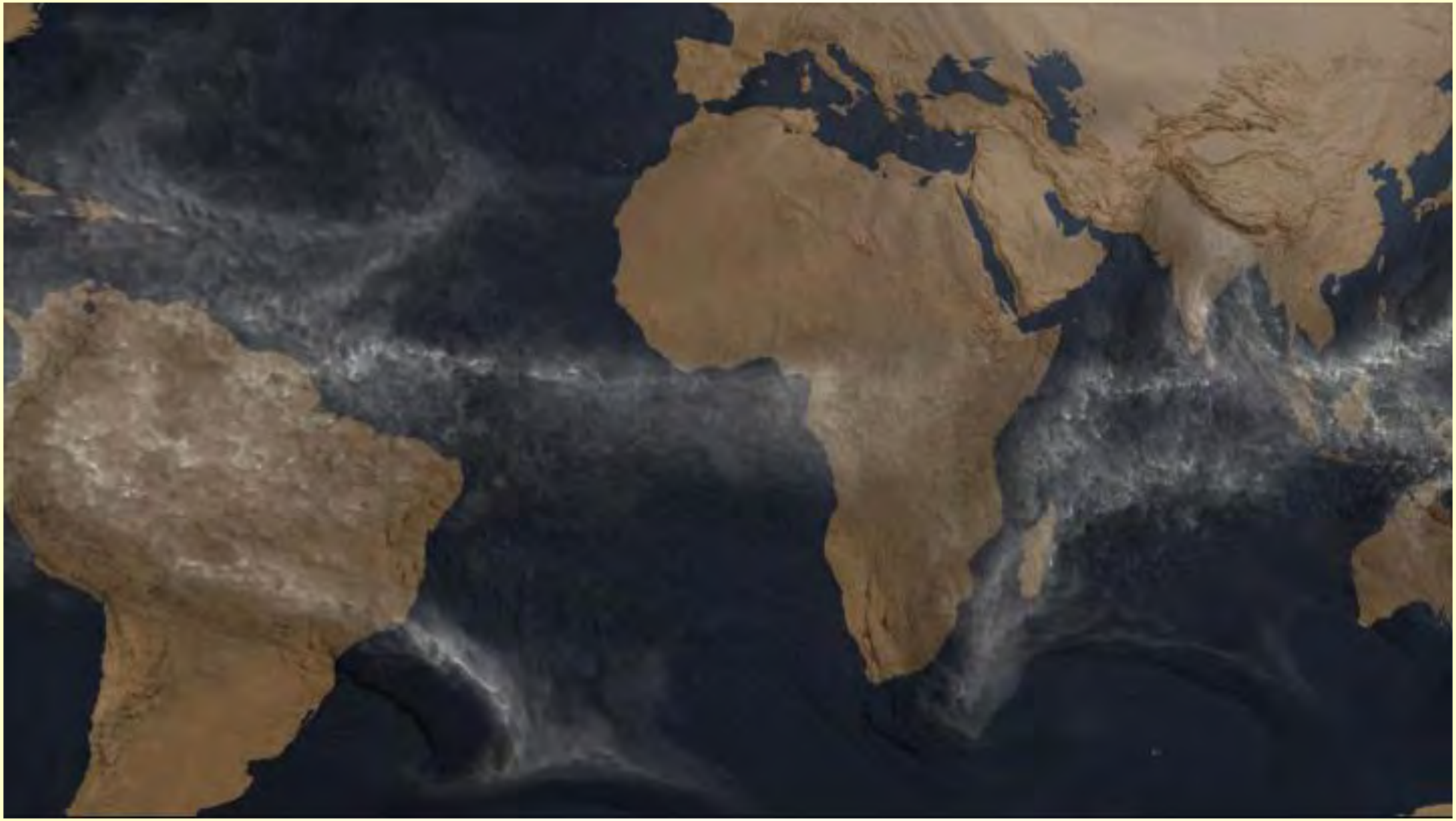
Back to fundamentals: better constraining and representing processes at small time/space scales

Column integrated water vapor—observational estimate from microwave retrievals*



*Satellite instruments: AMSR-E, SSMI; dynamic interpolation Wimmers & Velden (2007); footprint of input ~15 km; swath width ~1400 km; retrieval algorithm Alishouse et al. (1990)

Column water vapor from NCAR CAM4* at 0.125° resolution



*National Center for Atmospheric Research Community Atmosphere Model, HOMME spectral element dynamical core. Courtesy Mark Taylor (Sandia NL) & Rich Neale (NCAR).

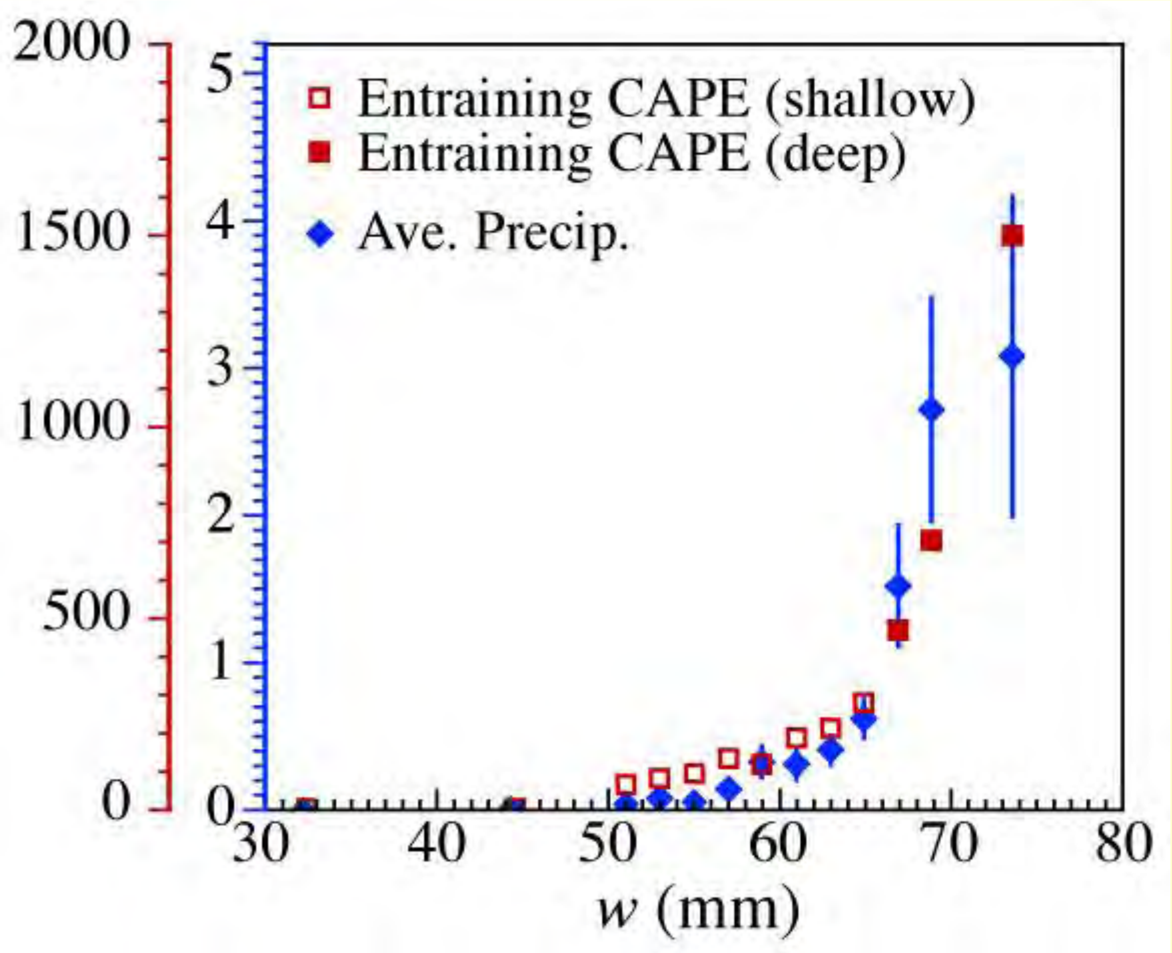
An example of quantifying convective onset:

