# Tropical precipitation change under global warming

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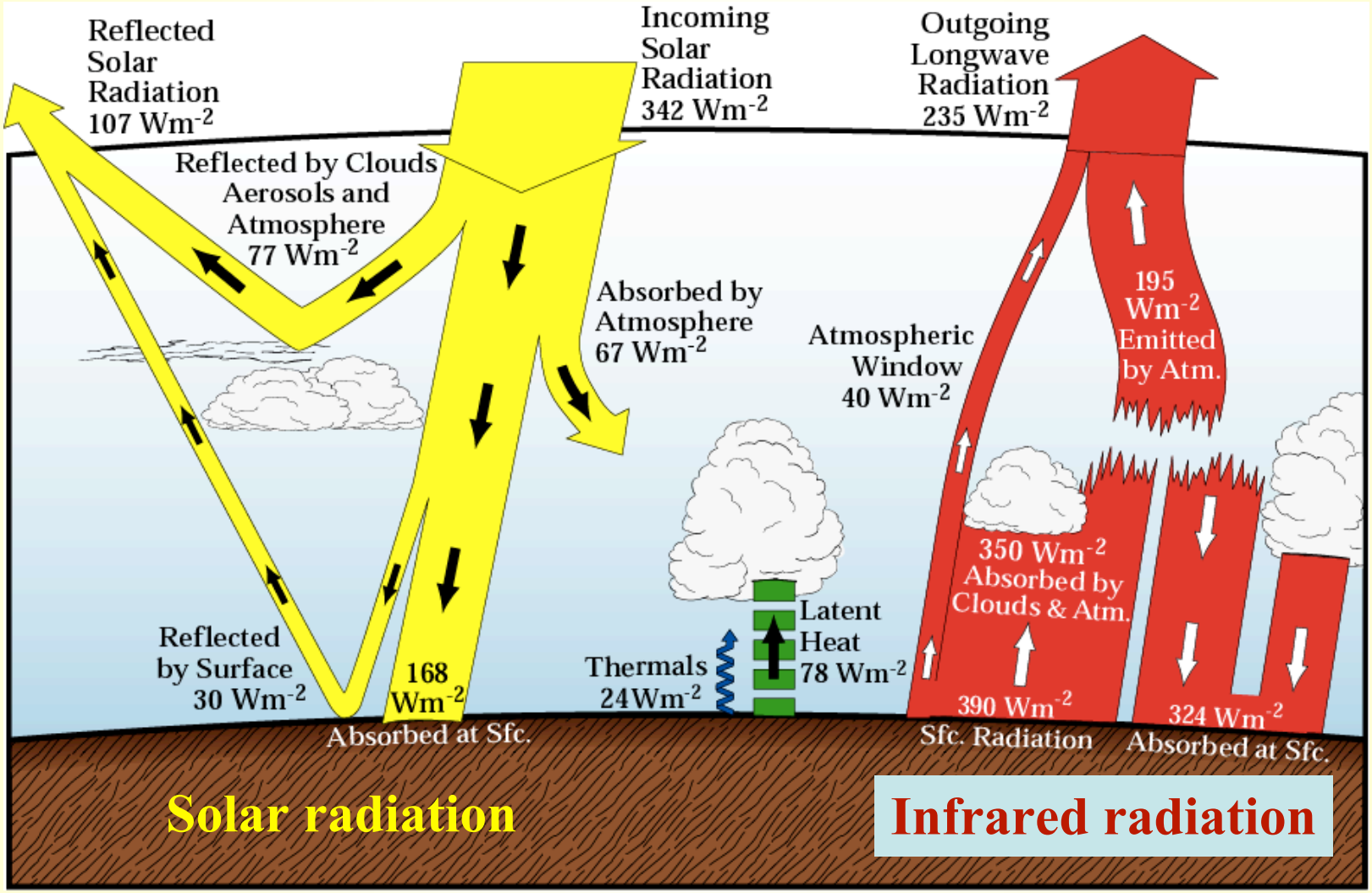
- **Background: Global warming basics; rainfall issues**
- **[Precipitation regional response to El Nino teleconnections** (Su & Neelin 2002; Neelin, Chou & Su 2003, *GRL*; Neelin & Su 2005, *J Clim.*) **]**
- **Mechanisms of precip. resp. to greenhouse gas** (Neelin et al 2003; Chou & N 2004, *J Clim.,* Chou, Neelin, Tu and Chen 2006, *J. Clim*., in press)
- **[Aerosol case** (Chou, Neelin, Lohmann & Feichter 2005, *J Clim*.) **]**
- **Tropical precip. change in multi-model ensemble assoc. with Inter-governmental Panel on Climate Change (IPCC) 4th Assessment Report** (Neelin, Munnich, Su, Meyerson and Holloway 2006 *PNAS*)

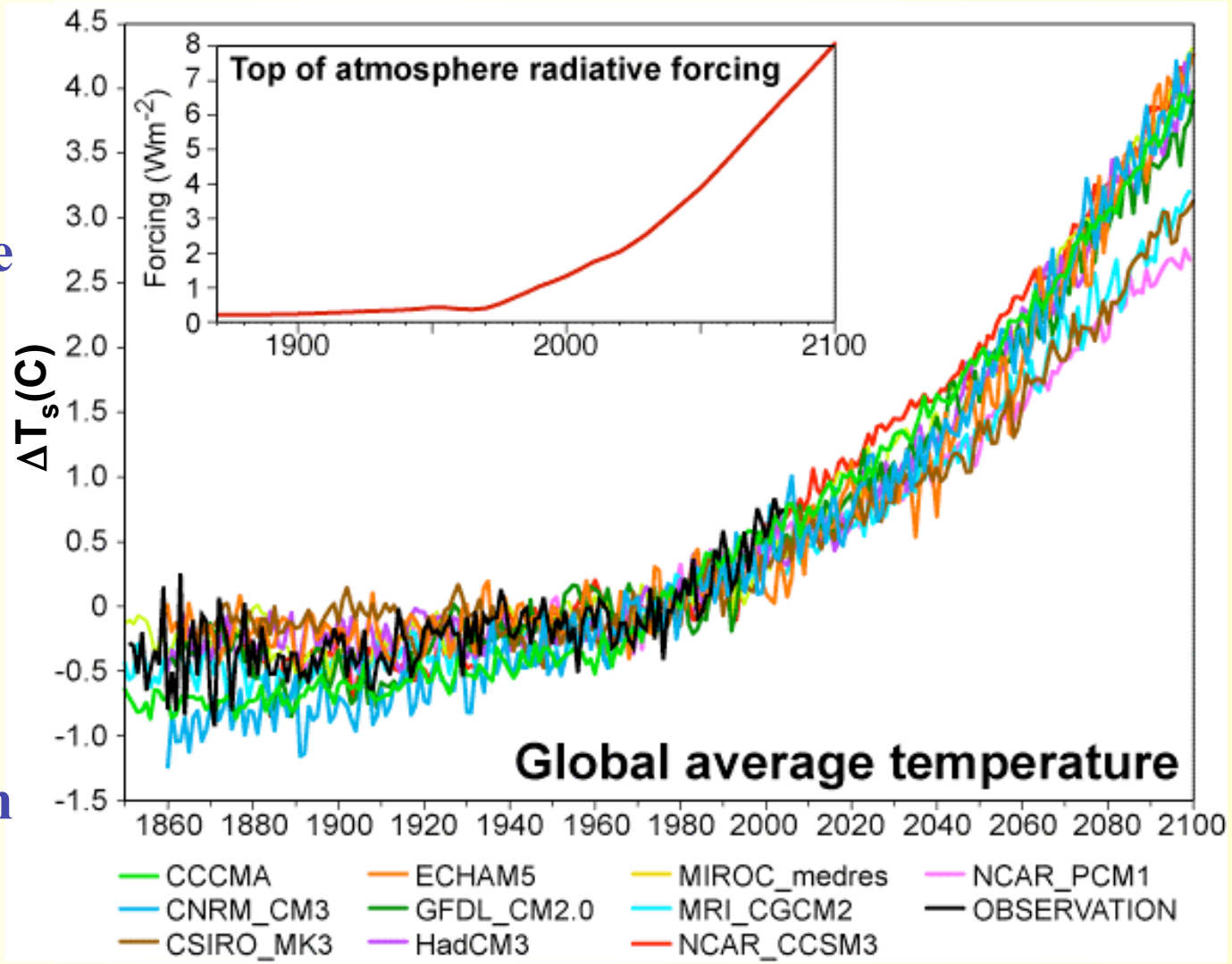
# Greenhouse effect in global-average energy budget




**Increase greenhouse gases ⇒ Incr. atm. IR absorption**
**⇒ Warming ⇒ Climate feedbacks: H2O, ice, clouds…**

# Global warming as simulated in 10 climate models

- Global avg. sfc. air temp. change (ann. means rel. to 1901-1960 base period)
- Est. observed greenhouse gas + aerosol forcing, 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"**

# Surface air temperature change (relative to 1961-90)

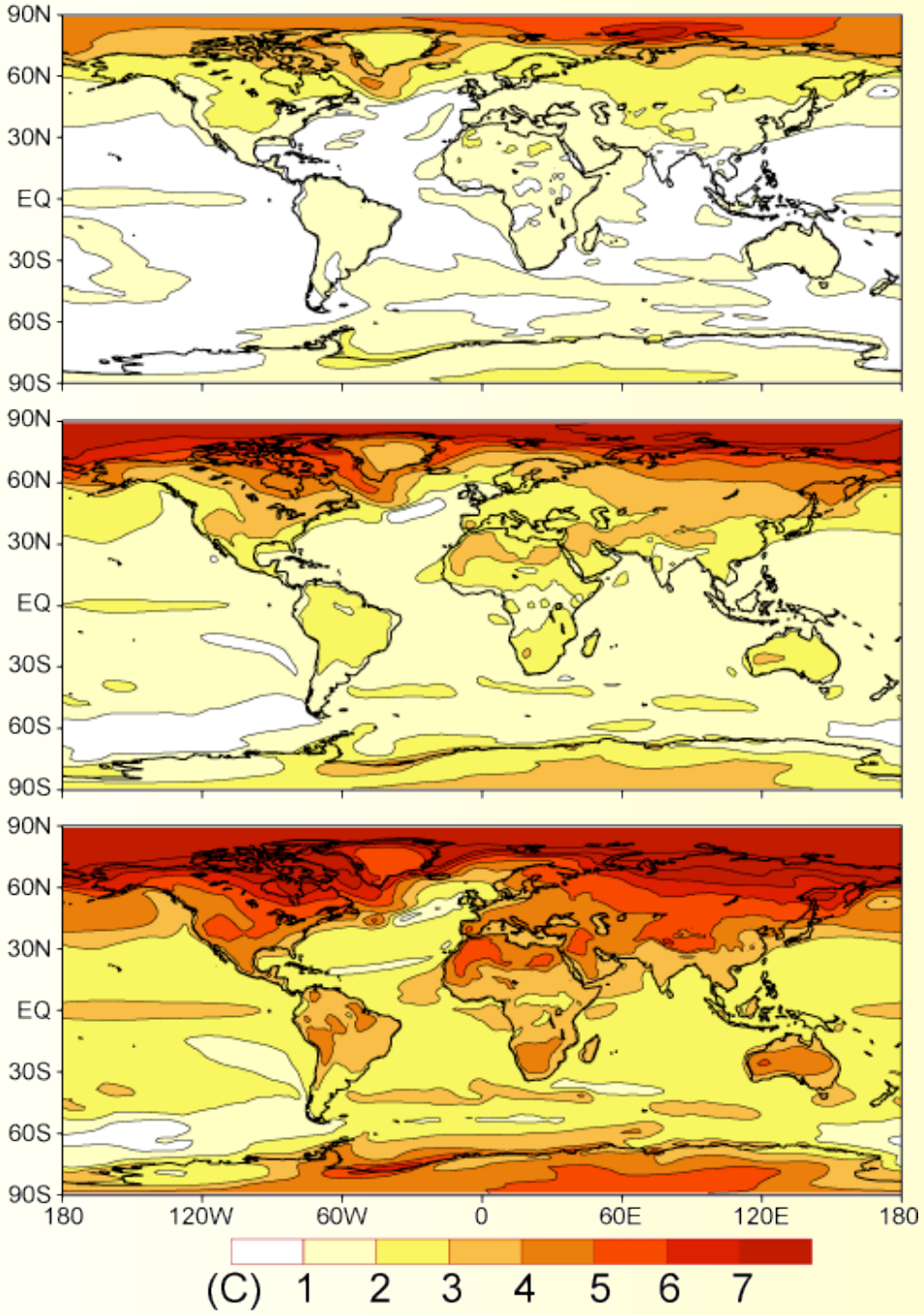
## NCAR CCSM3* annual avg.