Precipitation binned by column water vapor, *w*

- **buoyancy & precip. pickup at high *w***

- **Entraining convective available potential energy (CAPE) can match onset---if include enough turbulent entrainment into convecting parcel**

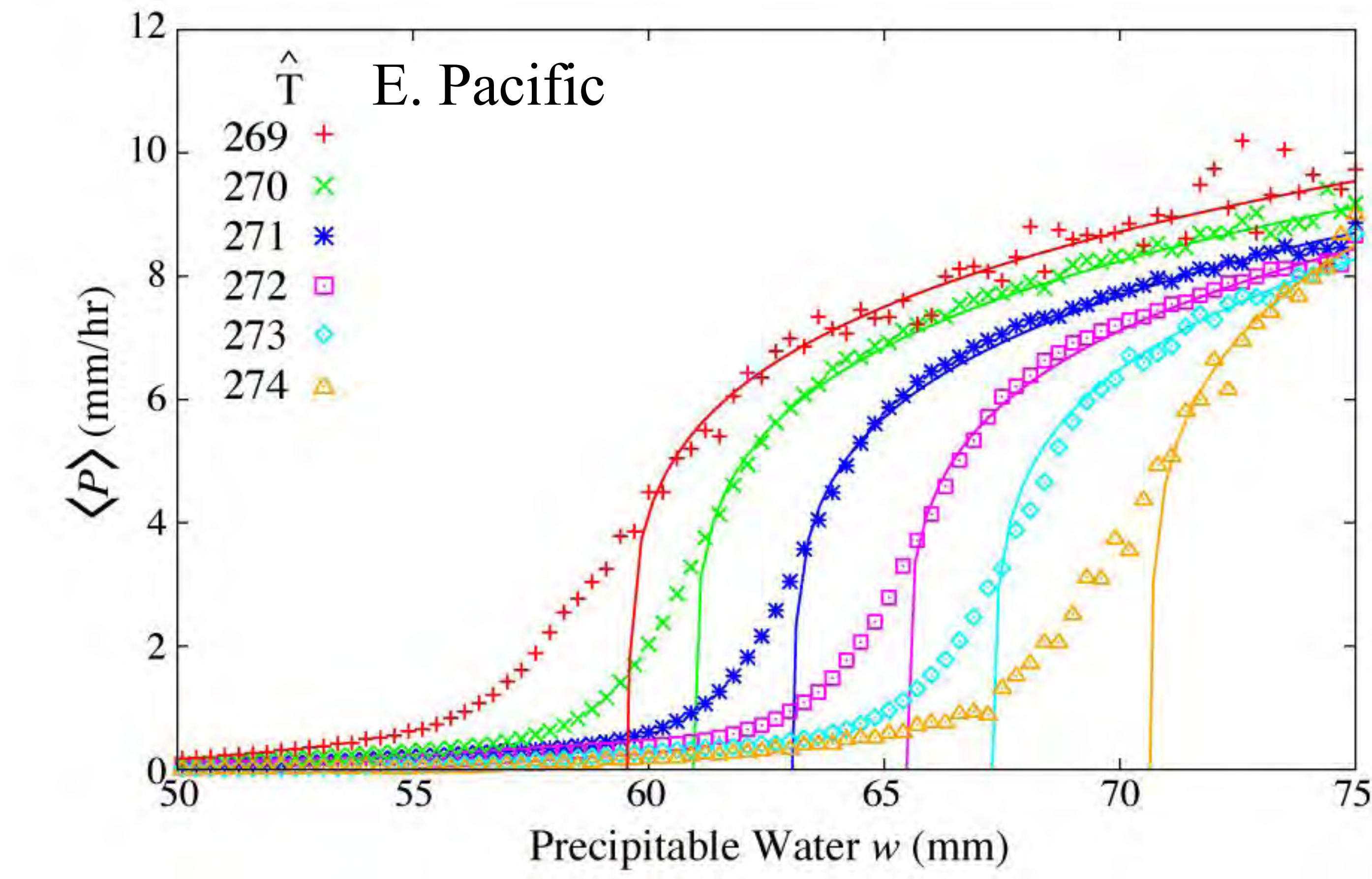
- ***w* useful because lots of microwave data available…**



Neelin, Peters, Lin, Holloway & Hales, 2008, *Phil Trans. Roy. Soc. A*

Transition to strong convection: Precip. dependence on tropospheric temperature & column water vapor

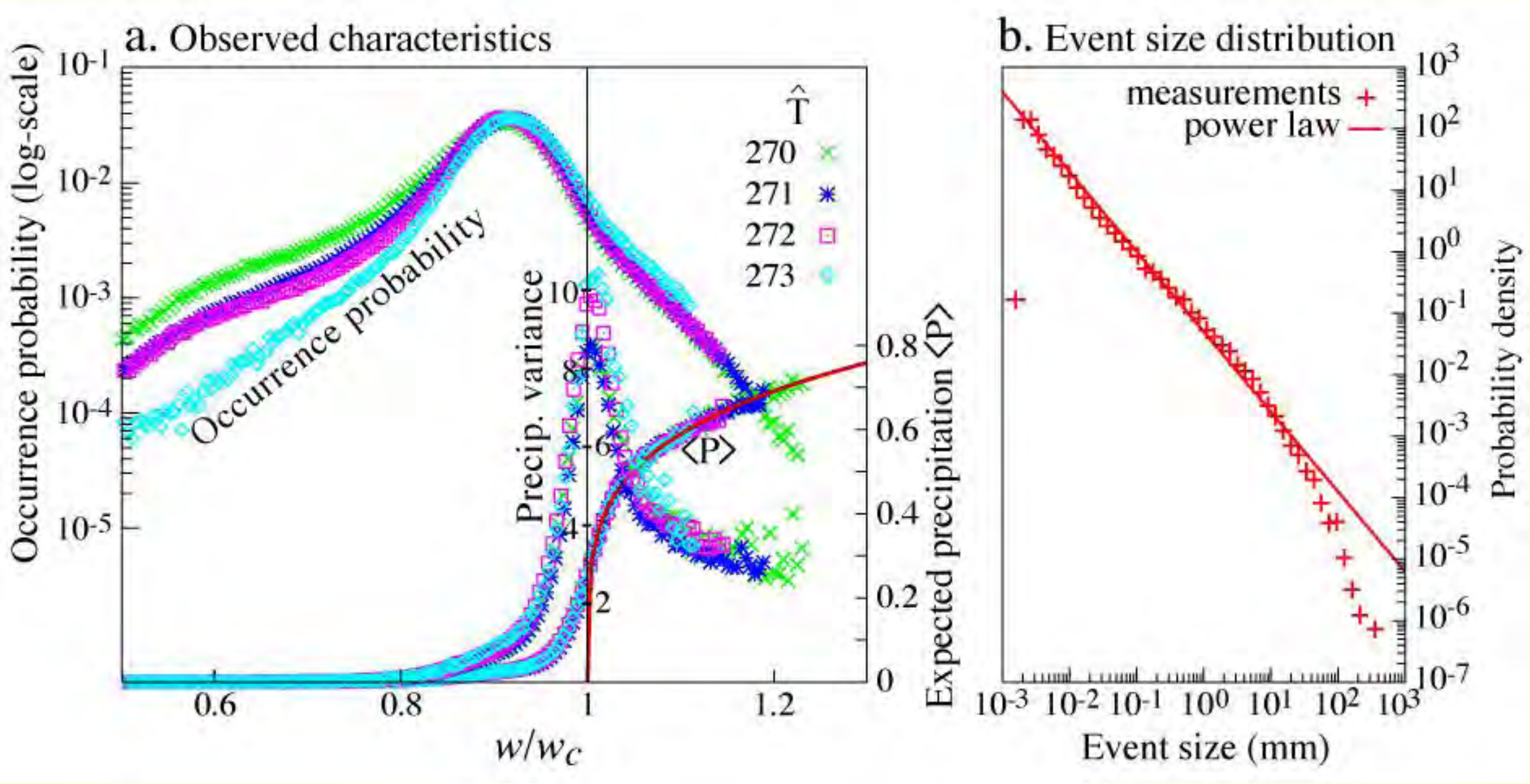
- **Averages conditioned on vert. avg. temp. $\hat{T}$, as well as w (T 200-1000mb from ERA40 reanalysis)**
- **Power law fits above critical: w_c changes, same β**
- **[note more data points at 270, 271]**



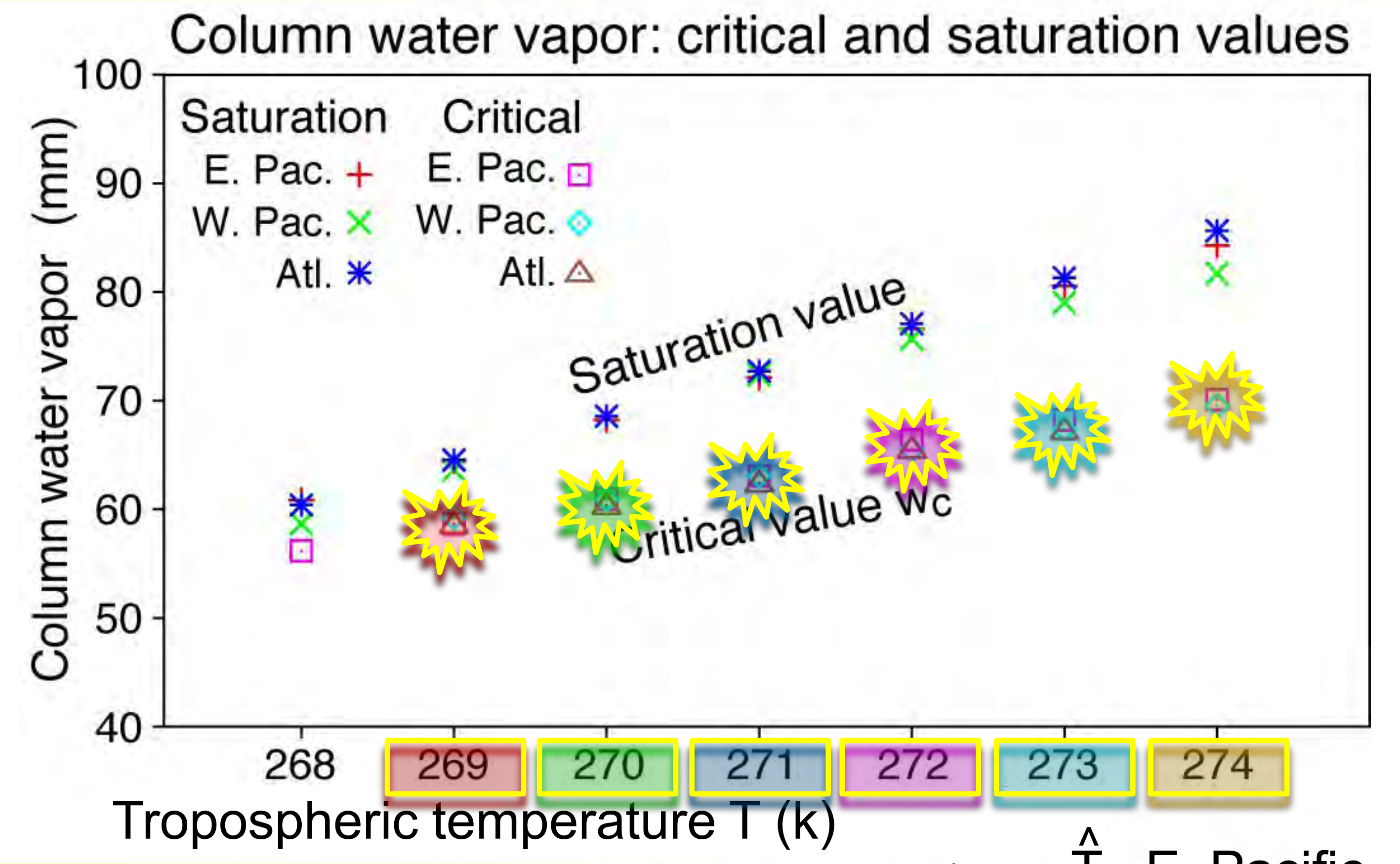
- **Analysed in tropics 20N-20S**

Neelin, Peters & Hales, 2009 *JAS*

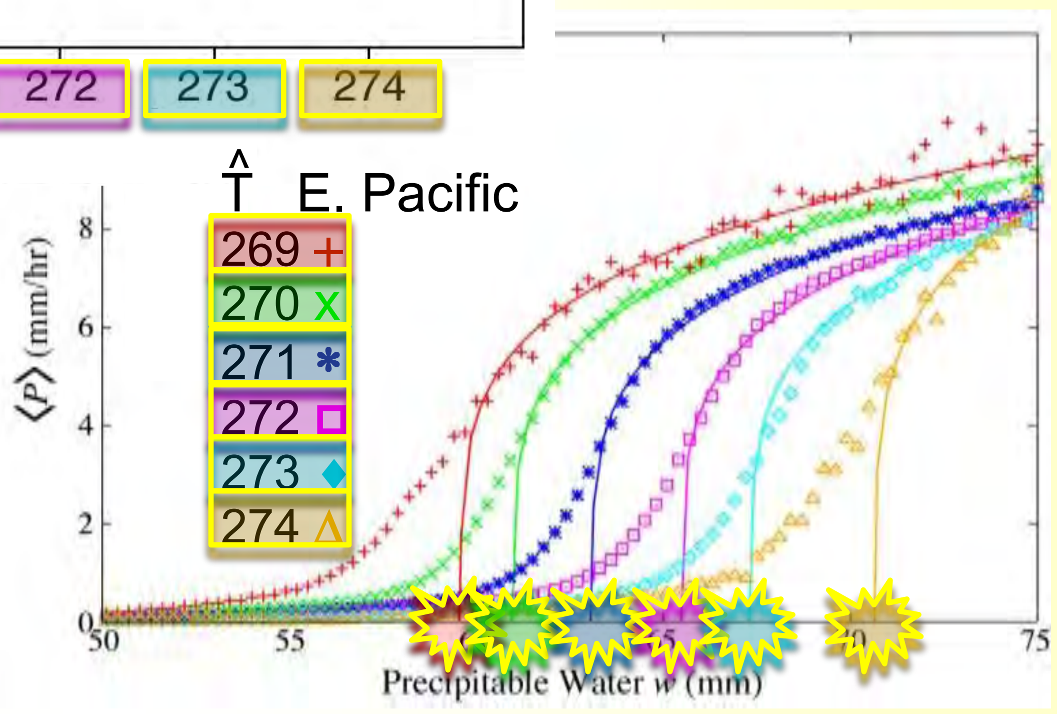
Collapsed statistics for observed precipitation