## Response to the SRES A2 scenario

2010-2039

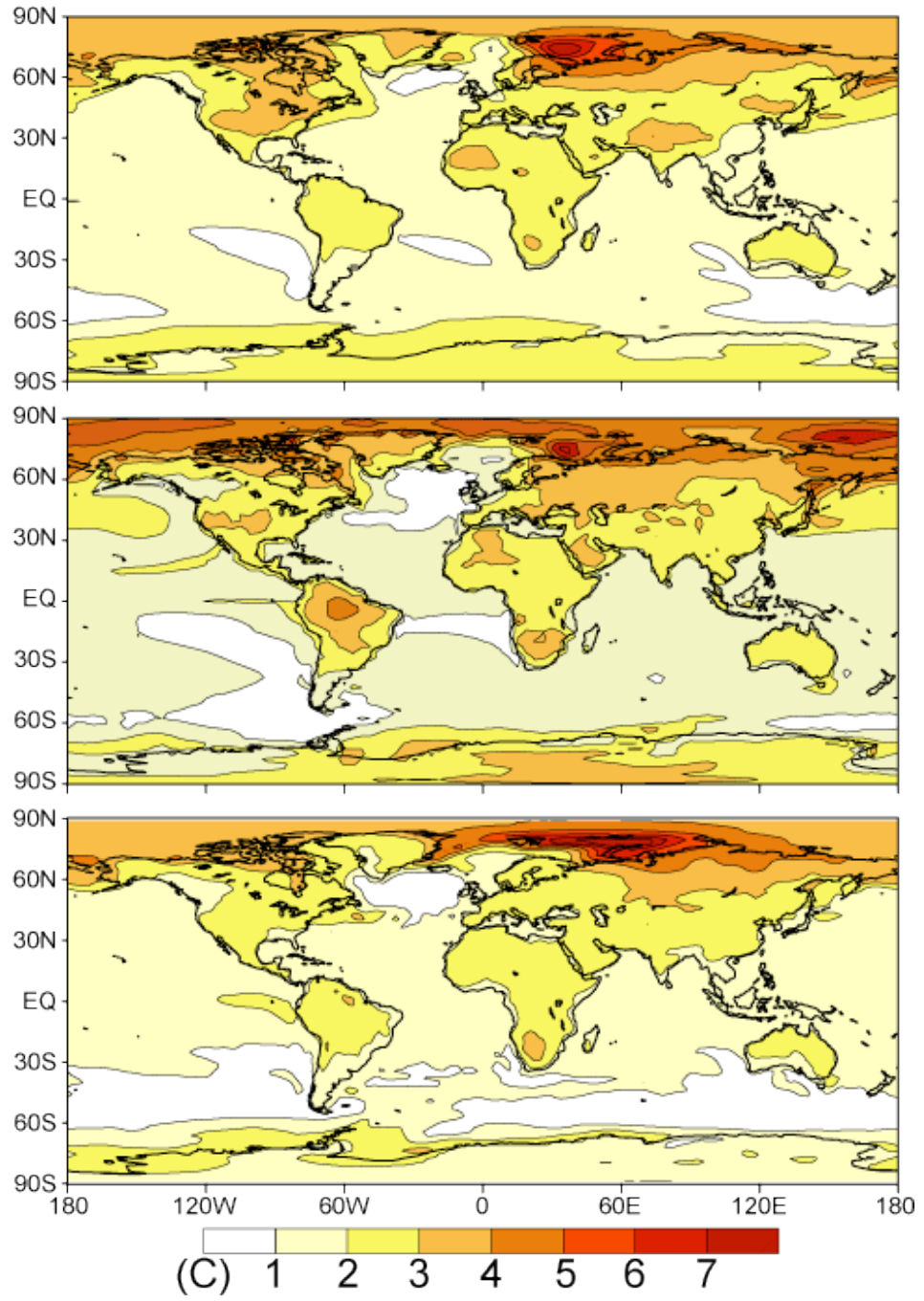
2040-2069

2070-2099




*Unexplained acronyms denote climate model names

# Surface air temperature change for three models* 2040-2069 annual avg. (rel. to 1961-90)




*Unexplained acronyms denote climate model names

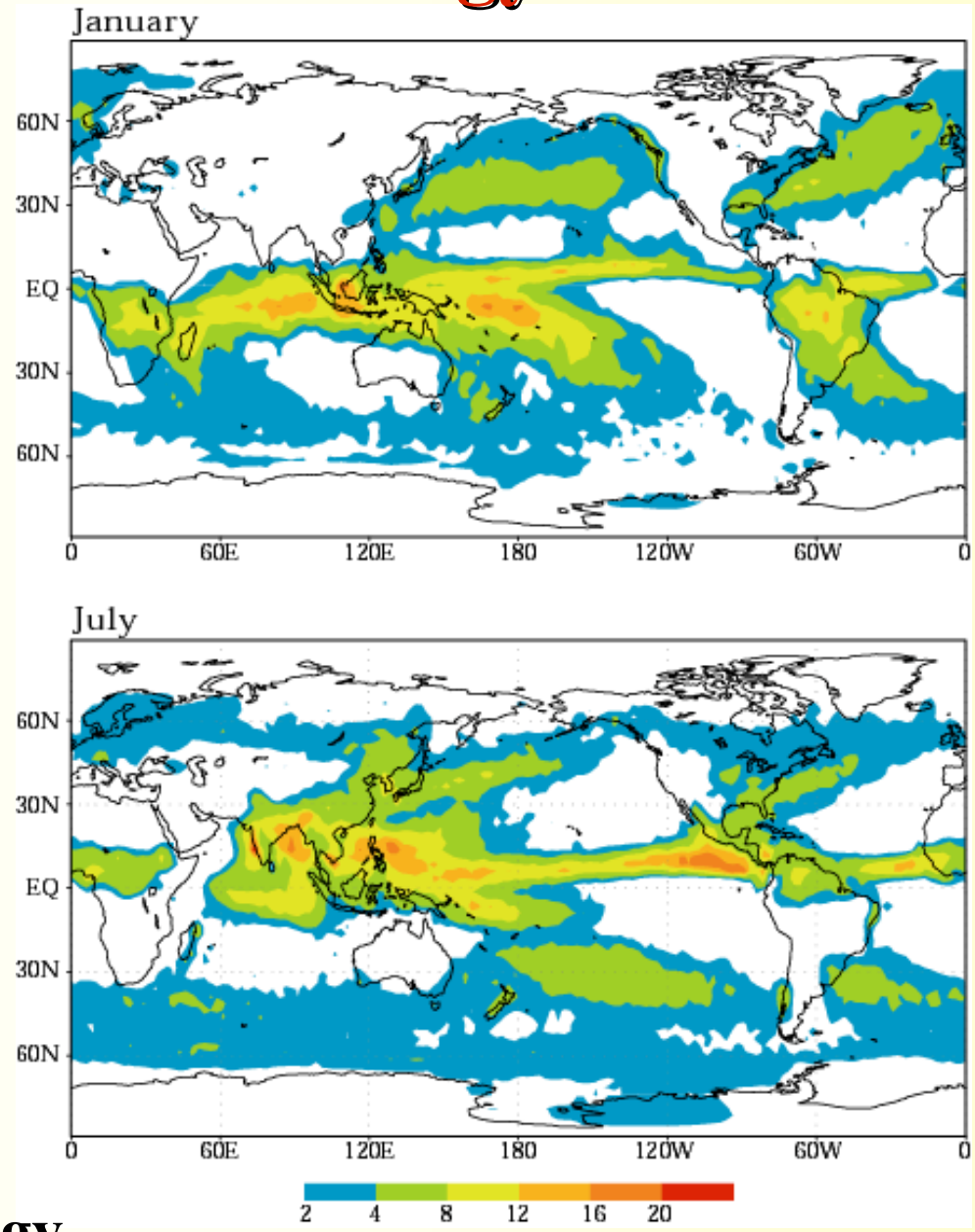
# Precipitation: climatology

## January

**Note intense tropical moist convection zones (intertropical convergence zones)**

## July

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

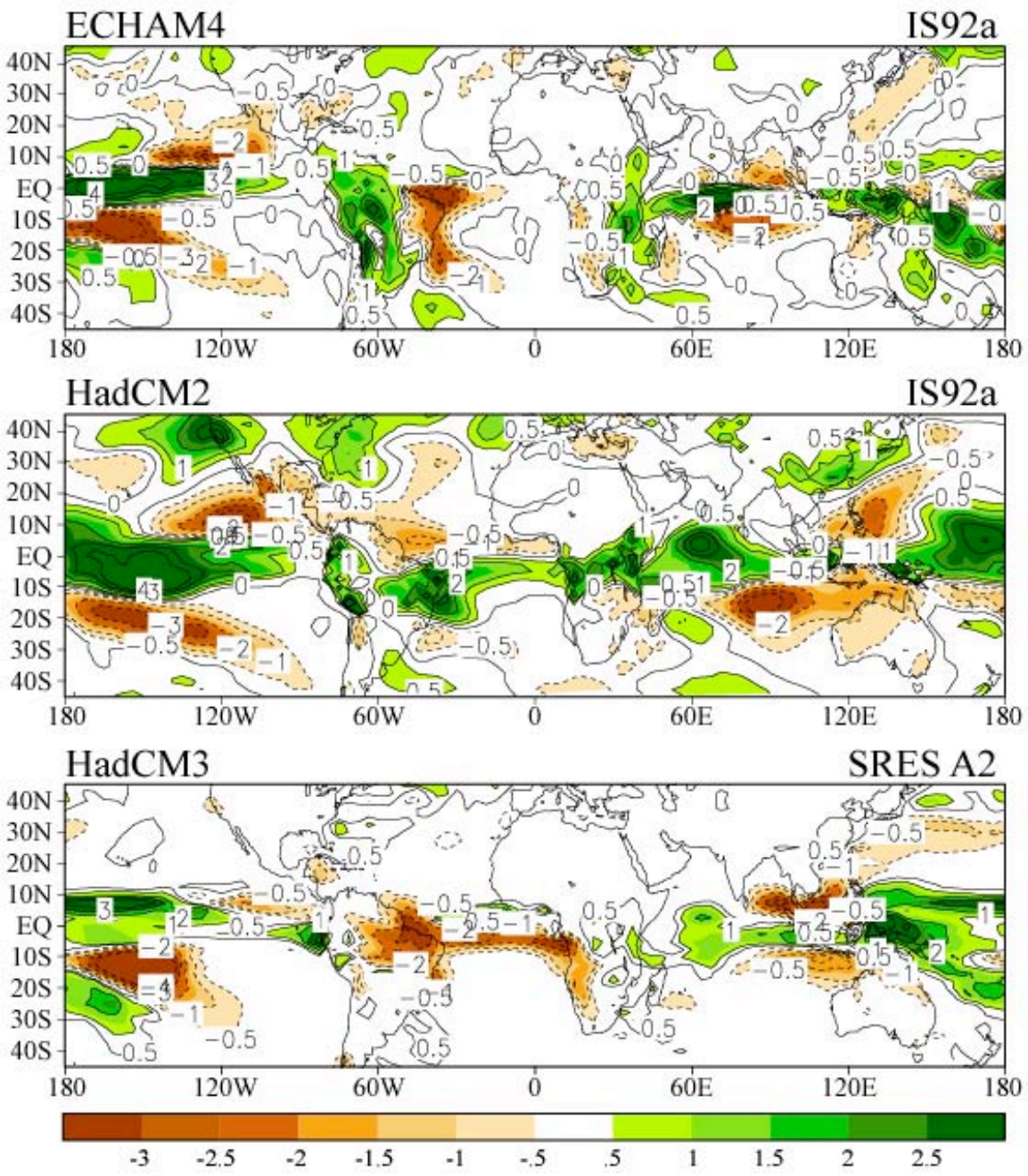


# Precipitation change under global warming

**Dec.-Feb. (DJF) precip. anomaly For 2070-2090 (rel. to 1961-1990). Three ocean-atmos. climate models (Greenhouse gas + aerosol forcing scenarios)**

**See also eg. Wetherald & Manabe 2002, JGR; …**

**Neelin et al 2003, *GRL***

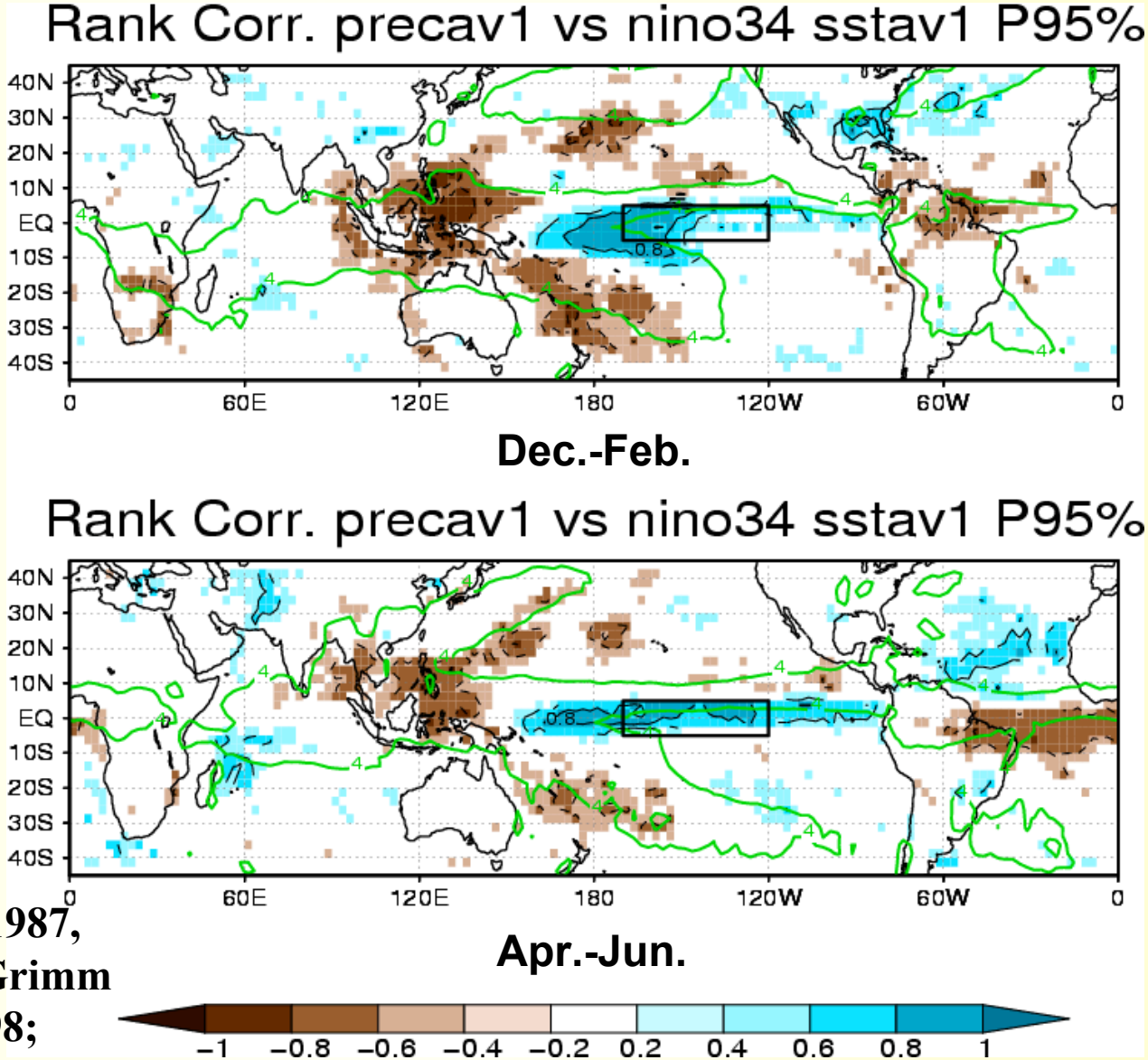


# Detour: Tropical remote precip. relation to El Nino

- **Observed Precip rank correlation to equatorial Pacific sea surface temperature index**
- **Clim. precip. as 4 mm/day contour (green) for reference**

**(CMAP Precip; Reynolds OIv2 Nino3.4 SST; 1982-2003;** CMAP=Climate prediction center Merged Analysis of Precipitation)

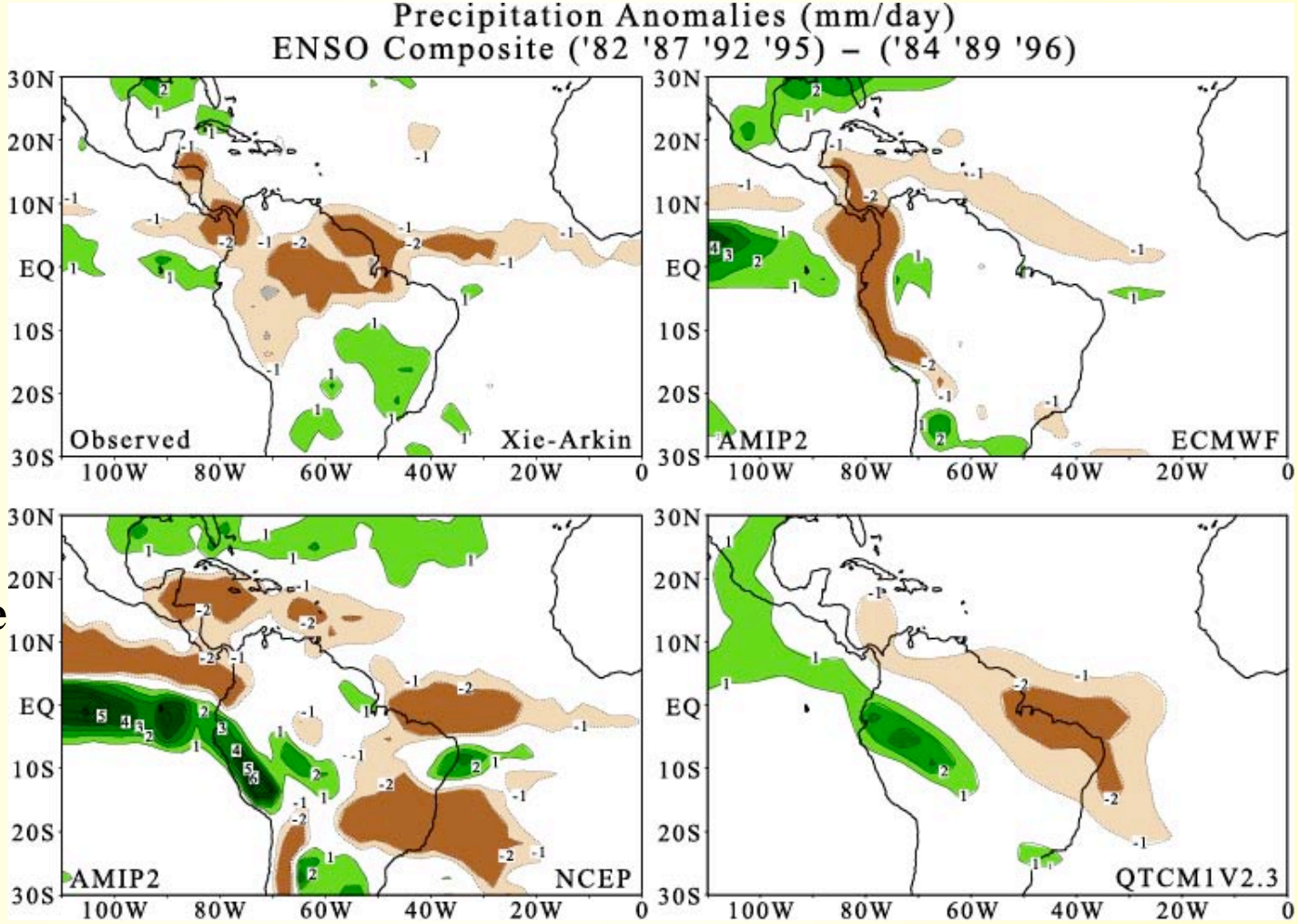
**cf. Ropelewski & Halpert (1987, 1989); Hastenrath (1990); Grimm et al 1998; Wallace et al 1998; Giannini et al (2000); Paegle & Mo 2002; Chiang & Sobel (2002)**