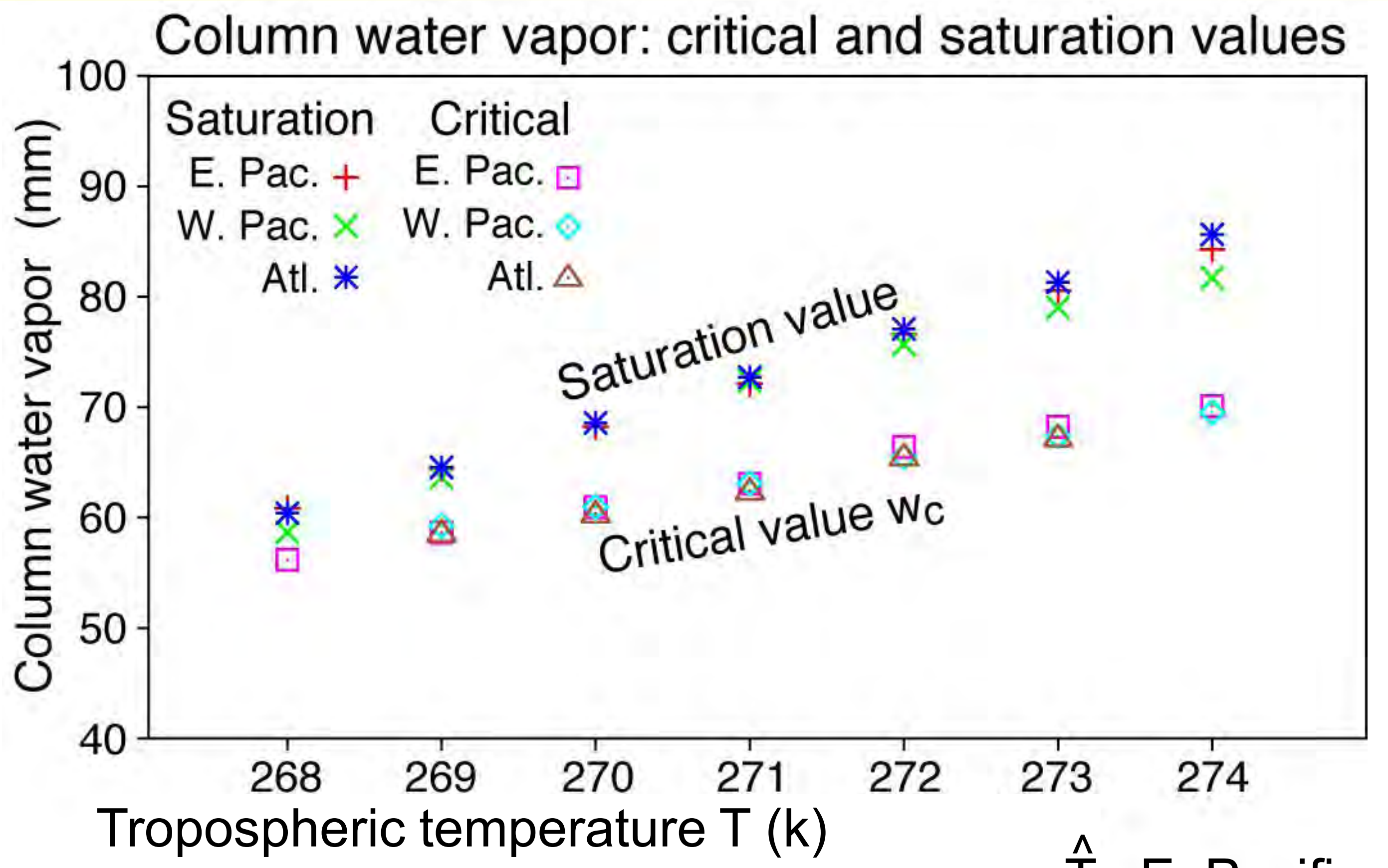
- **Precip. mean & variance dependence on *w* normalized by critical value w_c; occurrence probability for precipitating points (for 4 *T* values); Event size distribution at Nauru**

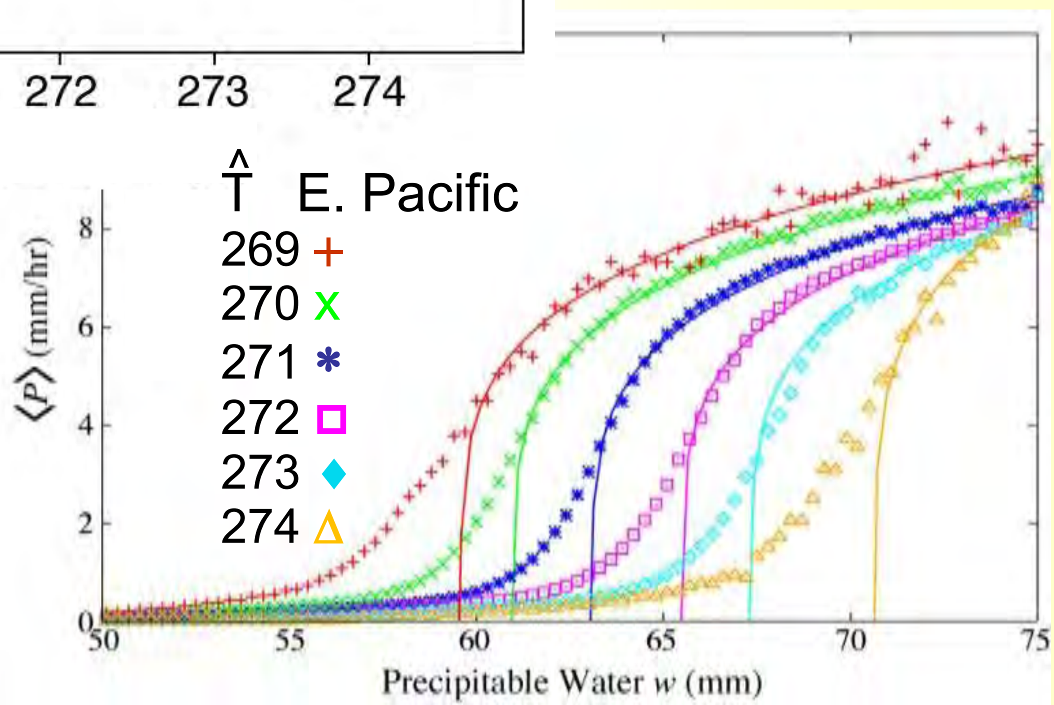


Column water vapor: critical and saturation values
Saturation
E. Pac.
W. Pac.
Atl.
Critical
E. Pac.
W. Pac.
Atl.
Saturation value
Critical value Wc
Column water vapor (mm)
100
90
80
70
60
50
40
268
269
270
271
272
273
274
Tropospheric temperature T (k)



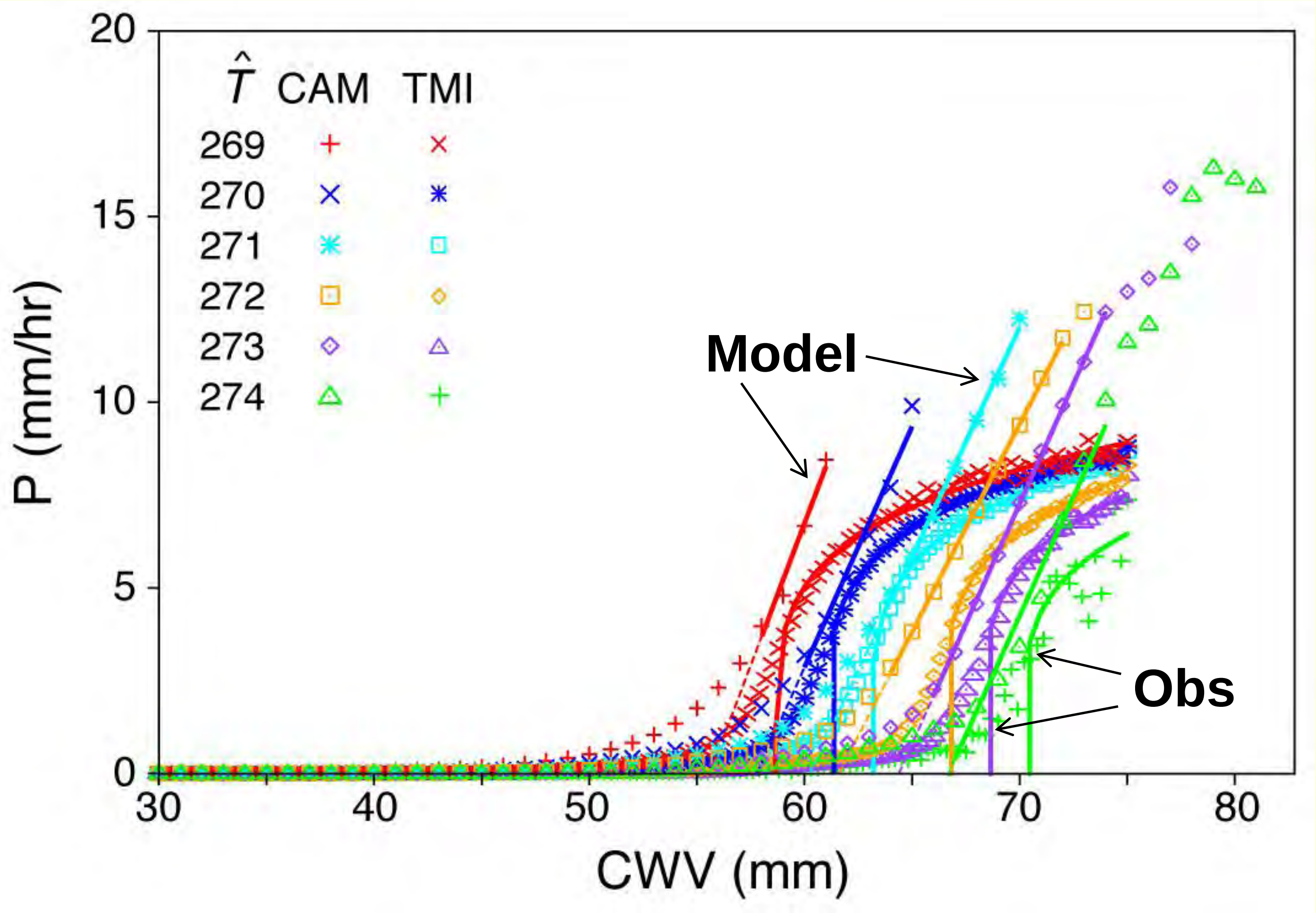
T̂ E. Pacific
269
270
271
272
273
274
⟨P⟩ (mm/hr)
8
6
4
2
0
50
55
75
Precipitable Water w (mm)





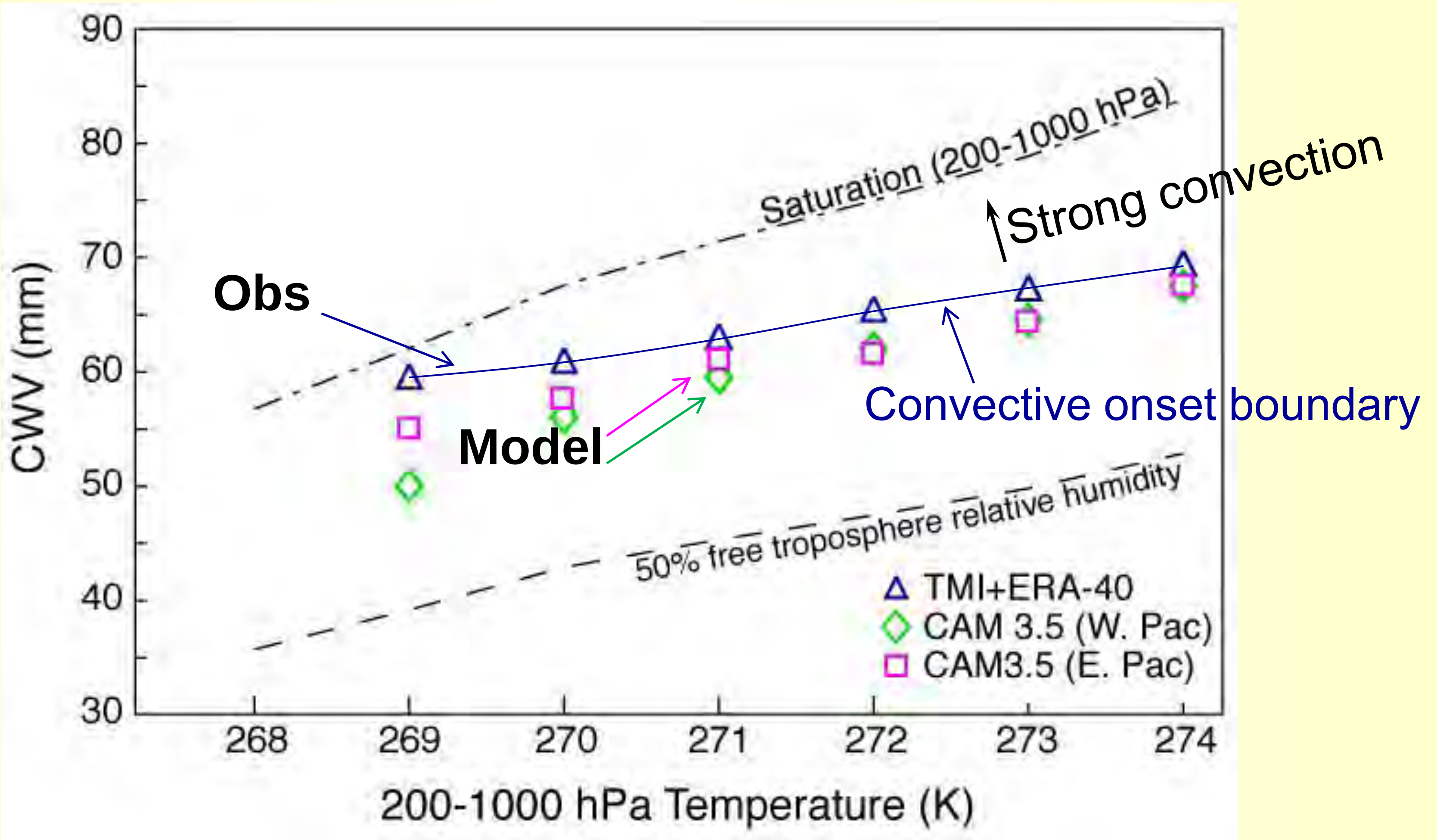
- **Defines an empirical thermodynamic surface for the onset of strong convection to test models**
- **Not a constant fraction of column saturation**

Transition to strong convection: High-resolution global model (CAM3.5, 0.5°) compared to observations (TMI)



Sahany et al. 2011, subm.