# El Nino/Southern Oscillation (ENSO) precip. anoms

- **Warm-cold composite for Xie-Arkin obs, ECMWF-AMIP2, NCEP-AMIP2, QTCM**

**Observed vs. 3 models forced by observed sea surface temperature**
**(AMIP2=Atm. Model intercomparison project)**

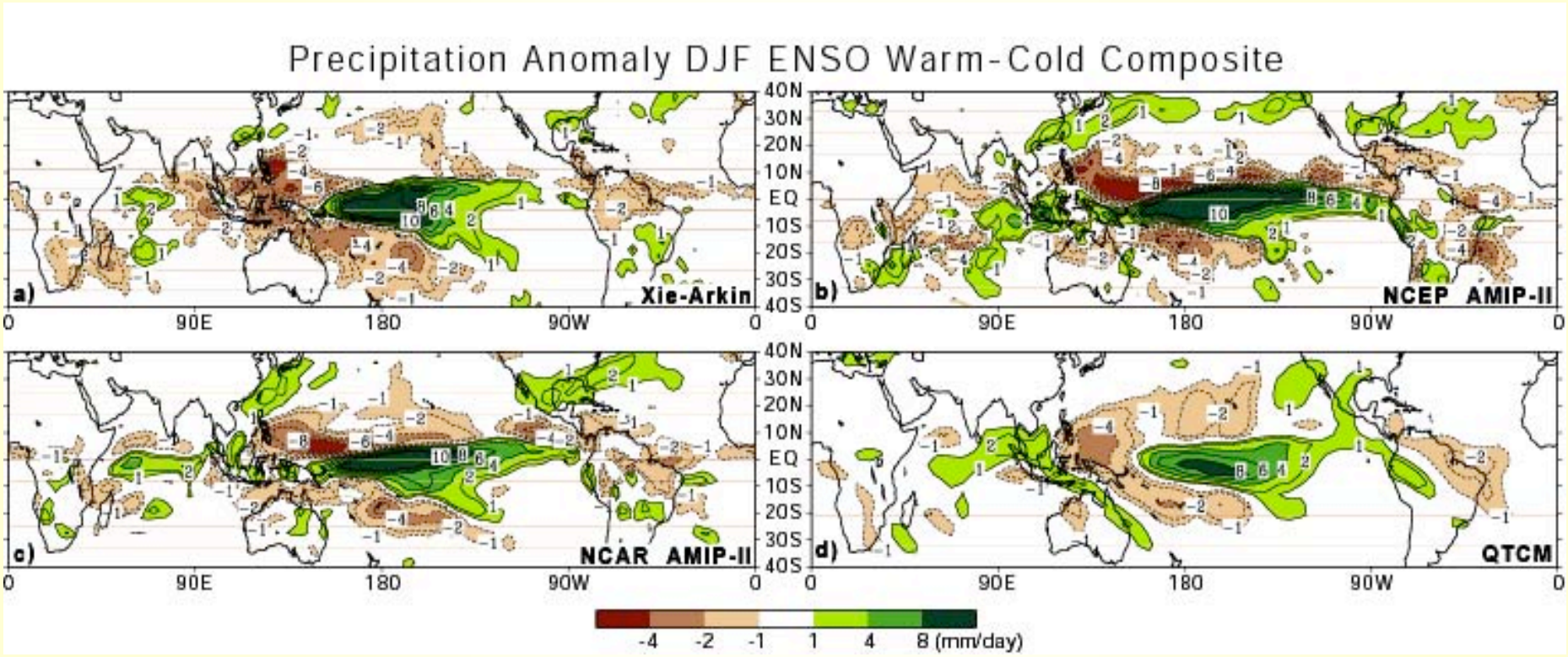



**Other models, see Sperber and Palmer 1996, Giannini et al 2001; Saravanan & Chang, 2000**

**(El Niño avg 1982-83, 87-88, 92-93, 95-96 – La Niña avg 1984-85, 89-90, 96-97)**

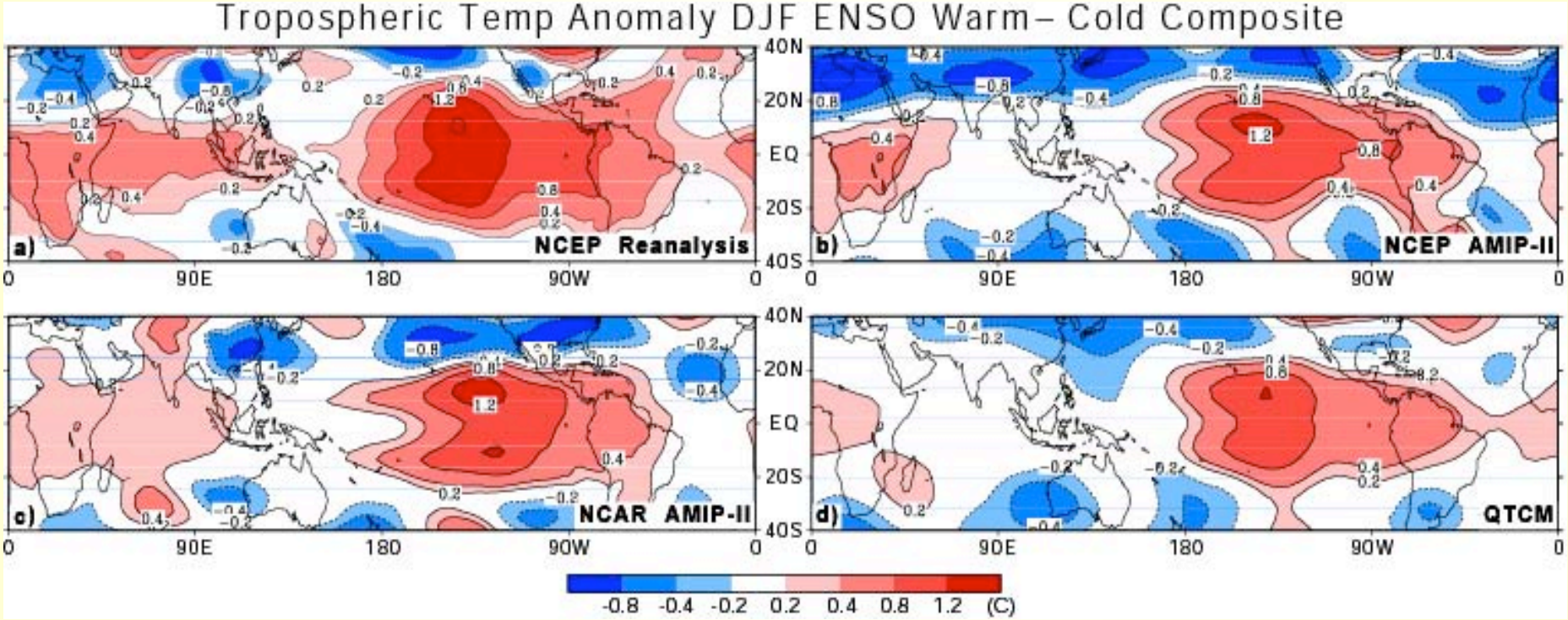
# ENSO precip anoms: obs vs atm models

- **Warm-cold composite for Xie-Arkin obs, NCEP-AMIP2, NCAR-AMIP2, QTCM**



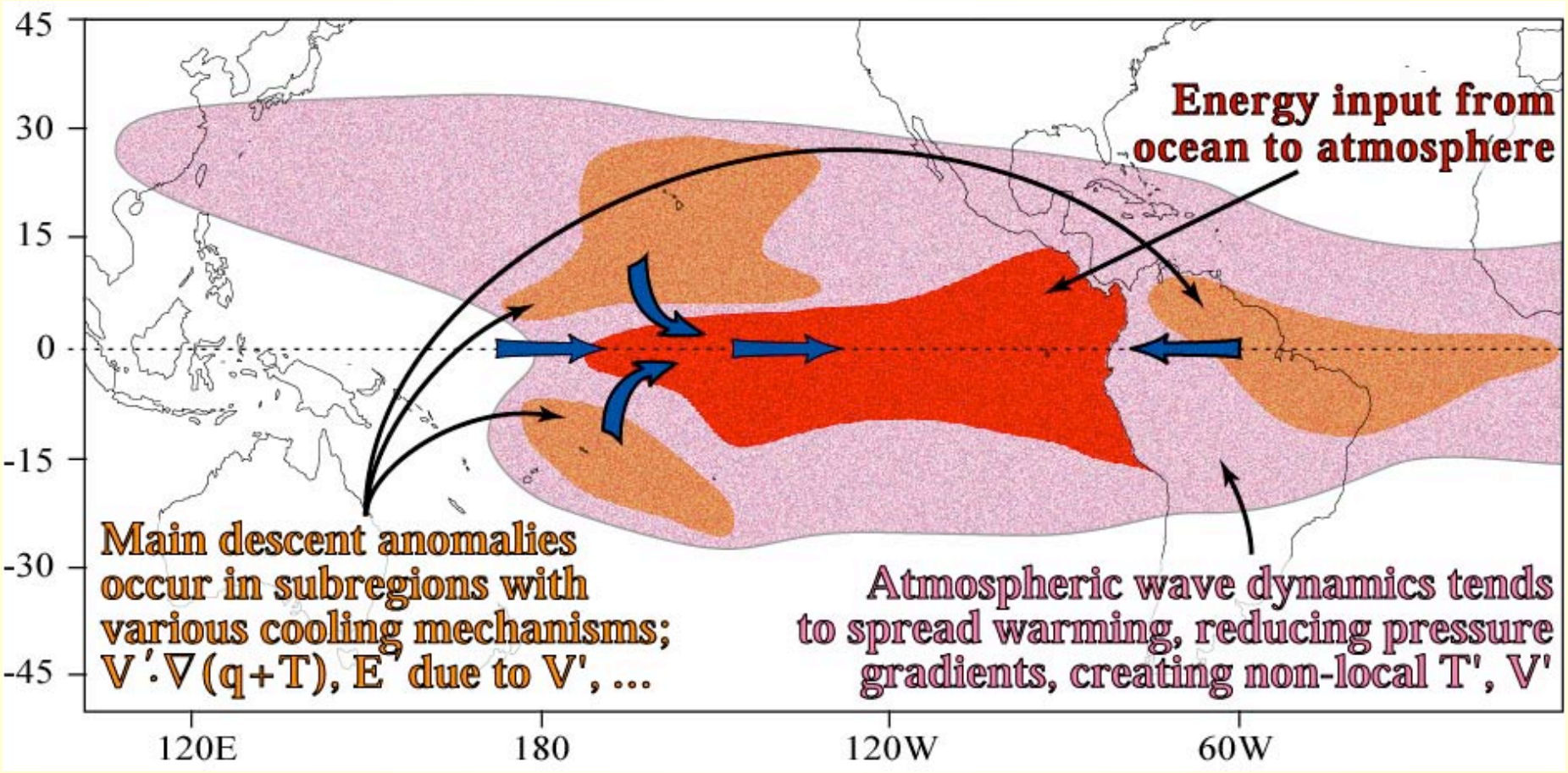
# ENSO tropospheric temperature anomalies

- Warm-cold composite
- NCEP reanalysis vs. atm models driven by obs SST (AMIP2): NCEP-AMIP2, NCAR-AMIP2, QTCM




(El Niño avg 1982-83, 87-88, 92-93, 95-96 – La Niña avg 1984-85, 89-90, 96-97)

# ENSO teleconnections to regional precip. anomalies

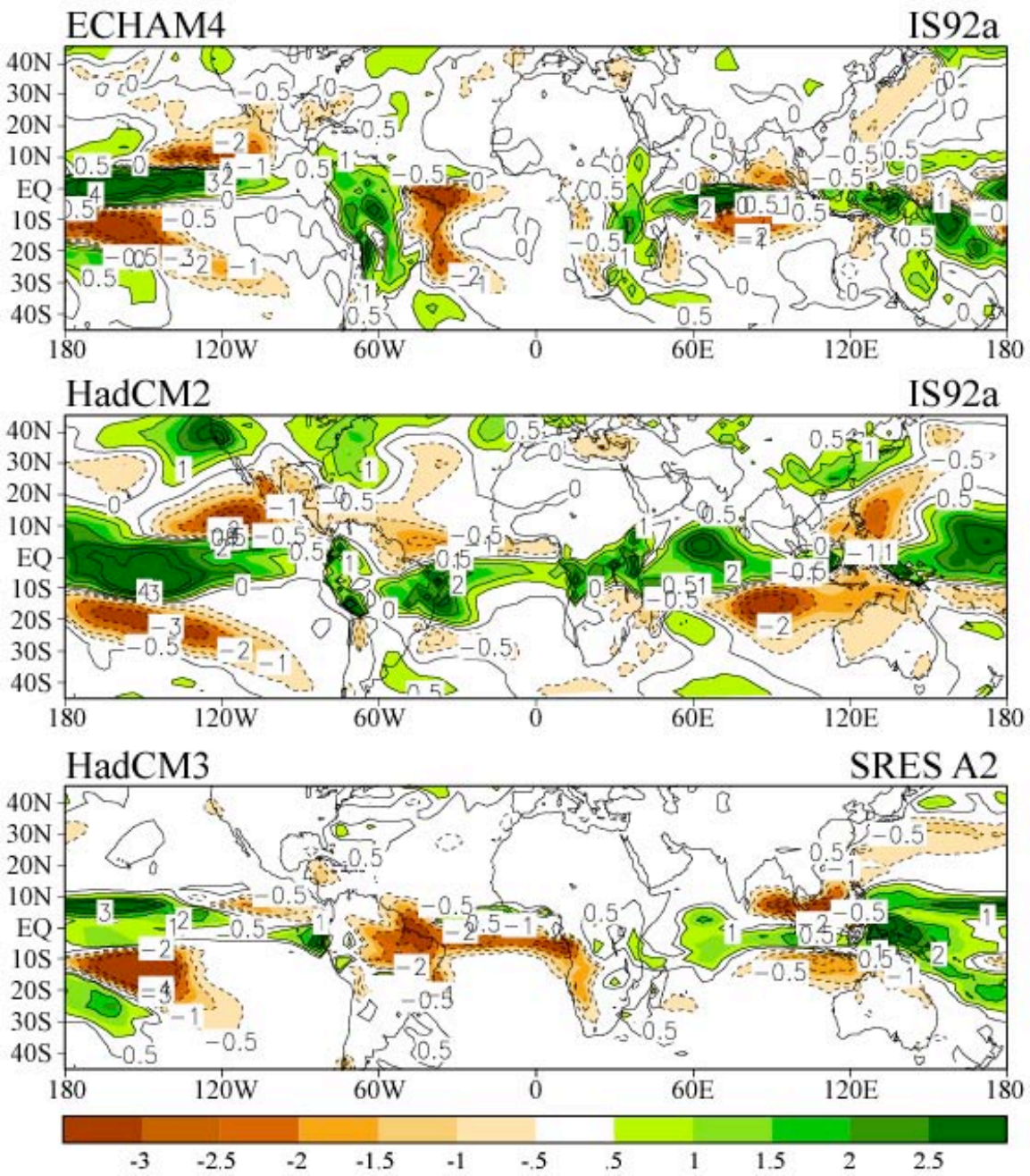



Su & Neelin, 2002

# Precipitation change under global warming

## Reprise…

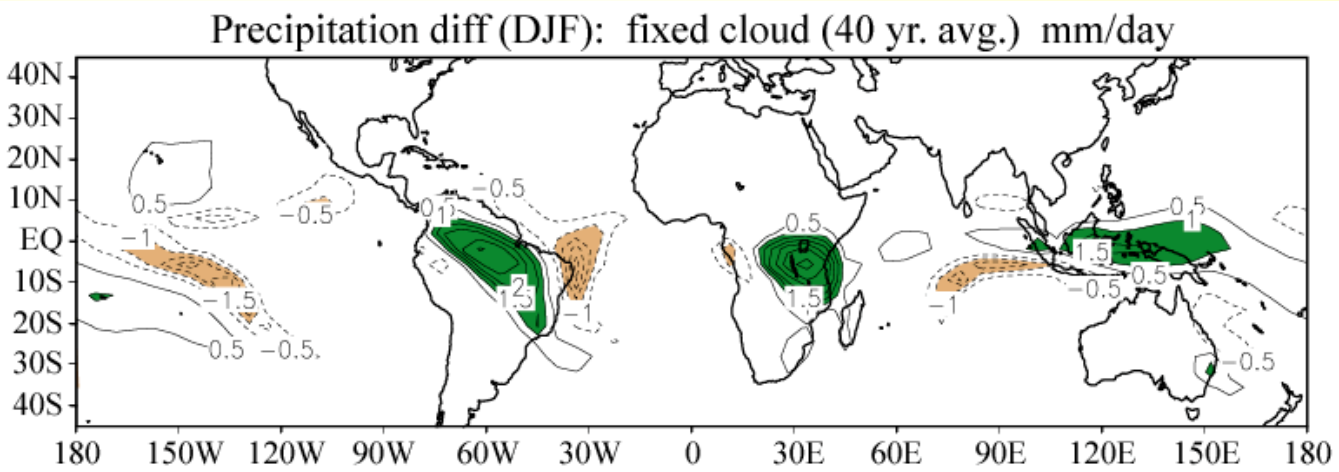
**Dec.-Feb. (DJF) precip. anomaly For 2070-2090 (rel. to 1961-1990). Three ocean-atmos. climate models (Greenhouse gas + aerosol forcing scenarios)**



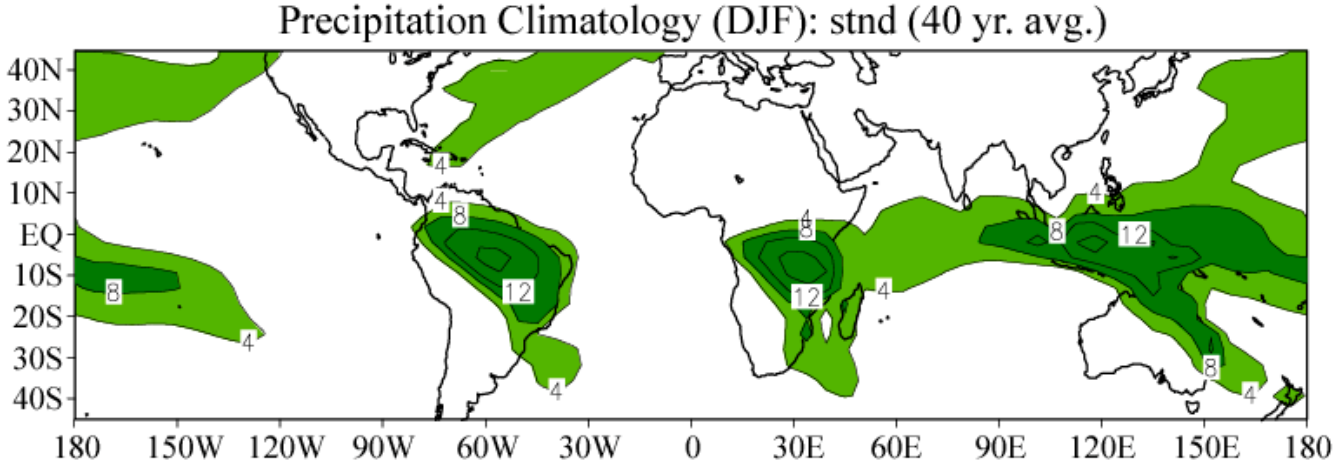

Neelin et al 2003, *GRL*

# Simpler case: doubled $CO_2$ experiments QTCM+mixed-layer ocean

**Dec - Feb Precip change 2x$CO_2$ rel. to base**

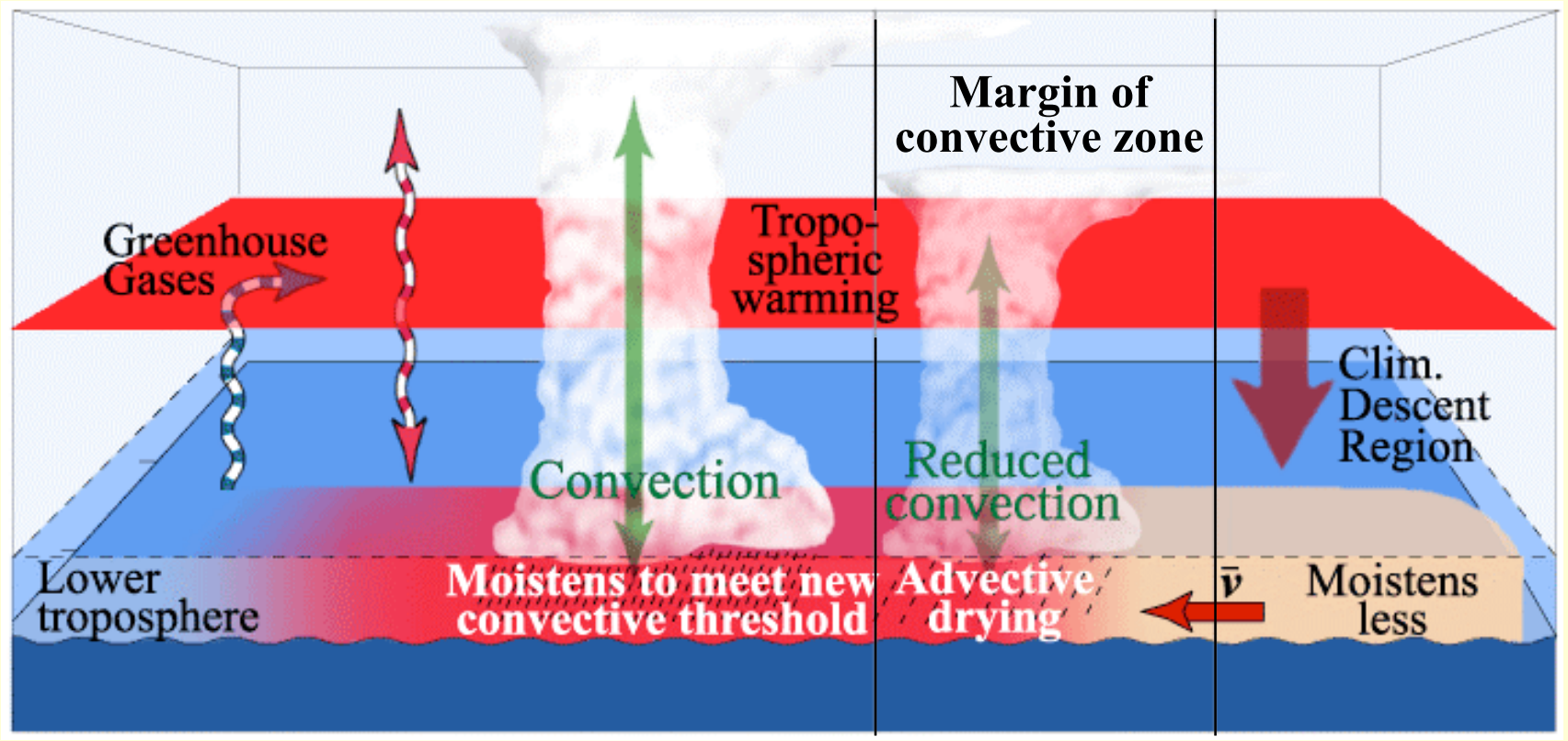



**Dec - Feb QTCM Precip climatology**




Neelin et al 2003; Chou & Neelin 2004

# The "upped-ante" mechanism




Neelin, Chou & Su, 2003 *GRL*

# Temperature $T$ and Moisture $q$ equations

*dry static energy* $s = T + \phi$

$$(\partial_t + \mathbf{v} \bullet \nabla)T + \omega\partial_p s - \partial_p R + \partial_p S - \partial_p F_{SH} = Q_c$$

$Q_c$: *convective heating*

$\omega$: *vertical velocity*

$R$, $S$, $F_{SH}$: *Fluxes: longwave radiation(R), solar(S) sensible(SH), latent heat(L)*

$$(\partial_t + \mathbf{v} \bullet \nabla)q + \omega\partial_p q - \partial_p F_L = Q_q$$

$Q_q$: *moisture source/sink*

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**Energy constraint in vertical integral $\langle\ \rangle$**

$$\langle Q_c \rangle = -\langle Q_q \rangle$$

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**$\langle$Moist static energy equation$\rangle$**

$$\langle(\partial_t + \mathbf{v} \bullet \nabla)(T + q)\rangle + \langle\omega\partial_p h\rangle - F_{net} = 0$$

*Transport of moist static energy by divergent flow* ≈ (measure of divergence) x gross moist stability

*Moist static energy* $h = s + q$

*Net energy flux into column*

# MSE diagnostics for mechanisms

- Moist Static Energy transport by divergent flow $\approx M\nabla\cdot v$
- Gross Moist Stability $M = M_s - M_q$, ($M_q$ inc. with moisture)

MSE budget for perturbations T′ + ocean mixed layer / land

$$\bar{M}\,\nabla\cdot v' = -M'\nabla\cdot\bar{v} - (v\cdot\nabla q)' - c\partial_t T_s' + F_{top}^{net'} + (v\cdot\nabla T)' \ldots$$

Yields precip anoms as $T' \Rightarrow q' \Rightarrow \nabla q'$, $M'$; $v'$, $q' \Rightarrow E'$ etc.

$$P' \approx \frac{\bar{M}_q}{\bar{M}}\left[-(\bar{v}\cdot\nabla q)' + \nabla\cdot v(-M') - c\partial_t T_s' + \cdots\right]$$

GMS multiplier effect

Upped-ante Rich-get-richer

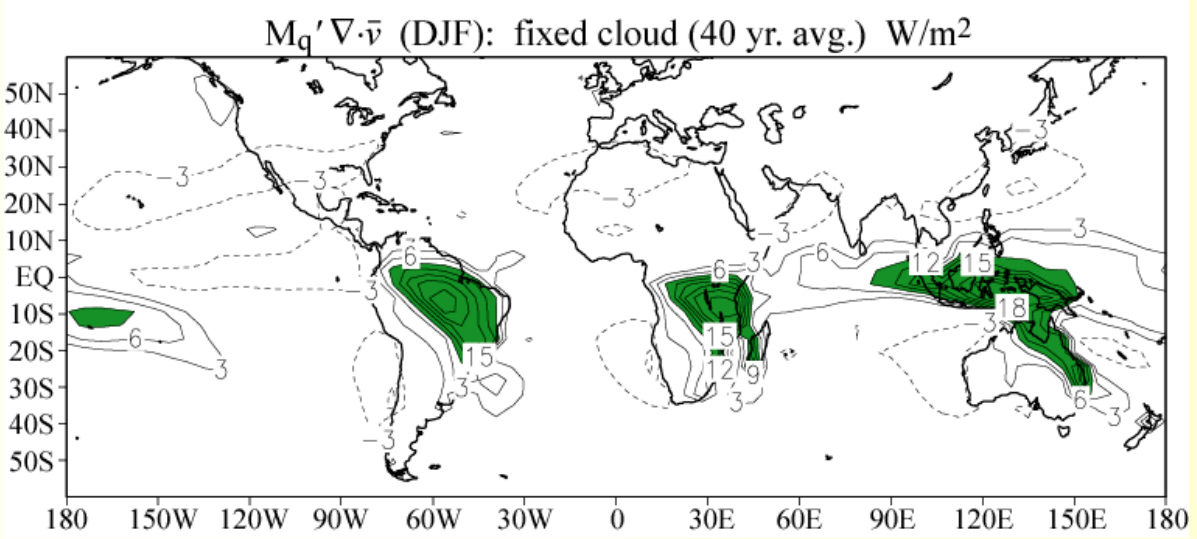
SST disequilibrium

Rad cooling, $(v\cdot\nabla T)'$
ocean transp, …

# QTCM doubled $CO_2$ experiments
# Moisture budget contributions

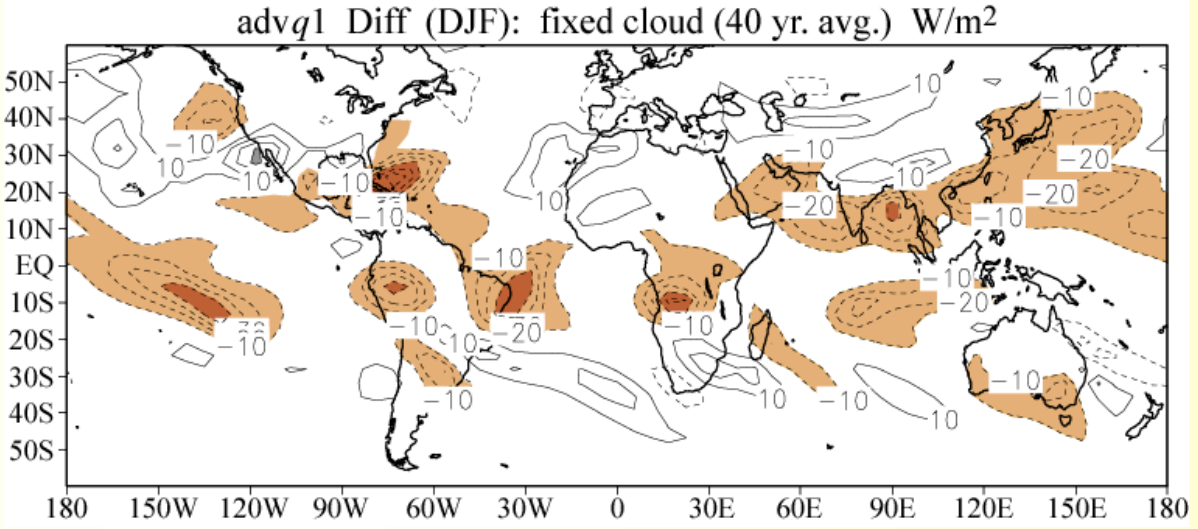
**$M_q' \nabla \cdot \bar{v}$**

**Anomalous moisture convergence due to moisture anom. $q'$**

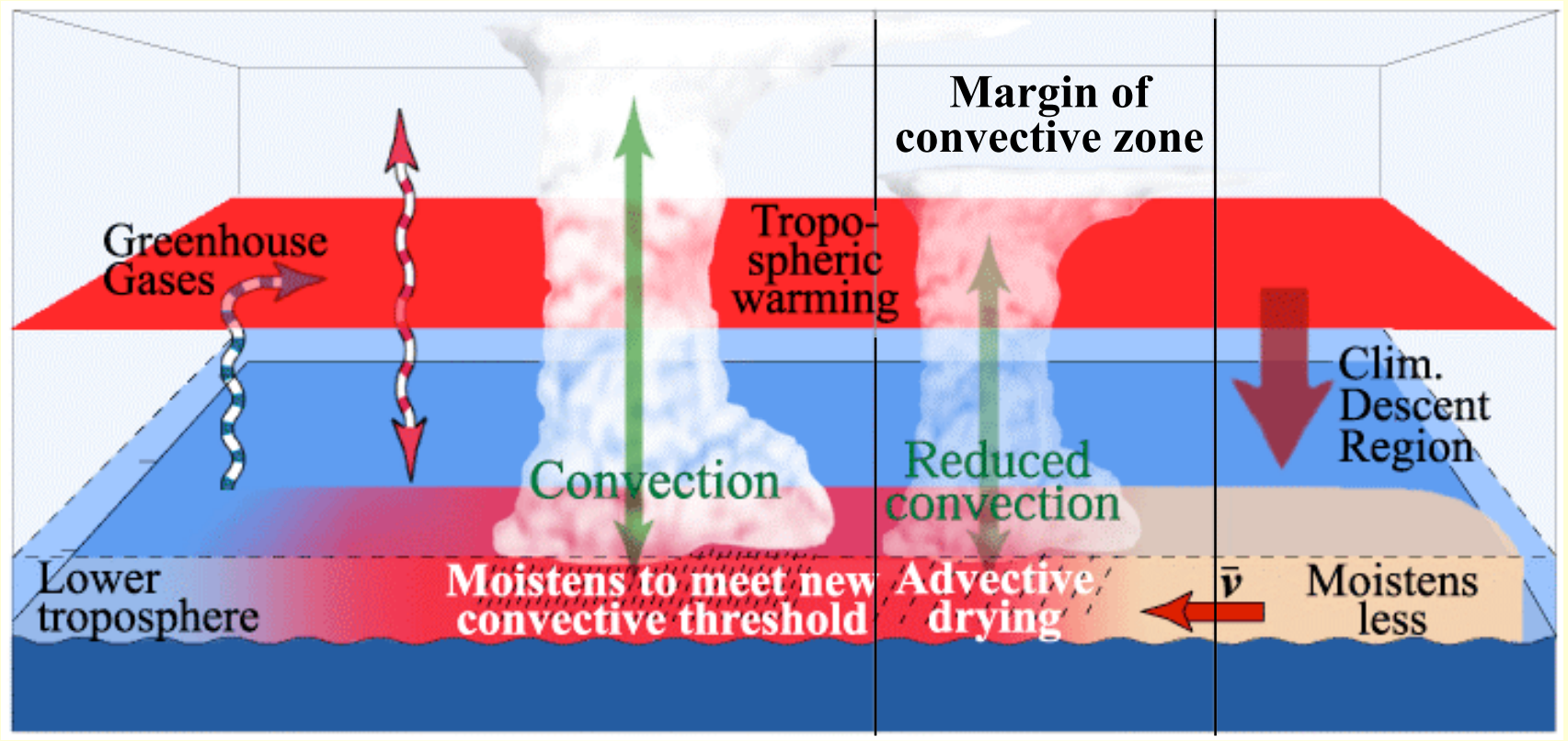



**$(v \cdot \nabla q)'$**

**Anomalous moisture advection**



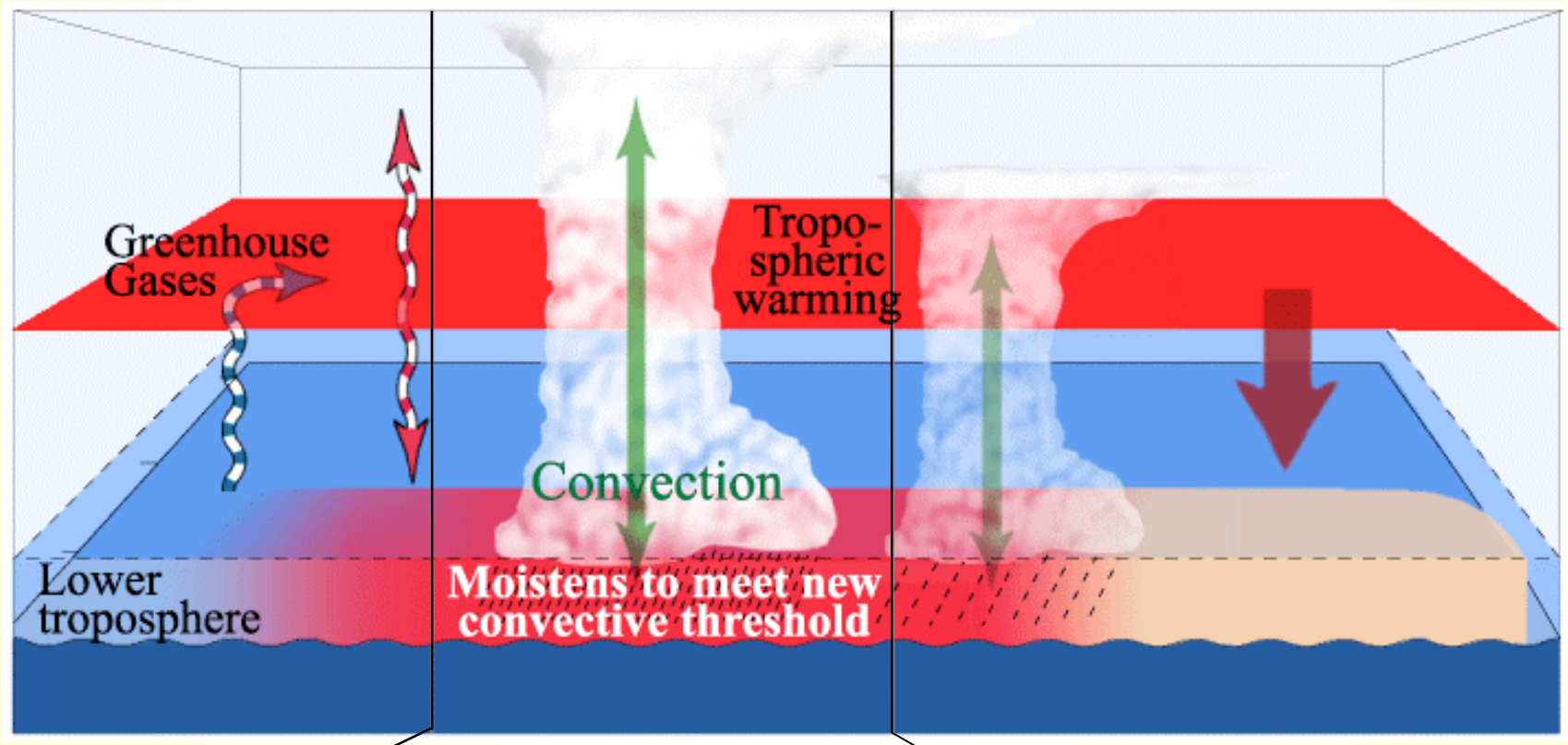
# The "upped-ante" mechanism




Neelin, Chou & Su, 2003 *GRL*

# The Rich-get-richer mechanism

## Formerly M′ (anomalous Gross Moist Stability) mechanism




**Center of convergence zone: incr. moisture ⇒ lower gross moist stability ⇒ incr. convergence, precip**

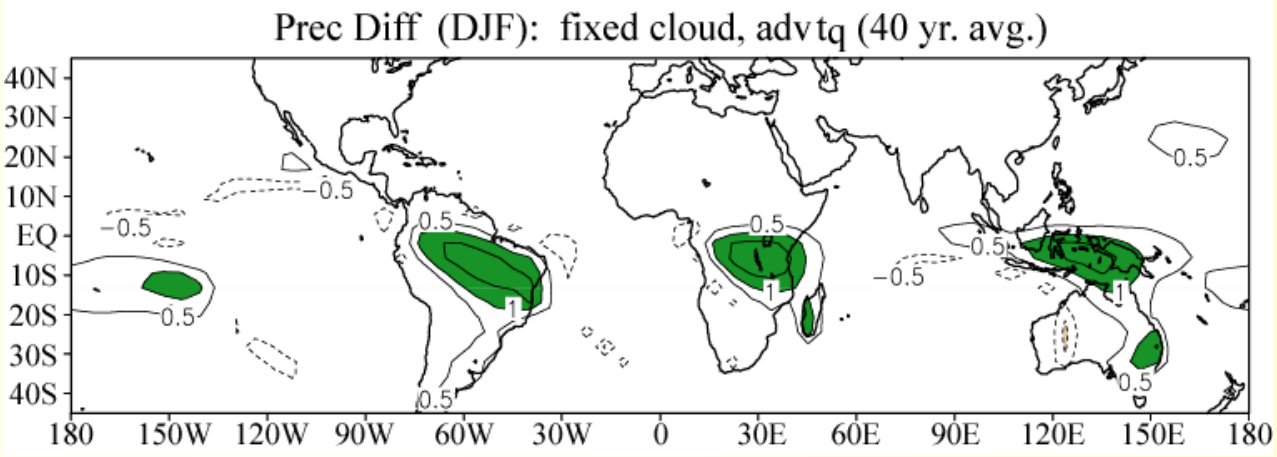
**Descent region: incr. descent ⇒ less precip.**

Chou & Neelin, 2004

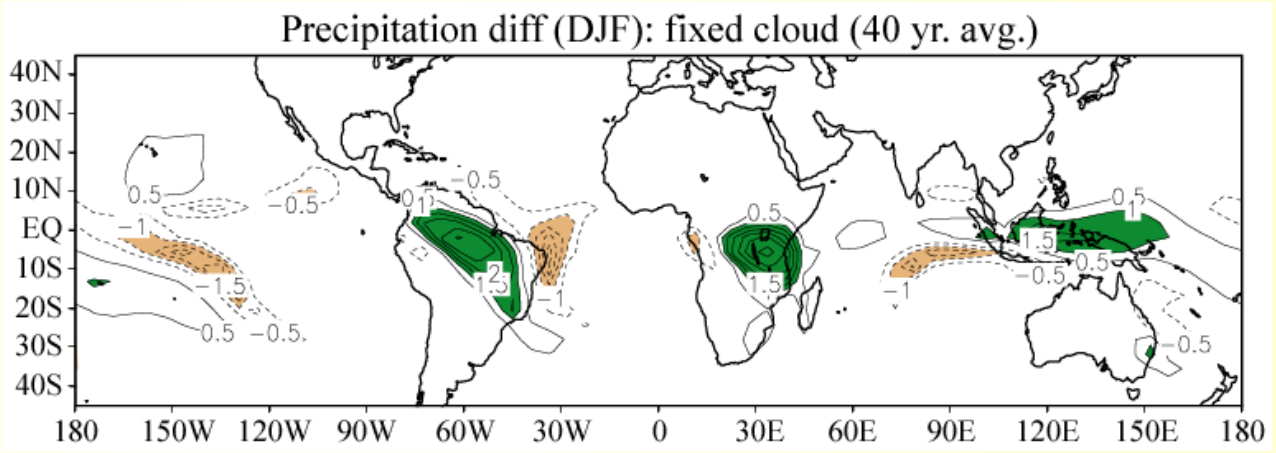
# QTCM 2x$CO_2$ Expt. suppressing change in moisture advection

## Testing the upped-ante mechanism

**Suppression experiment**
**2x$CO_2$ Precip. change (mm/day)**




**Control**
**2x$CO_2$ Precip. change**

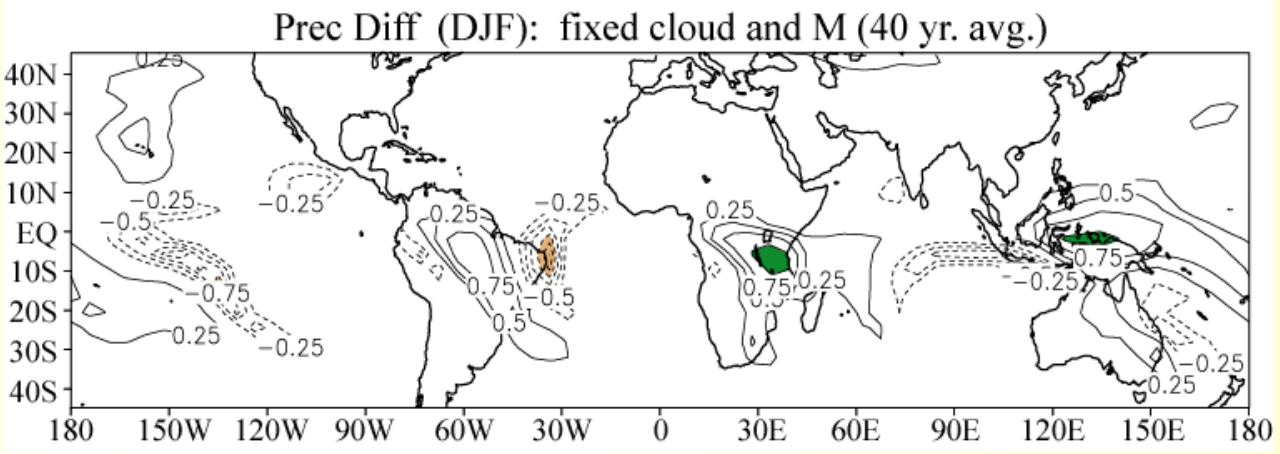



Neelin, Chou & Su, 2003 *GRL*

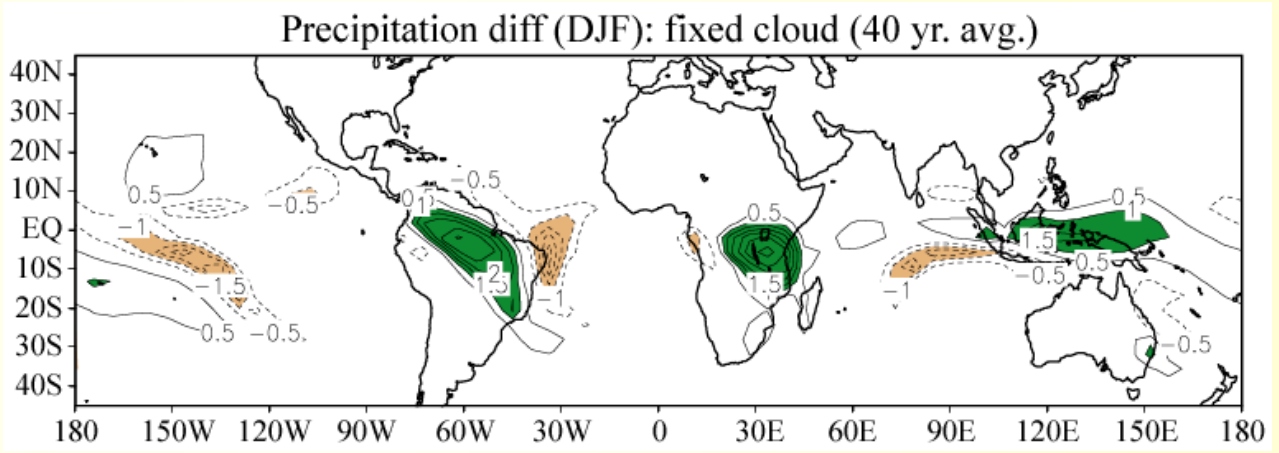
# QTCM 2x$CO_2$ Expt. suppressing change in gross moist stability, M