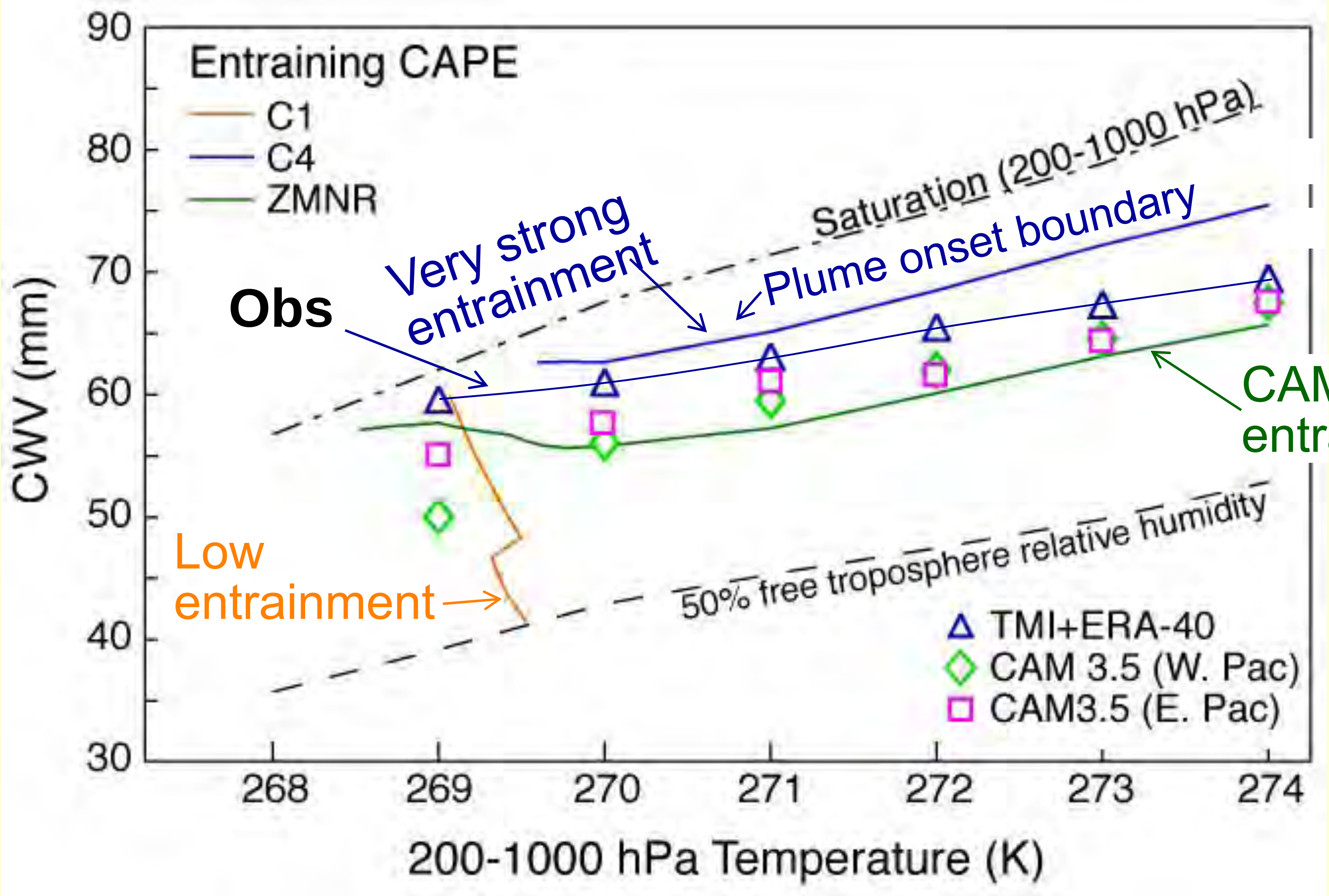
Transition to strong convection: High-resolution global model (CAM3.5, 0.5°) compared to observations (TMI)



Sahany et al. 2011, subm.

Transition to strong convection:

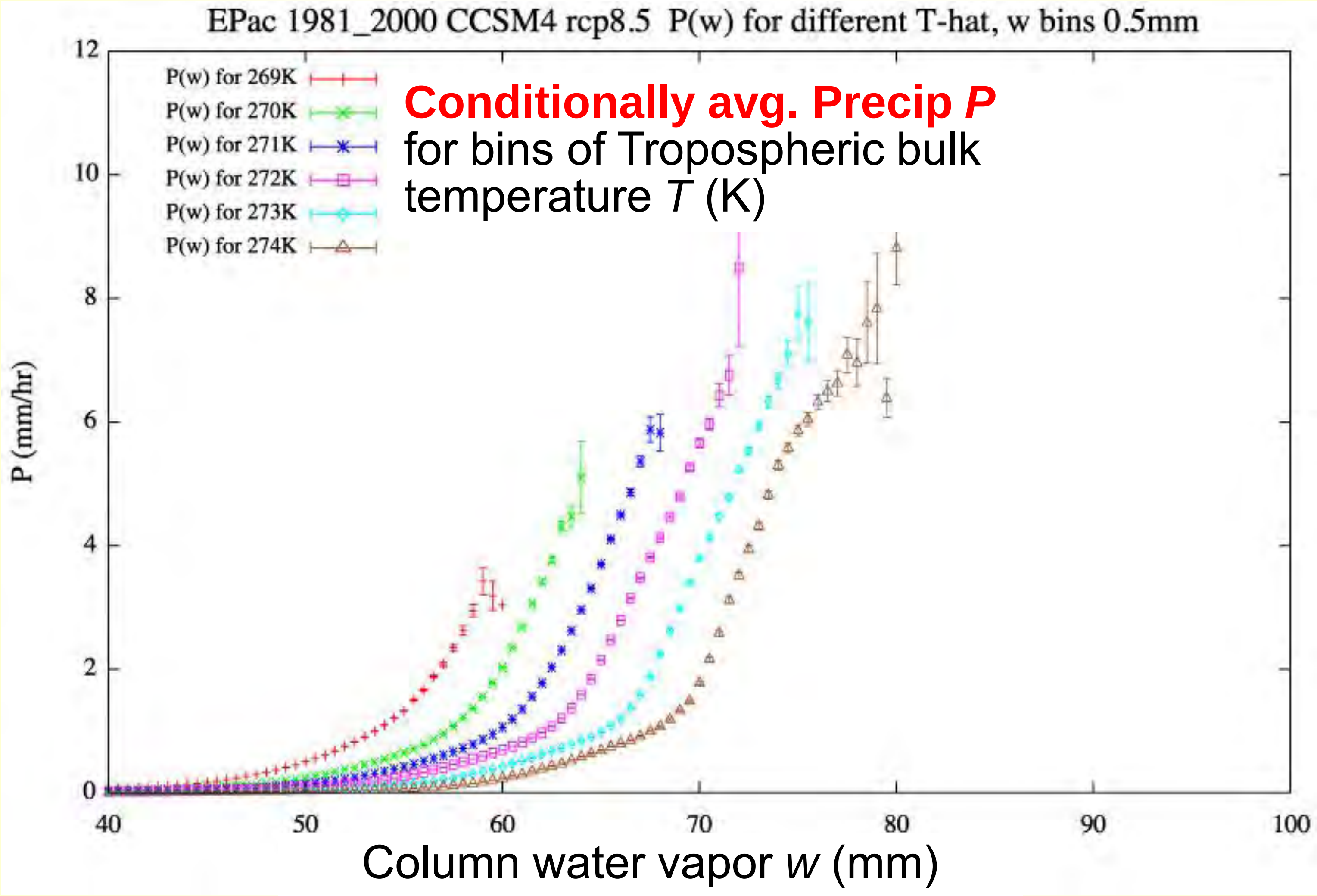
Obs. & model compared to simple convective plume instability calculation with different entrainment assumptions