## Testing the rich-get-richer (M′) mechanism

**Suppression experiment**
**2x$CO_2$ Precip. change (mm/day)**




**Control**
**2x$CO_2$ Precip. change**




Chou & Neelin, 2004, *J Clim*

# ECHAM4 + ocean mixed layer 2x$CO_2$ equilib.

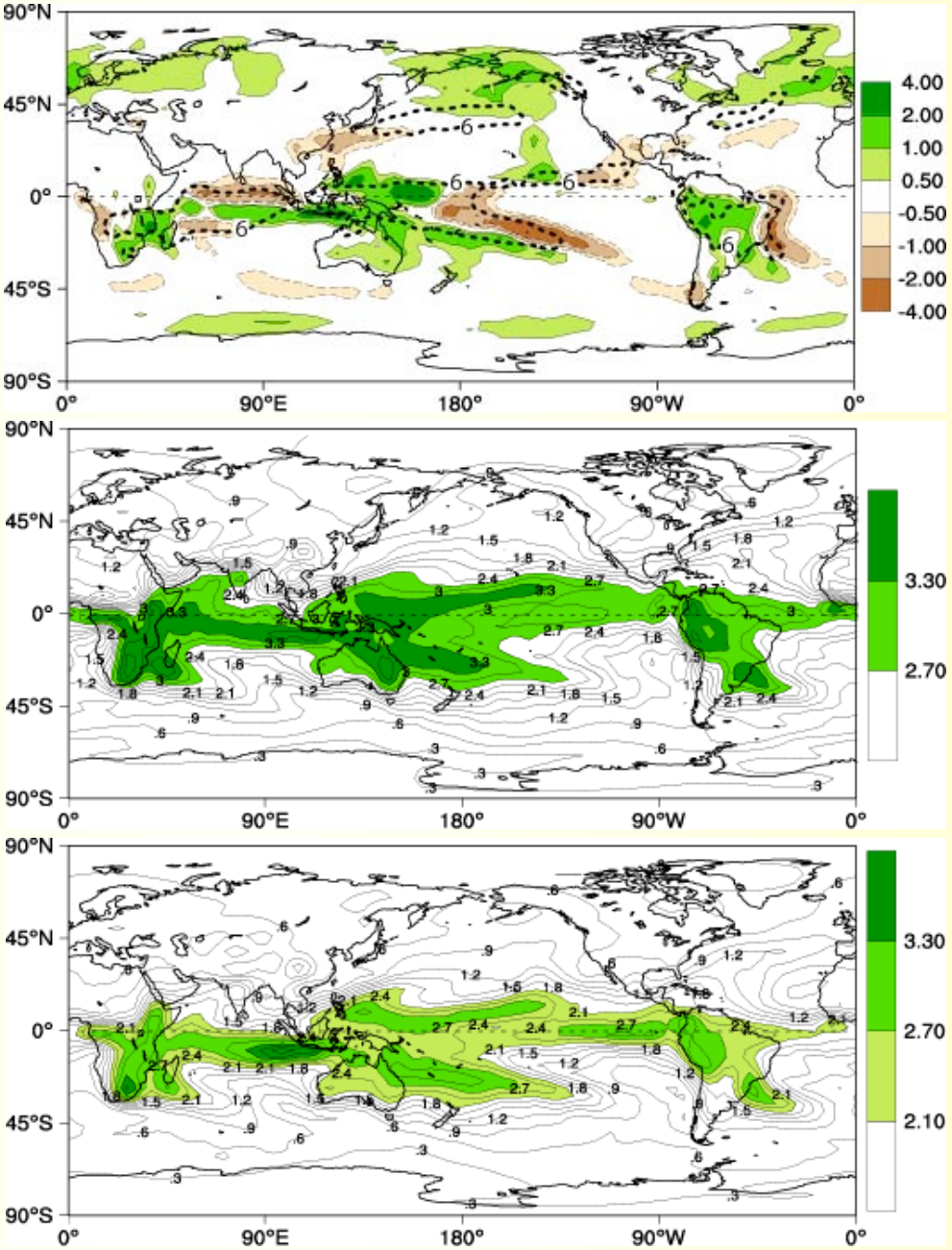
**Precip. anom. rel. to control**

**--- Clim. Precip. (6 mm/day contour)**

**Moisture anom. (1000-900 hPa)**

**Moisture anom. (900-700 hPa)**

Chou, Neelin, Tu & Chen (2006, *J. Clim.*, in press)



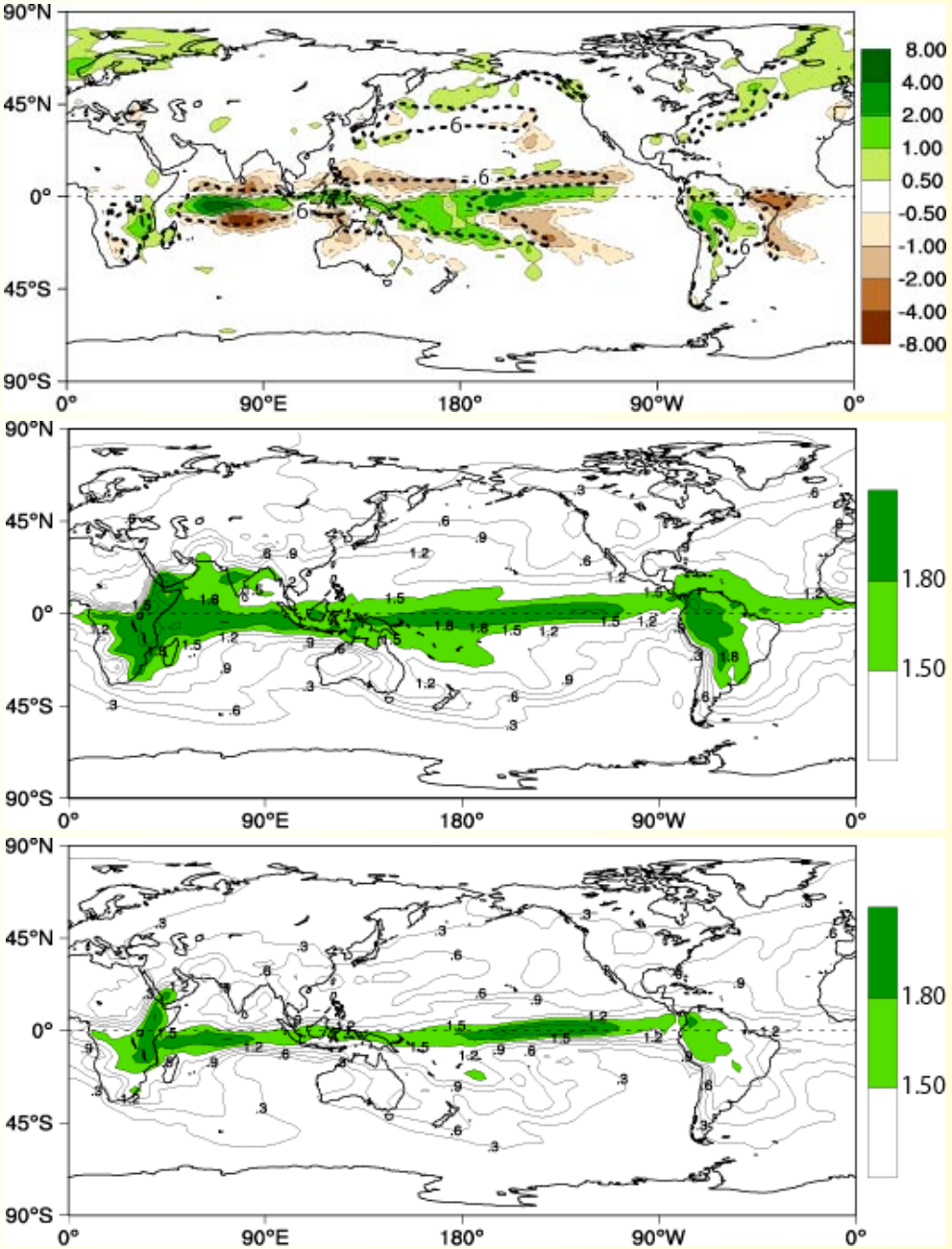
# ECHAM4/OPYC3 2030-2050 IS92a (GHG only)

**Precip. anom. rel. to control**

**--- Clim. Precip. (6 mm/day contour)**

**Moisture anom. (1000-900 hPa)**

**Moisture anom. (900-700 hPa)**




Chou, Neelin, Tu & Chen (2006, *J. Clim.*, in pr.)

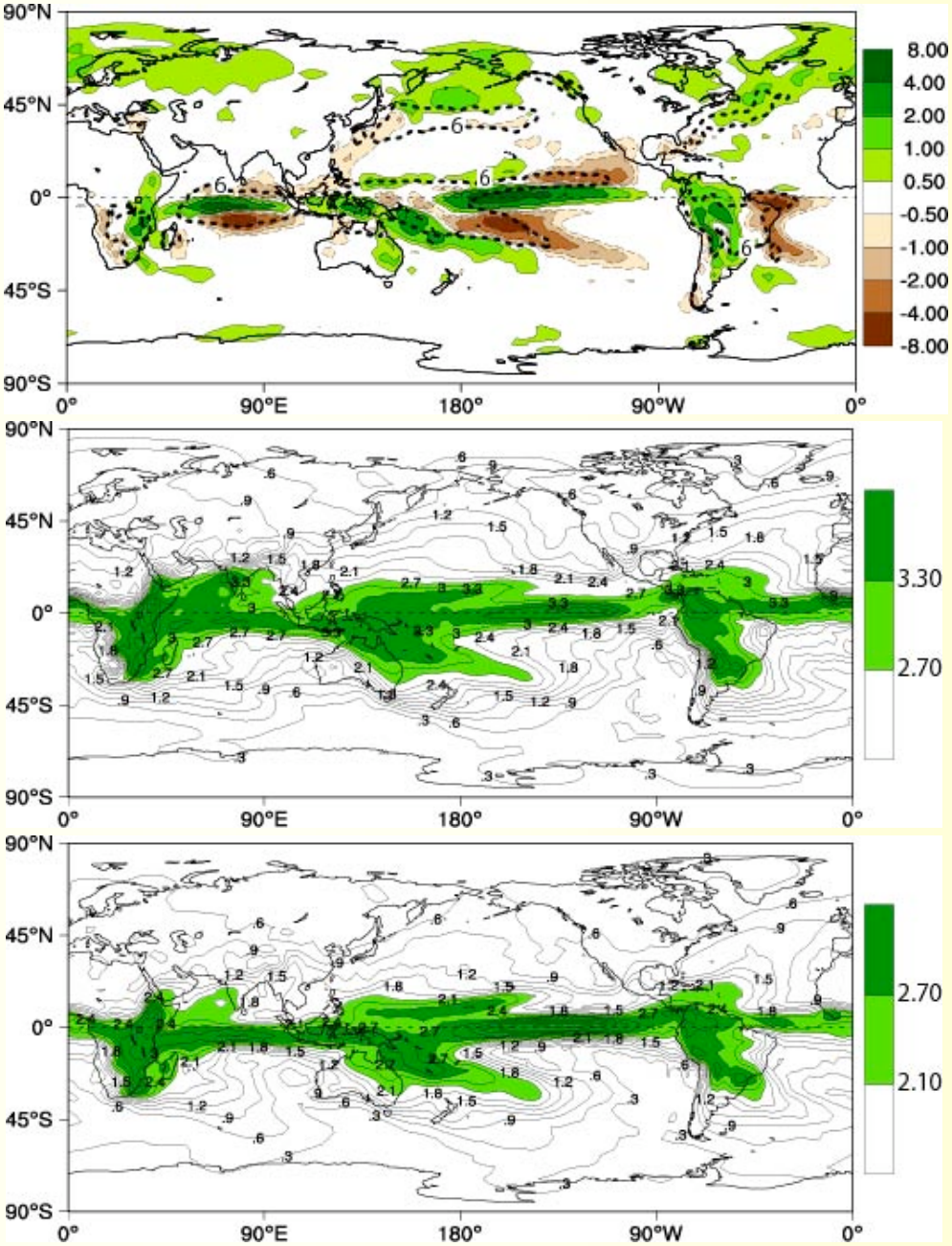
# ECHAM4/OPYC3 2070-2099 IS92a (GHG only)

**Precip. anom. rel. to control**

**--- Clim. Precip. (6 mm/day contour)**

**Moisture anom. (1000-900 hPa)**

**Moisture anom. (900-700 hPa)**

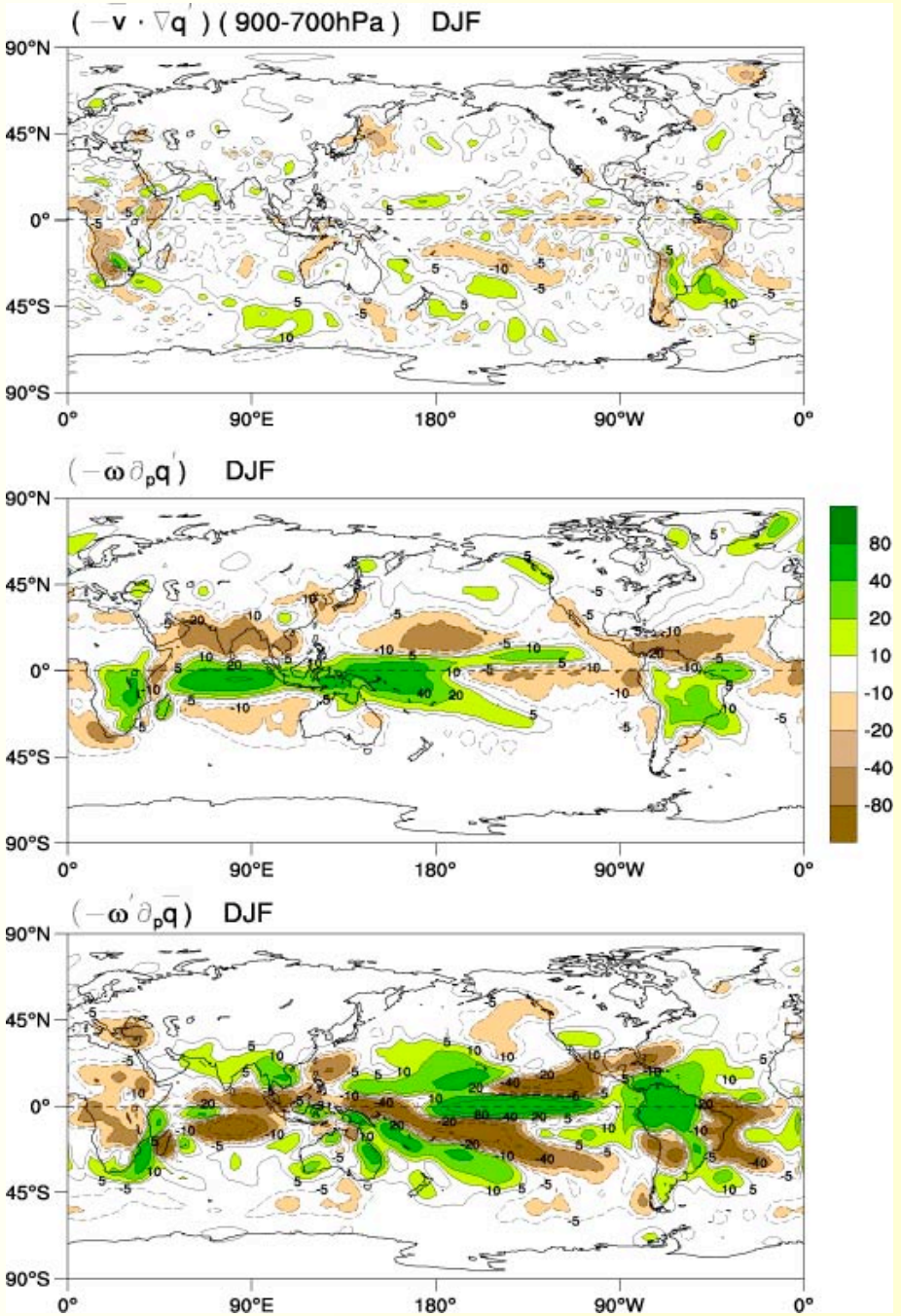


# ECHAM4 DJF Contributions to the moisture/MSE budget

Assoc. with upped ante

Assoc. with M′ mechanism

Assoc. with GMS multiplier




Chou, Neelin, Tu and Chen 2006, *J. Clim.*, in press

# Aerosol case: remote and local response

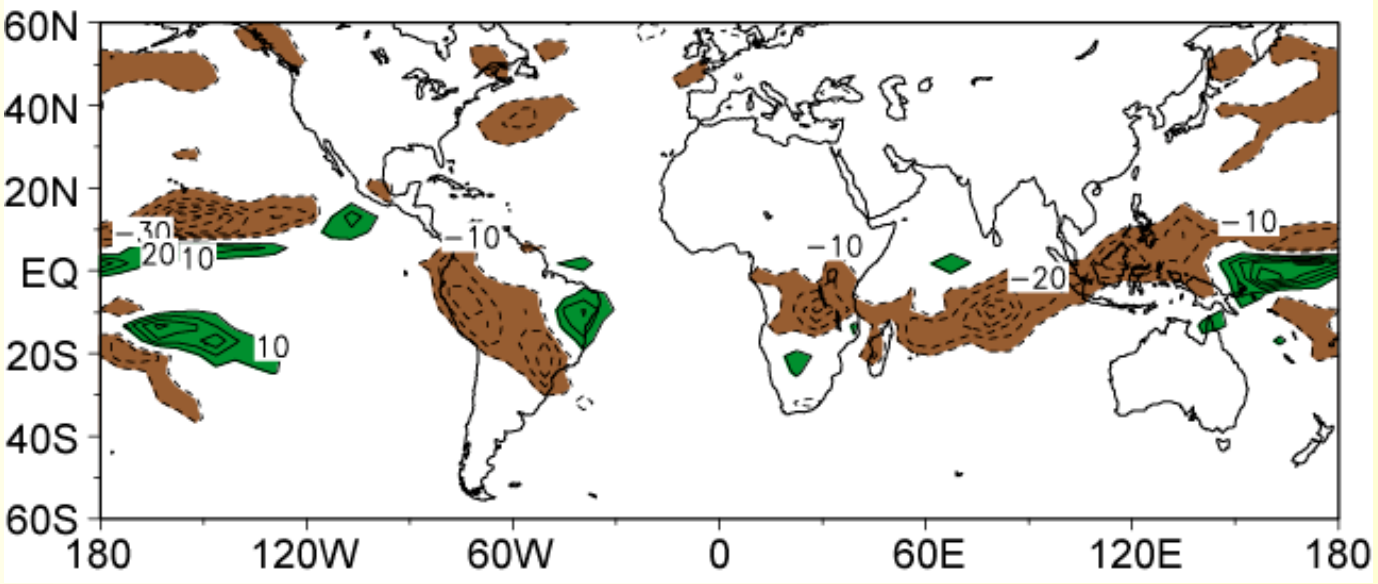
**Chou, Neelin, Lohmann & Feichter, 2005, J. Clim.**

0. Bump into Ulrike Lohmann in Toronto…
1. Shortwave radiative forcing anomaly from ECHAM4 runs with present day minus pre-industrial aerosol (Feichter et al 2004, J. Clim.) Estimate of indirect aerosol effects included per Lohmann et al (1999, 2000, JGR)
2. Specify in QTCM
3. Simulation adequately reproduces tropical precip and temperature change
4. Analyse mechanisms

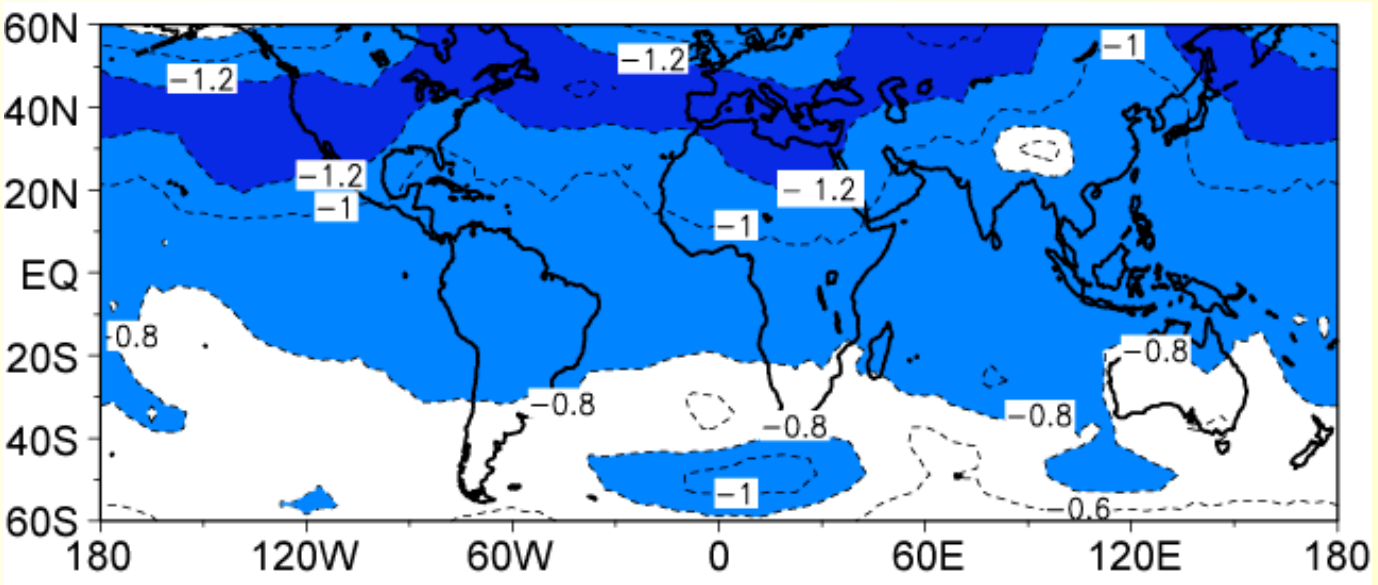
# Prec. & Temp. anomalies Dec-Feb ECHAM4

**Present Day – Pre-Industrial aerosol**

**Precipitation**
**(shaded ±10 W/m$^2$)**



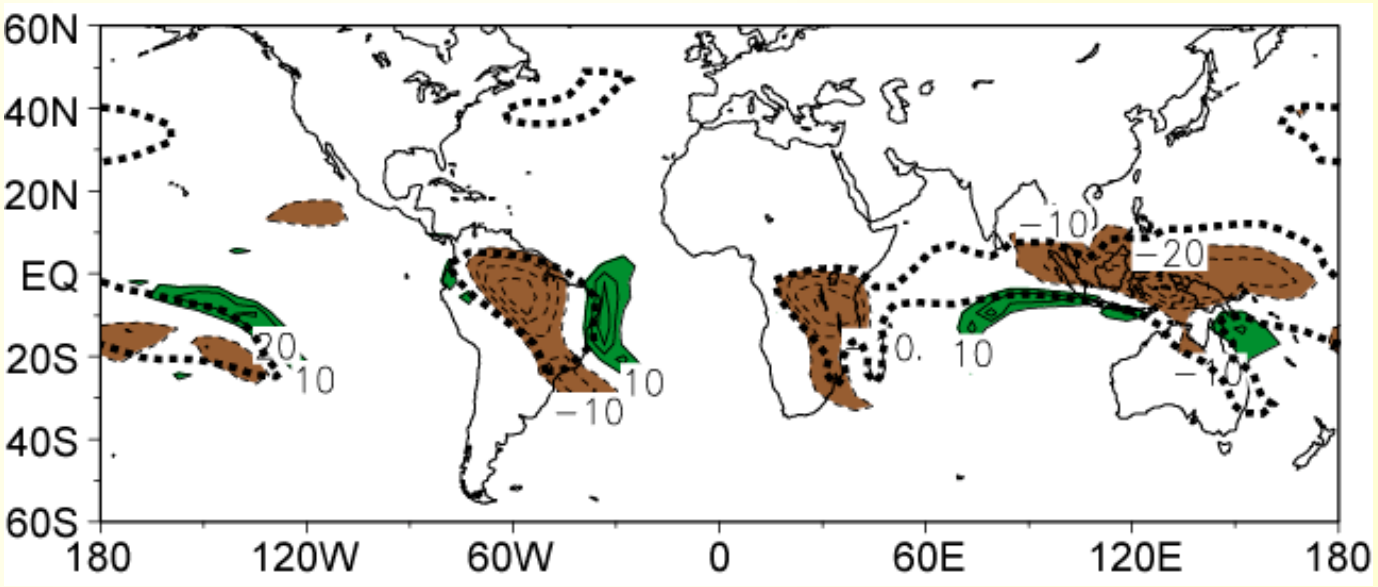

**Tropospheric Temperature**
**(850-200hPa)**
**shading below -0.8C**



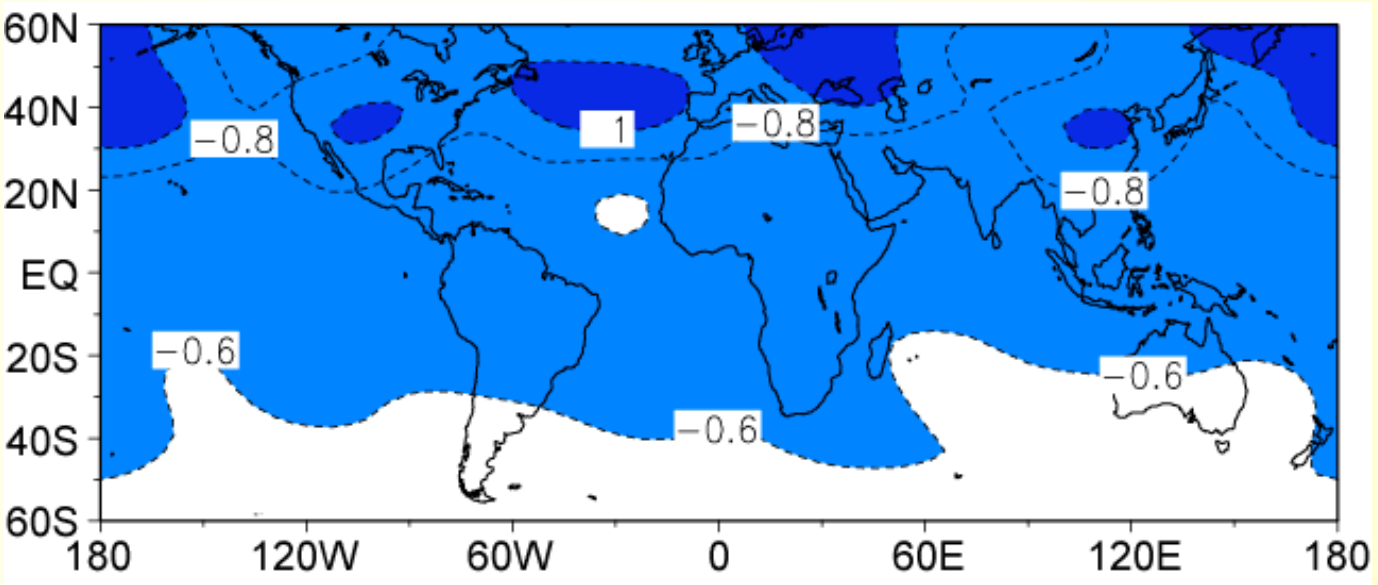
# Prec. & Temp. anomalies Dec-Feb QTCM

**Present Day – Pre-Industrial**

**Precipitation**
**(shaded ±10 W/m²)**
**--- Clim. Precip.**
**(150 W/m² contour)**




**Tropospheric Temperature**
**(850-200hPa)**
**shading below -0.6C**



# Aerosol case: remote and local response

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1. Shortwave radiative forcing anomaly from ECHAM4…
2. Specify in QTCM
3. Simulation adequately reproduces tropical precip and temperature change
4. Analyse mechanisms

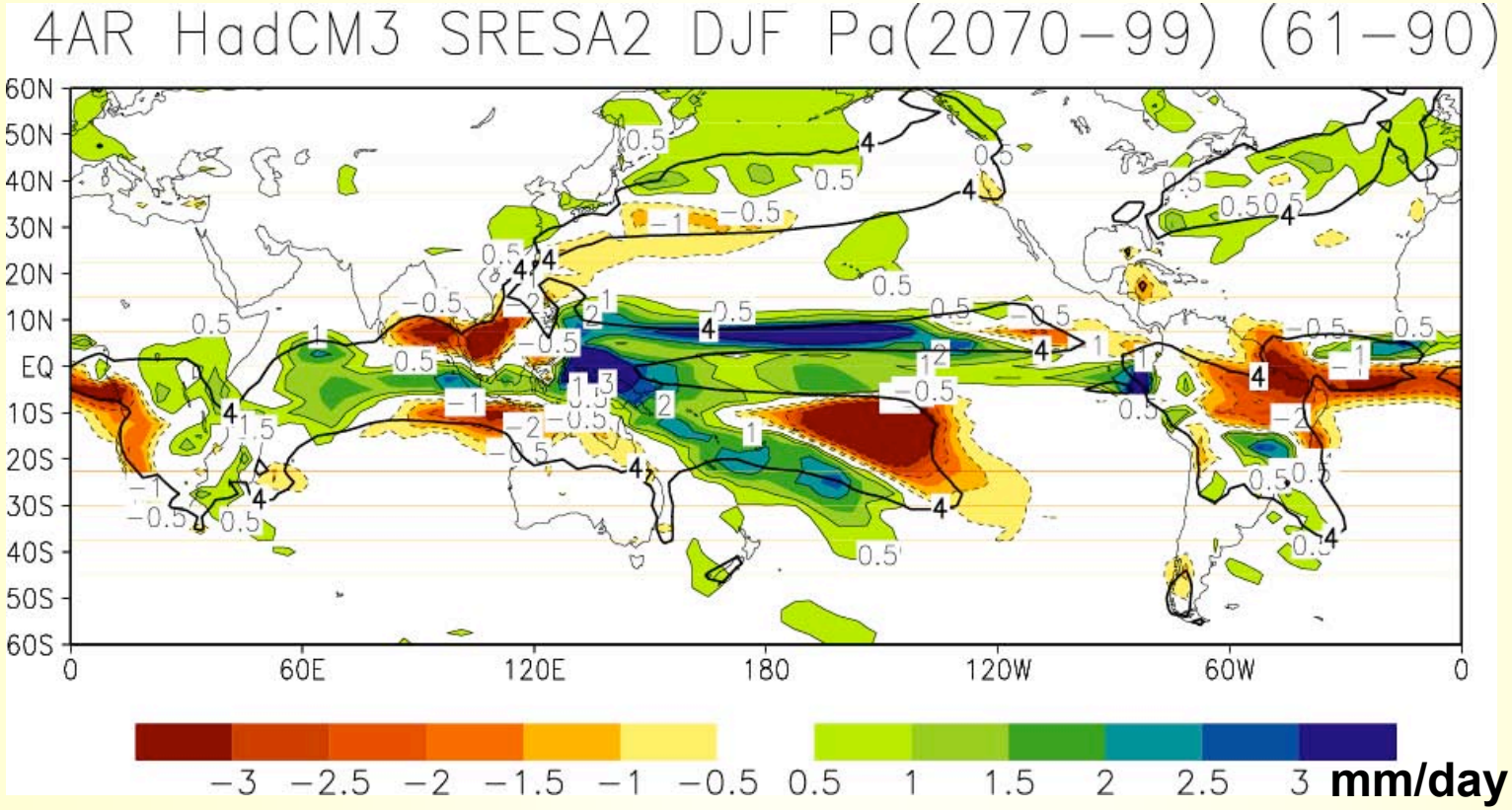
- **Remote effects on precipitation operate by same mechanisms as GHG warming but with opposite sign:**
- **cooler tropospheric temperature**
- **Upped-ante wet convective margins; weakened precip in centers of convection zones**
- **In transient scenario runs with both aerosol and greenhouse gas, the warming effects eventually dominate**

# 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***

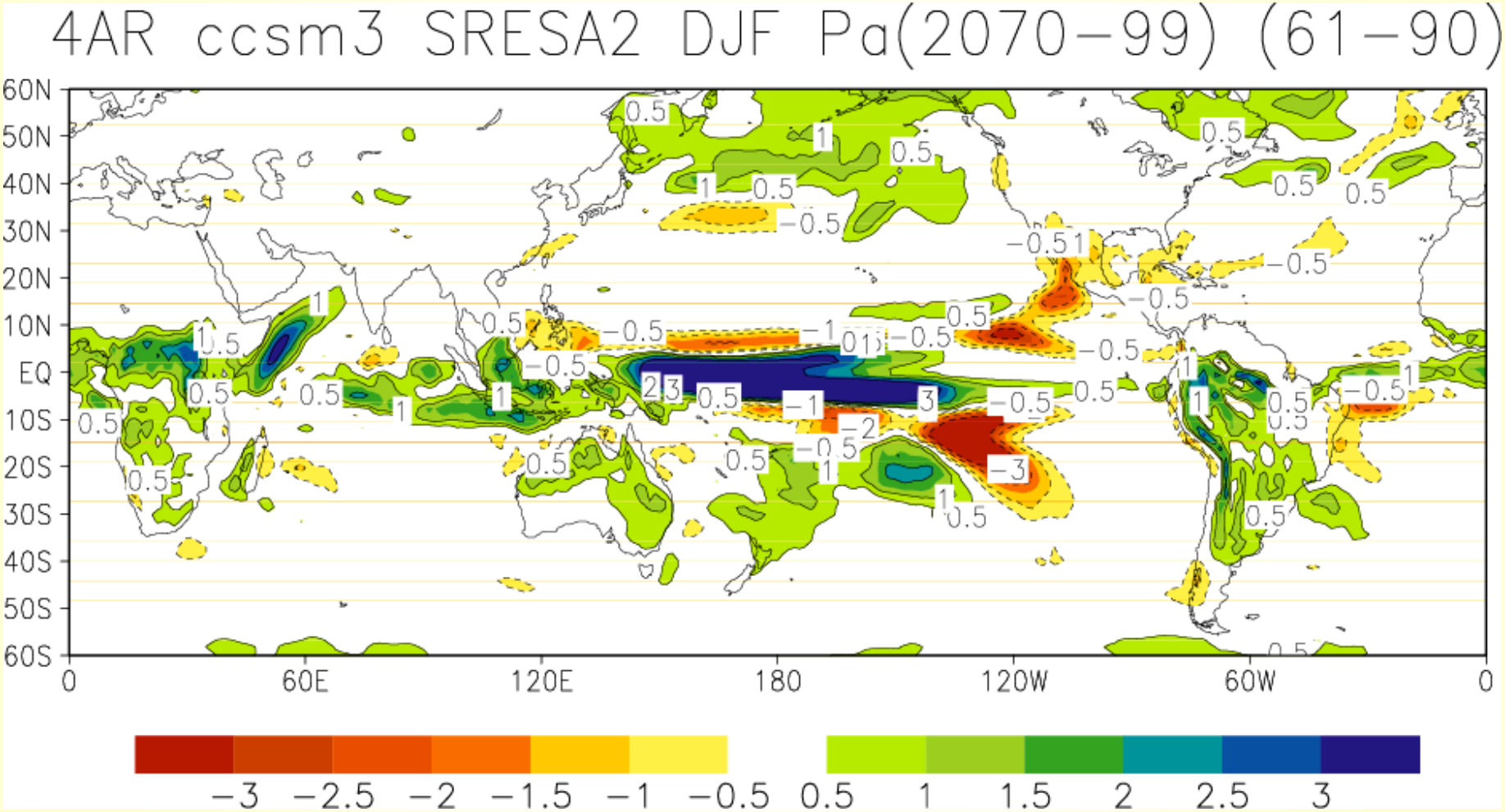
**Precipitation change: HadCM3, Dec.-Feb., 2070-2099 avg minus 1961-90 avg.**