Low values of entrainment are inconsistent with observed onset

Transition to strong convection: simulation of current conditions

Community Climate System Model 4 (CAM4, 1°)
Historical run 1981-2000

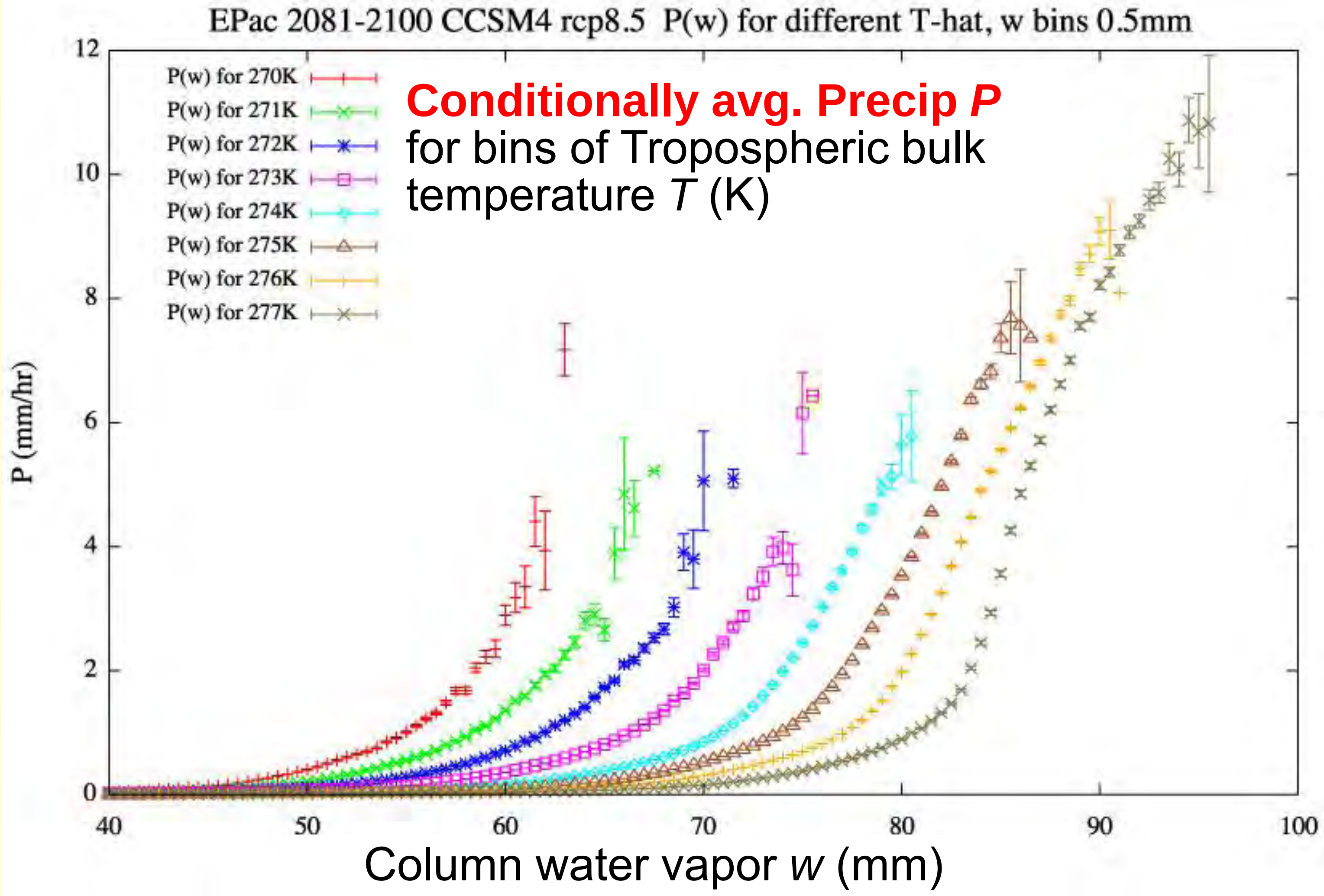


CAM4 Instantaneous precipitation data: R. Neale, Analysis K. Hales

Transition to strong convection: simulation under global warming

Community Climate System Model 4 (CAM4, 1°)

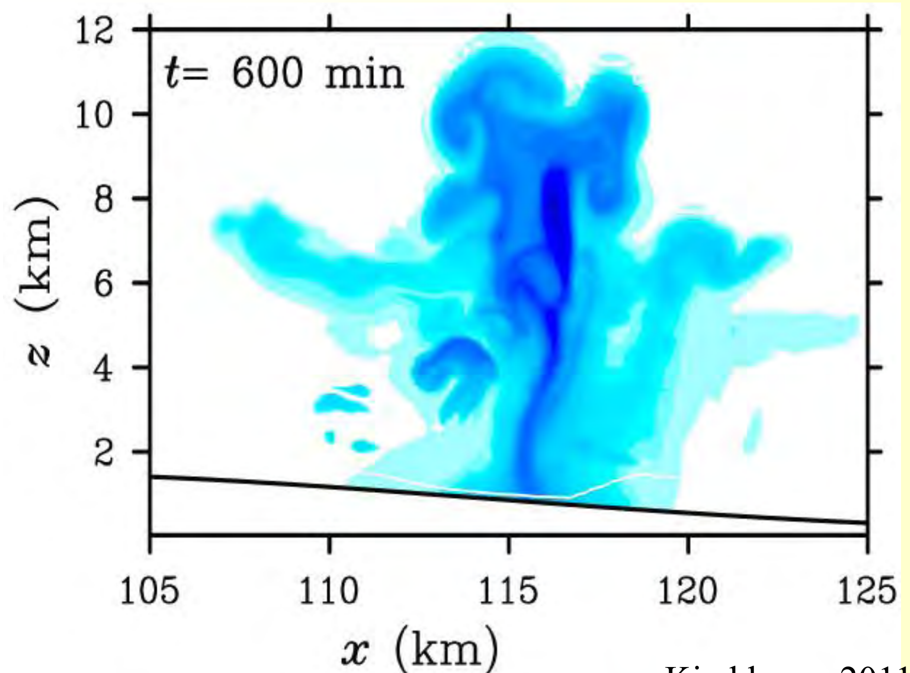
Representative Concentration Pathway run RCP8.5 2081-2100