**4 mm/day model climatology black contour for reference**

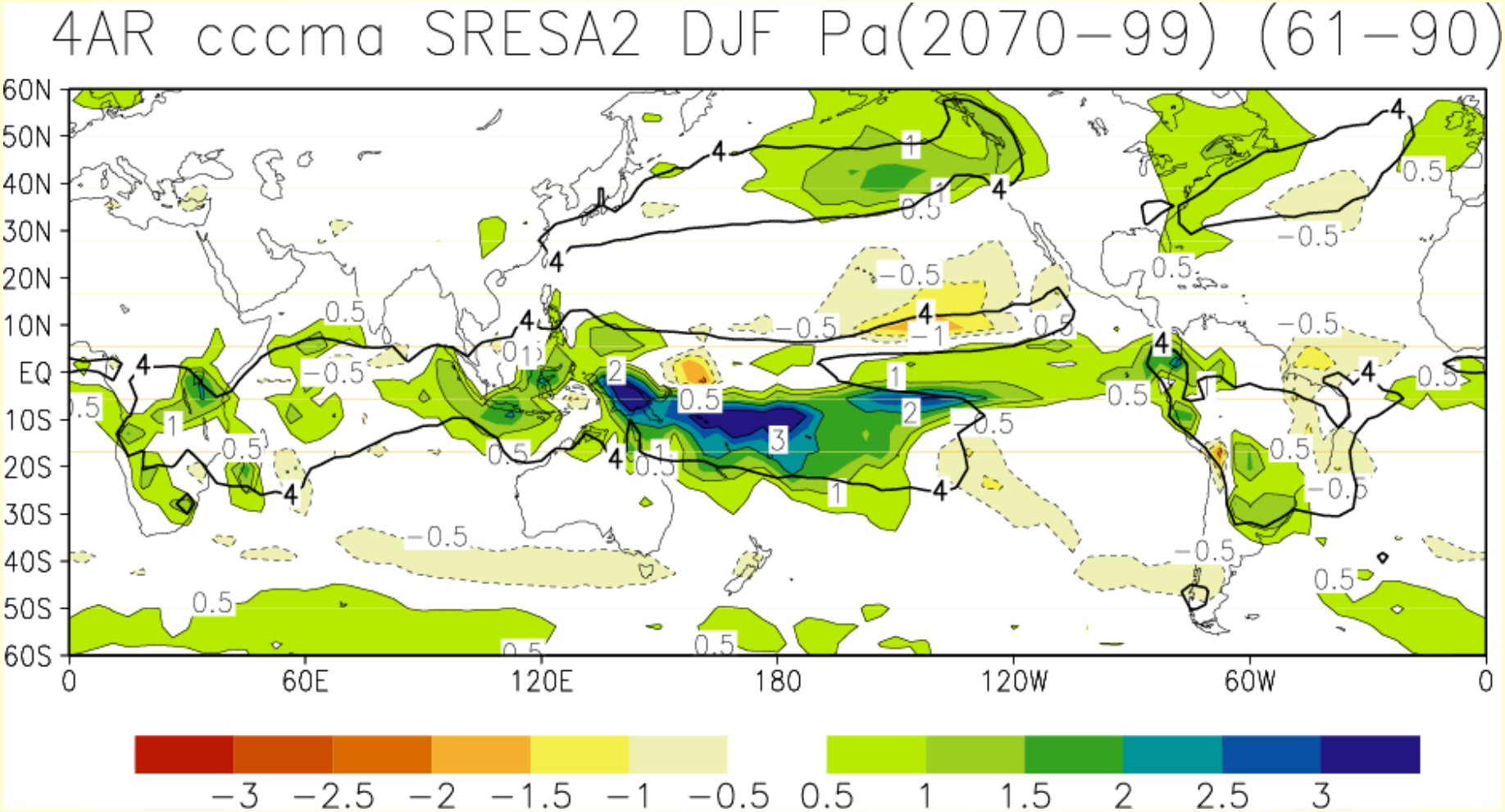
# NCAR_CCSM3

## DJF Prec. Anom.



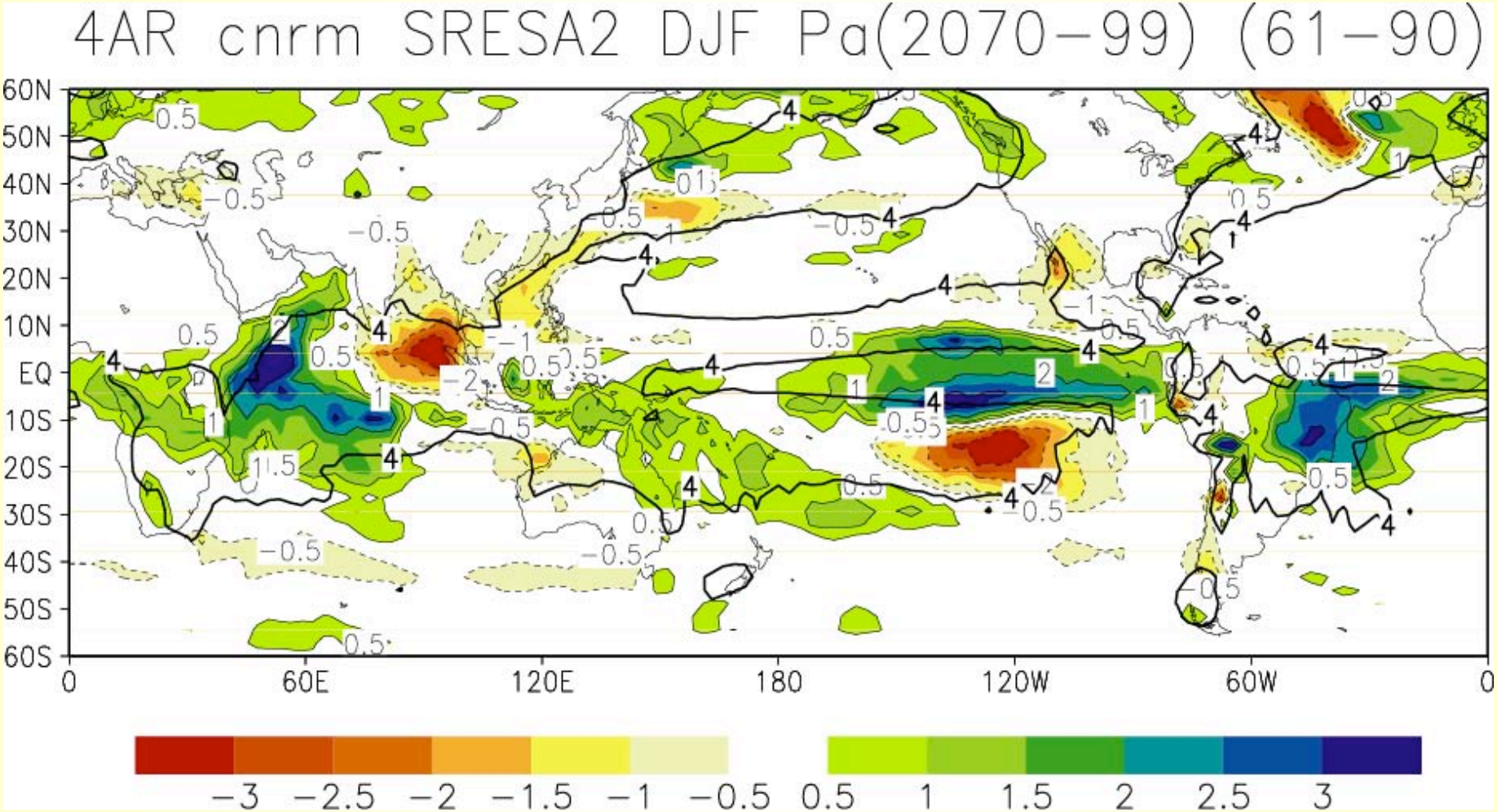
# CCCMA

## DJF Prec. Anom.



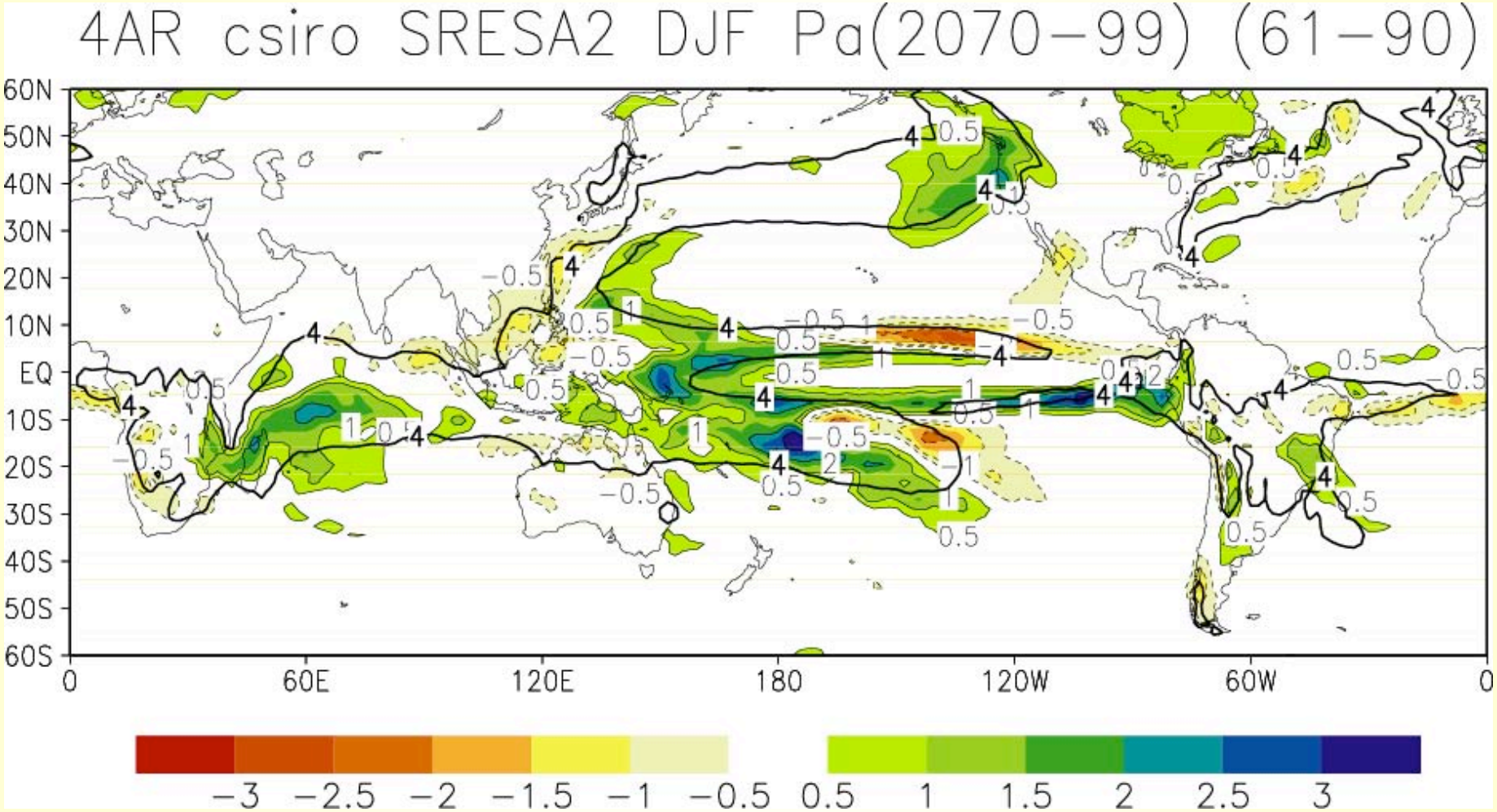
# CNRM_CM3

## DJF Prec. Anom.



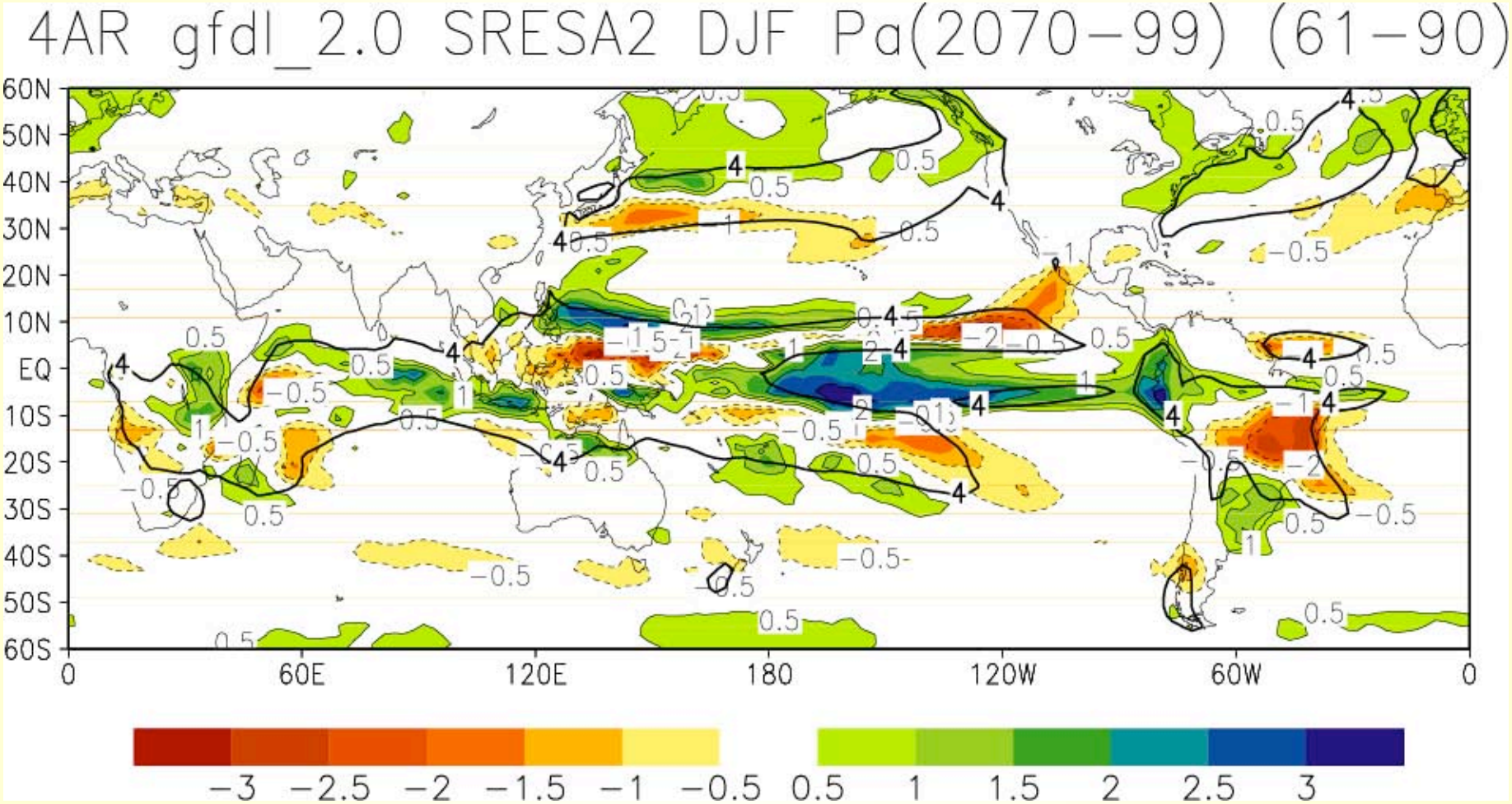
# CSIRO_MK3

## DJF Prec. Anom.



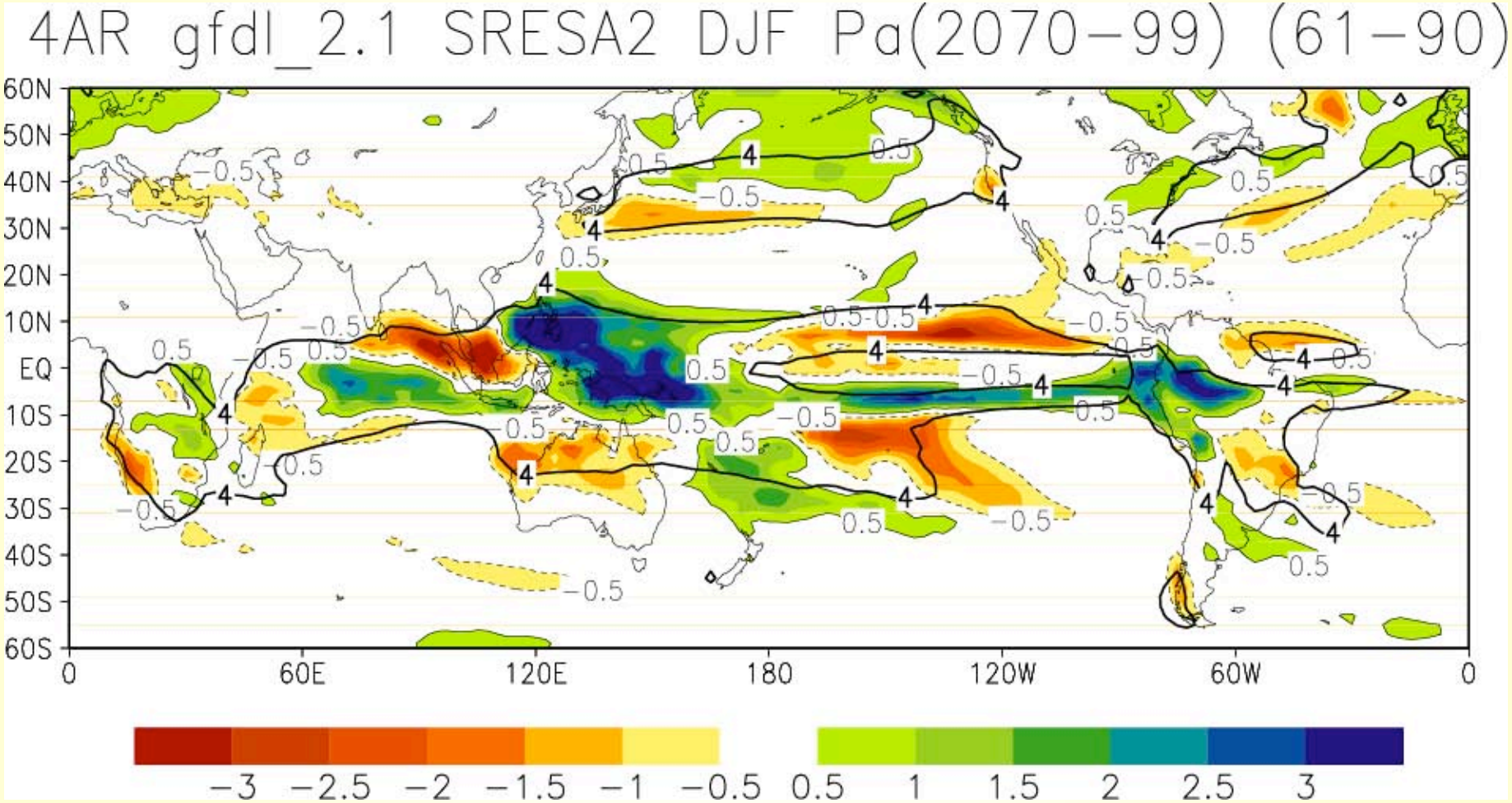
# GFDL_CM2.0

## DJF Prec. Anom.



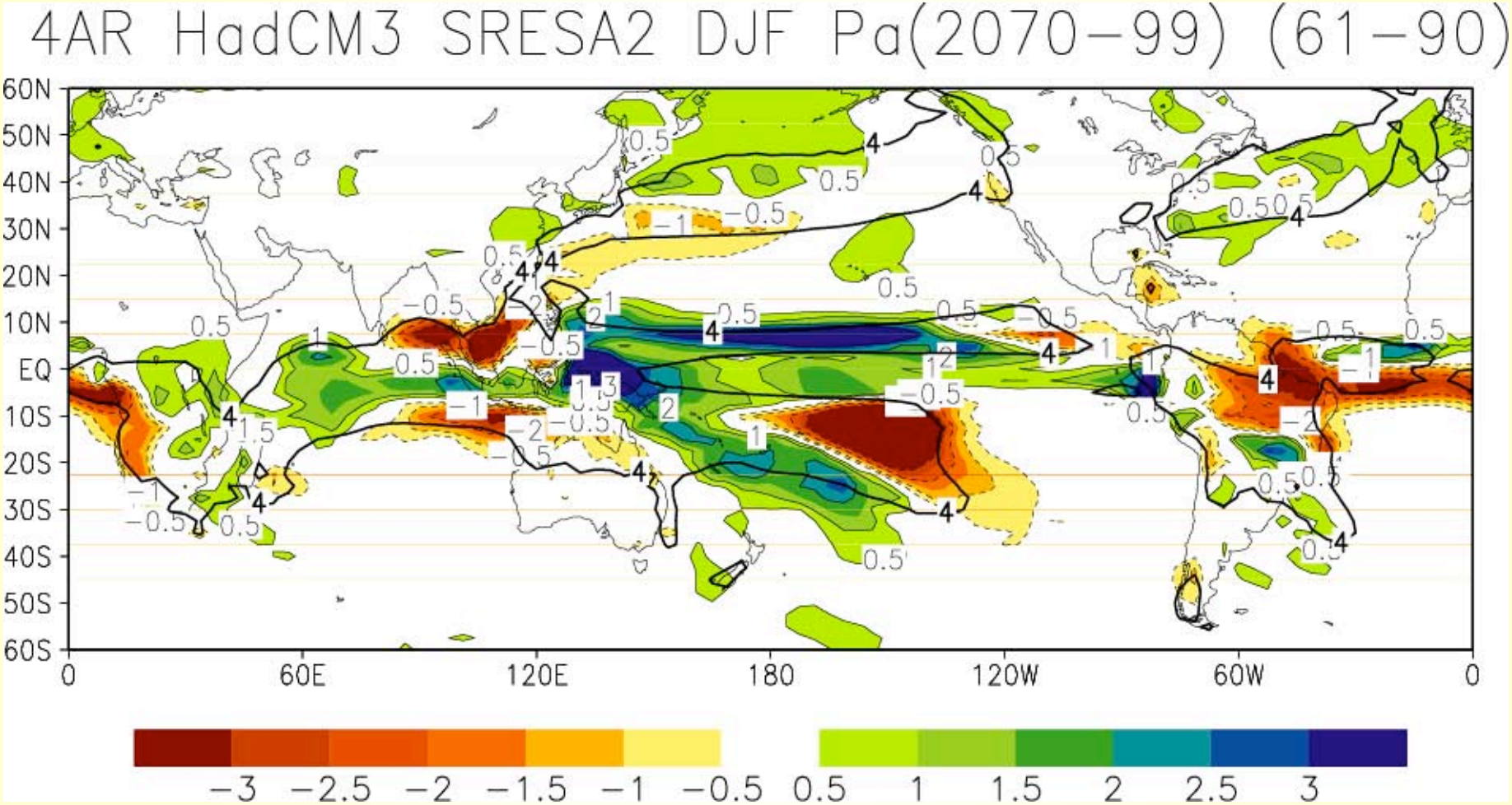