CAM4 Instantaneous precipitation data: R. Neale, Analysis K. Hales

Importance of very small scales

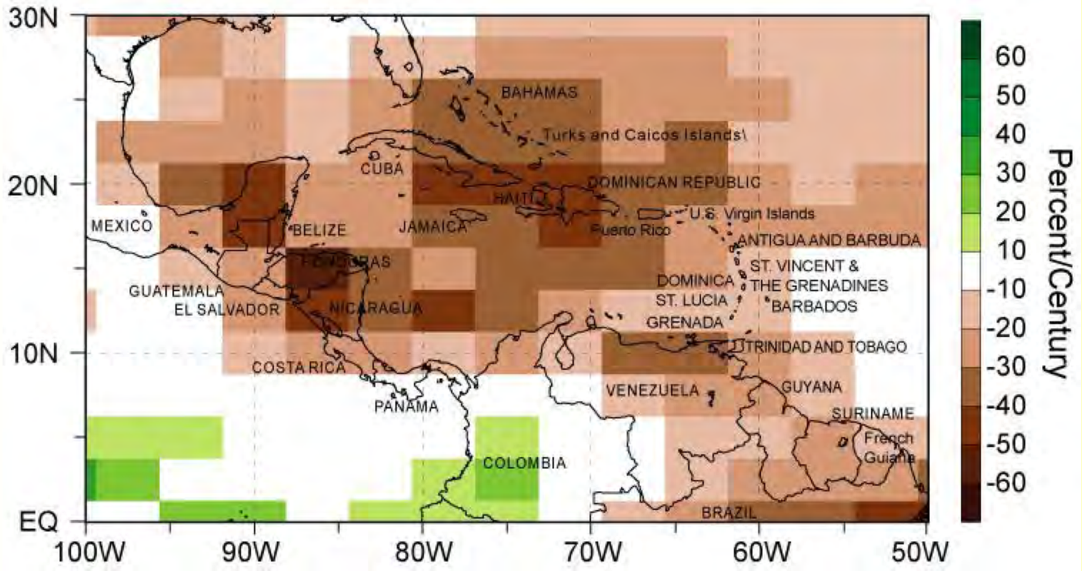
- Importance of entrainment to the onset of deep convection
- Explains the high sensitivity to free tropospheric water vapor (above the boundary layer)
- Bad news: Beyond the resolution of global climate models anytime soon (100m vs. 100 km)
- Good news: work for cloud resolving modelers; new observations add constraints; revised model comes close
- Bad news: interacts with other poorly constrained small scale processes — cloud microphysics



Kirshbaum 2011

Outlook

- The regional scale changes in the hydrological cycle are arguably the most important aspect of climate sensitivity over the 21st century

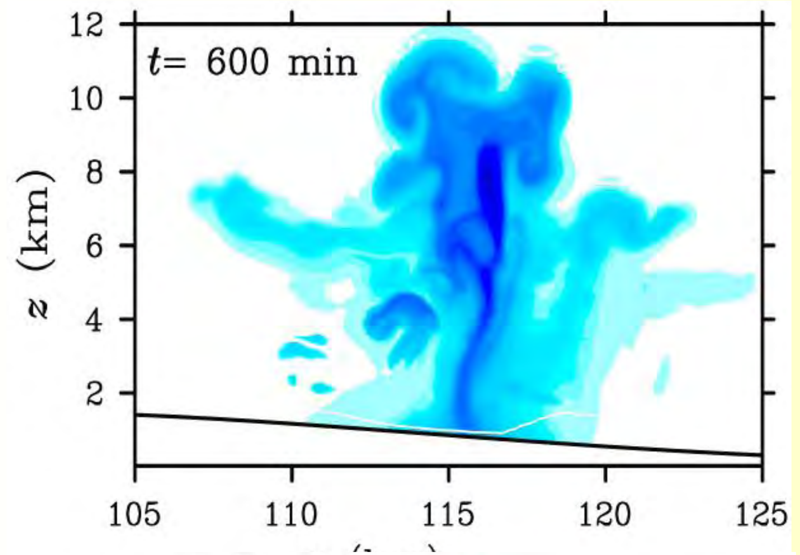


- Reducing regional uncertainty remains challenging with the current set of CMIP5 models---regions of agreement TBD

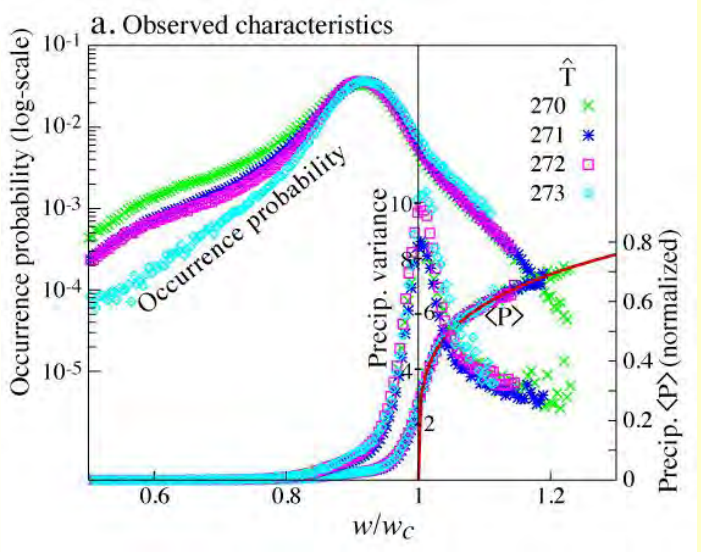
- Using climate model precipitation projections: Caution on simple statements; measure of uncertainty on multi-model ensemble mean; specific model validation for key phenomenon in the region of interest for each member of the ensemble

Outlook

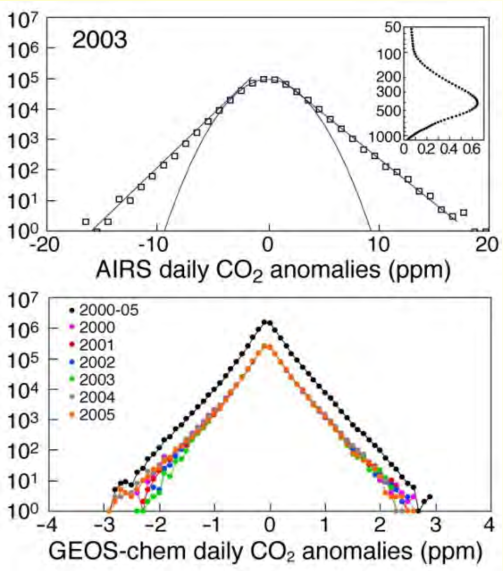
- The regional scale changes in the hydrological cycle are arguably the most important… Will we do any better at reducing uncertainty?



Current tackling of small scale processes, scale interactions, new observational constraints, systematic parameter estimation methods,…
seem likely to yield progress---although not high precision by July 2012



Some connections…



- **Long tails** seen in the probability distribution of water vapor also occur for **chemical tracers** including CO2: (B. Lintner, B. Tian, Q. Li, L. Zhang, P. Patra, M. Chahine)
- And **surface temperature** (T. Ruff)
- Simple stochastic model **Fokker-Planck** solutions indicate processes (S. Stechmann)
- **Nastier parameter dependence** can occur (M. Chekroun et al.)
- Do constraints on entrainment combine with new proxy data to resolve a surface temperature vs. glacial elevation conundrum at **last glacial maximum**? (A. Tripati, S. Sahany, D. Pittmann, R. Eagle, J. Eiler, J. Mitchell, L. Beaufort)
- theory for inflow air mass interacting with convective onset at the **margins of convection zones** can be tested in models (H.Y. Ma, C.R. Mechoso, X. Ji)