# GFDL_CM2.1

## DJF Prec. Anom.



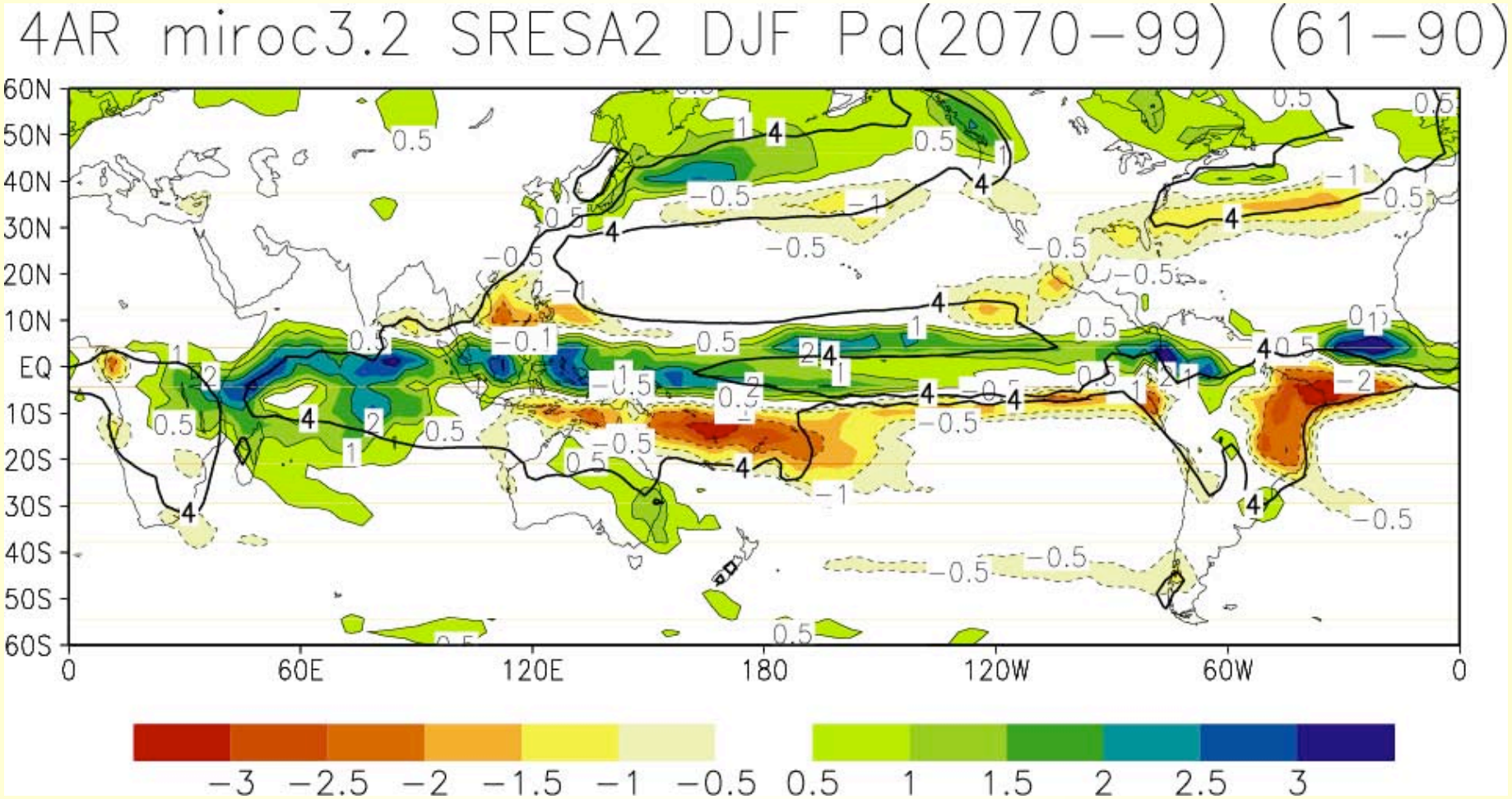
# UKMO_HadCM3

## DJF Prec. Anom.



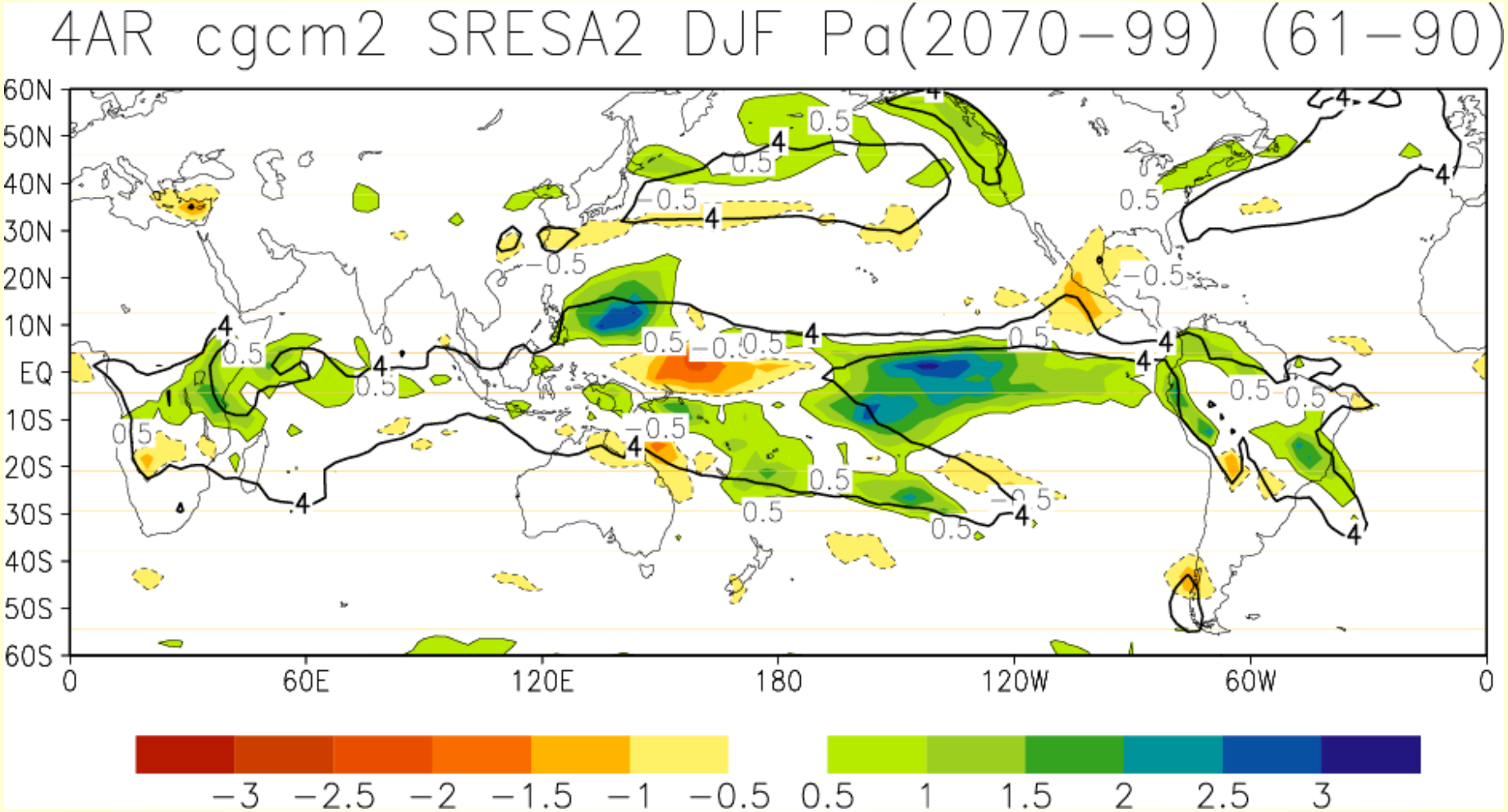
# MIROC_3.2

## DJF Prec. Anom.



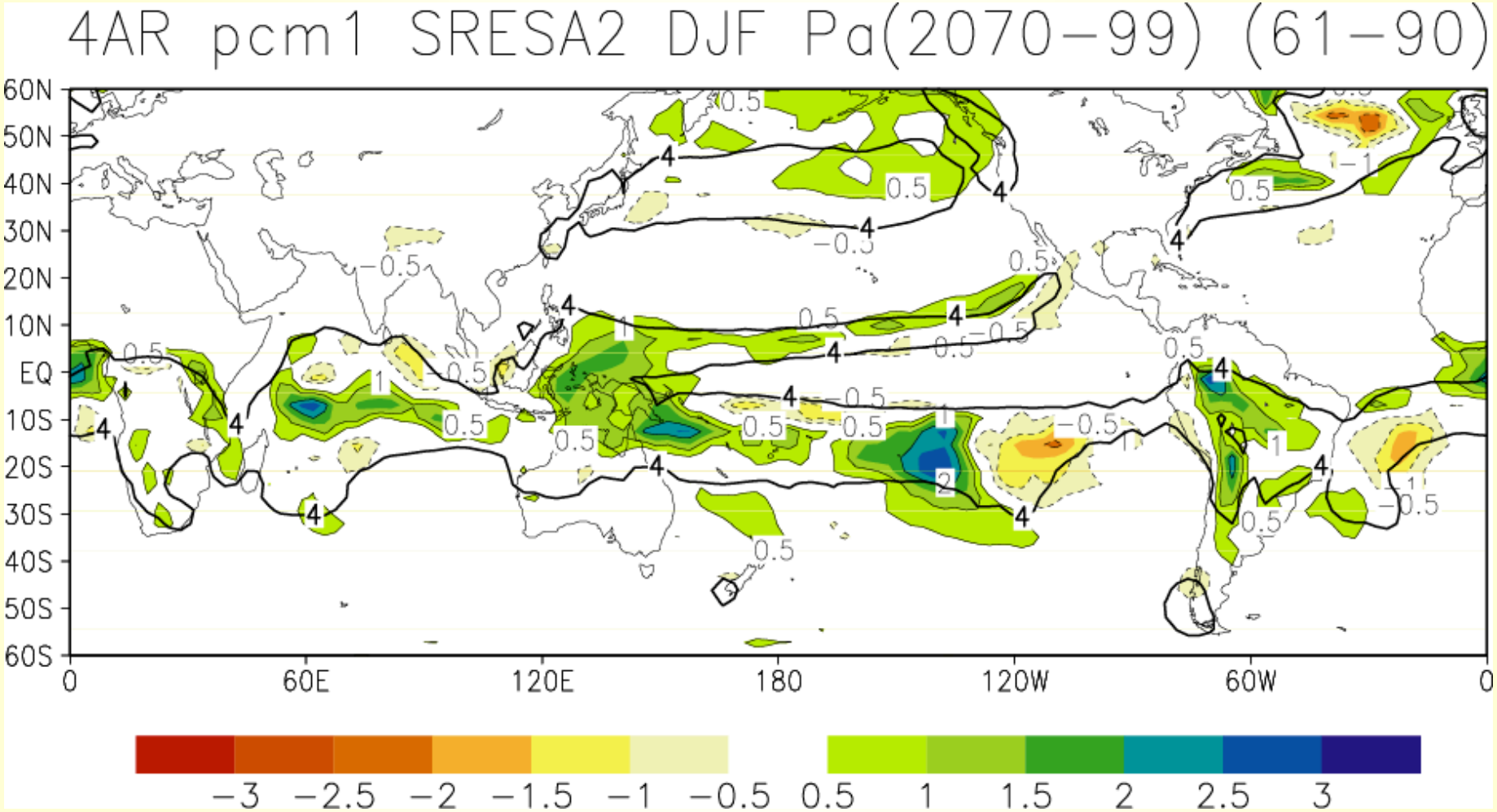
# MRI_CGCM2

## DJF Prec. Anom.



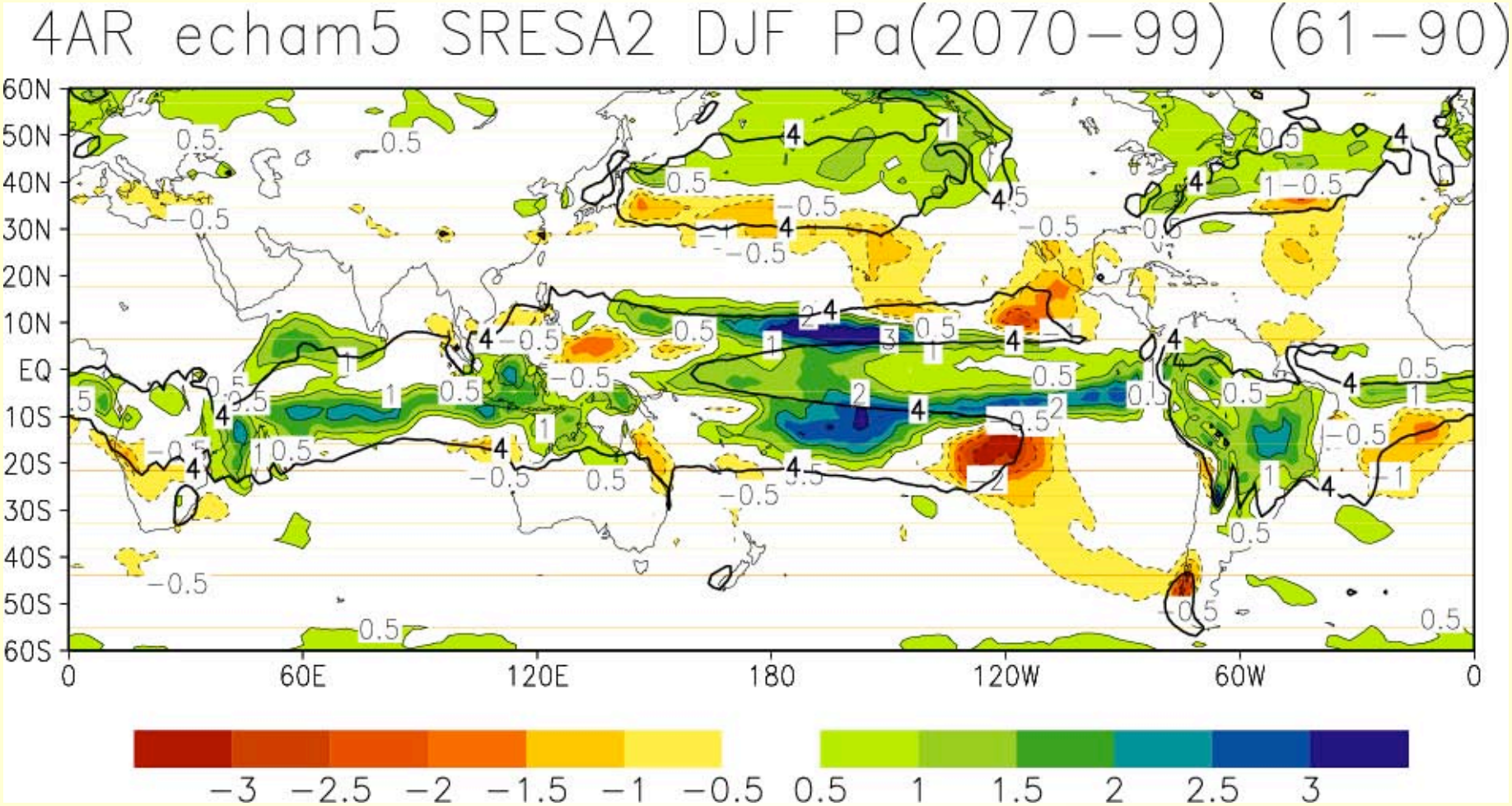
# NCAR_PCM1

## DJF Prec. Anom.



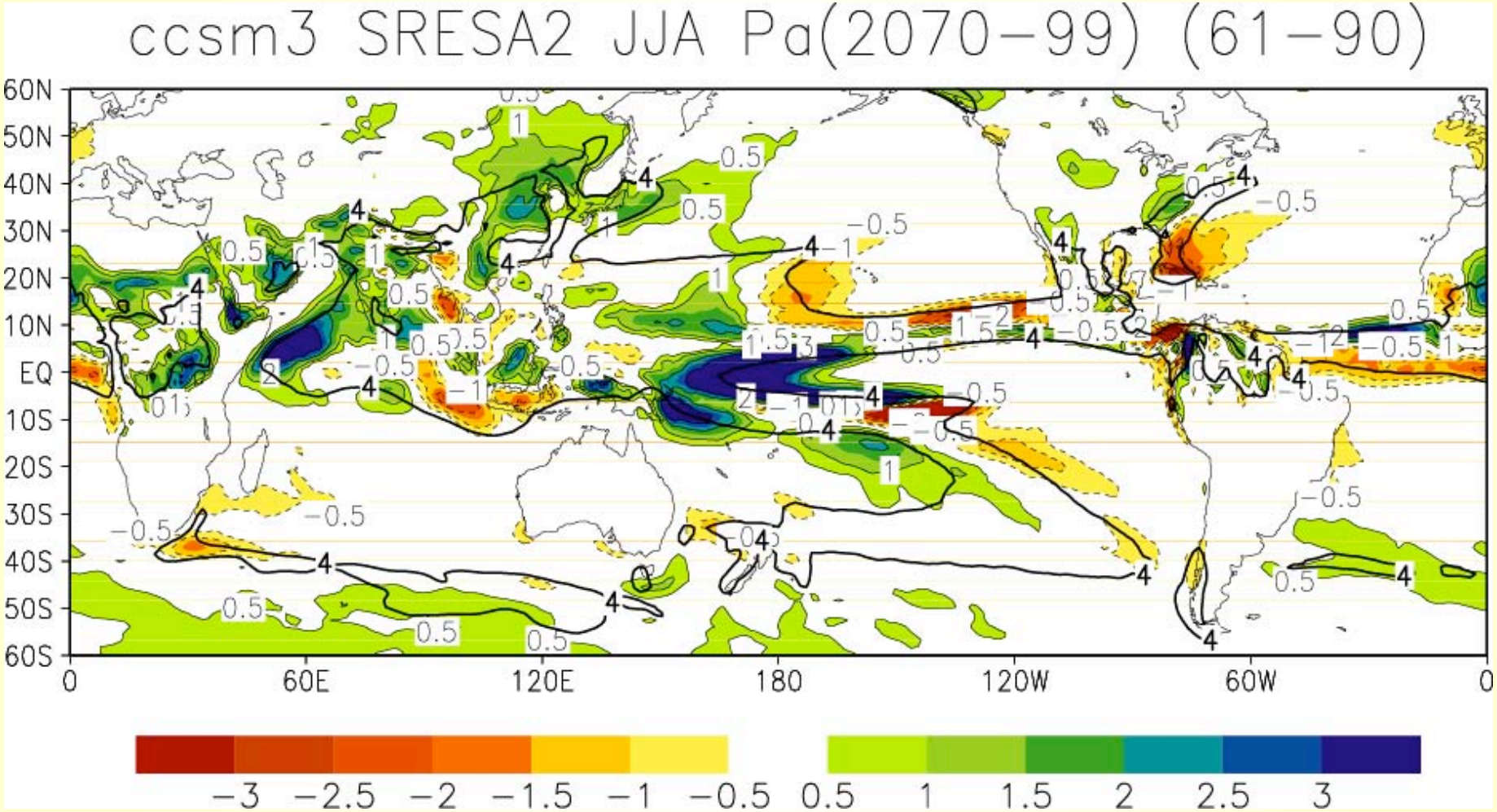
# MPI_ECHAM5

## DJF Prec. Anom.



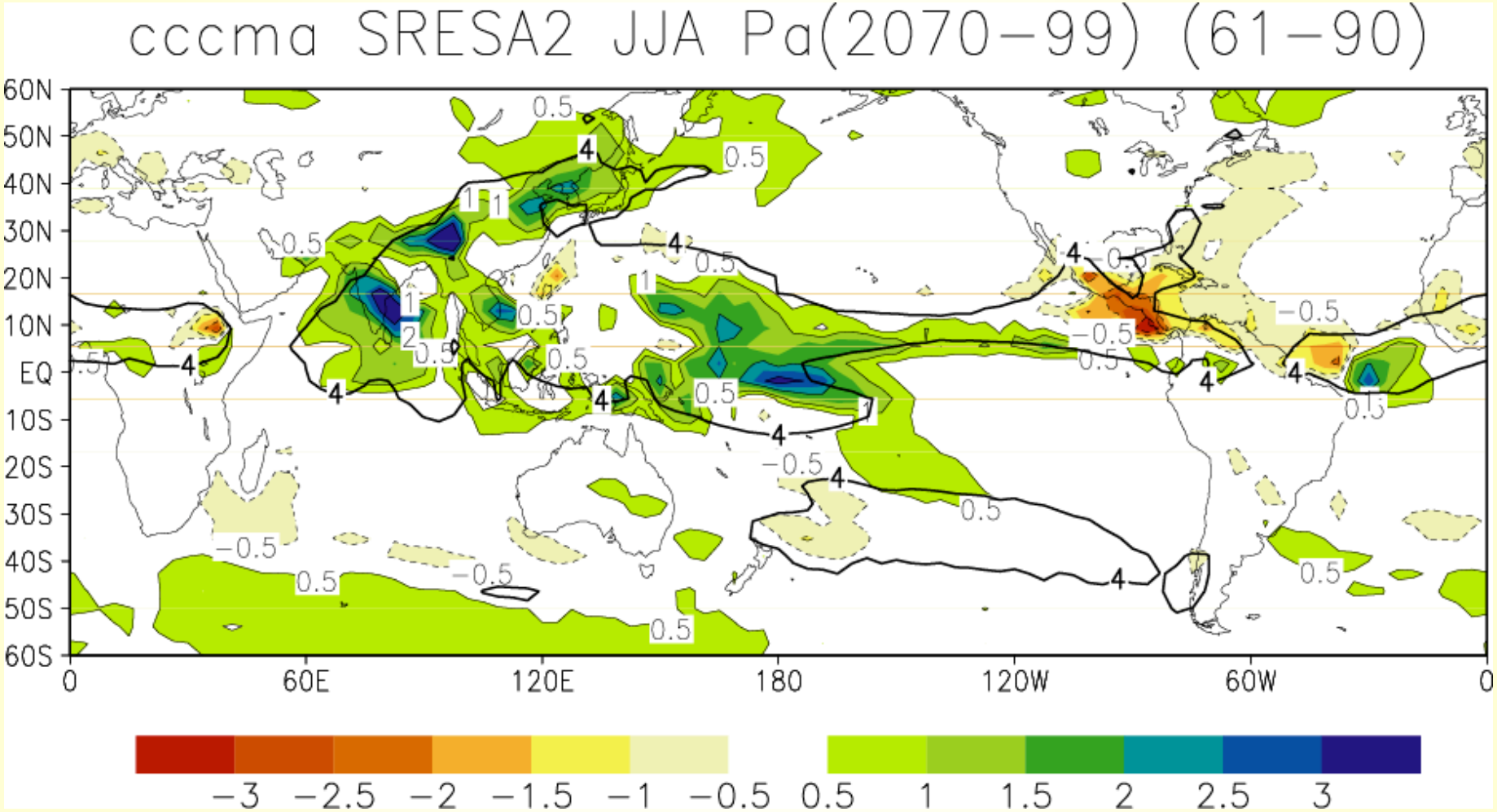
# NCAR_CCSM3

## JJA Prec. Anom.



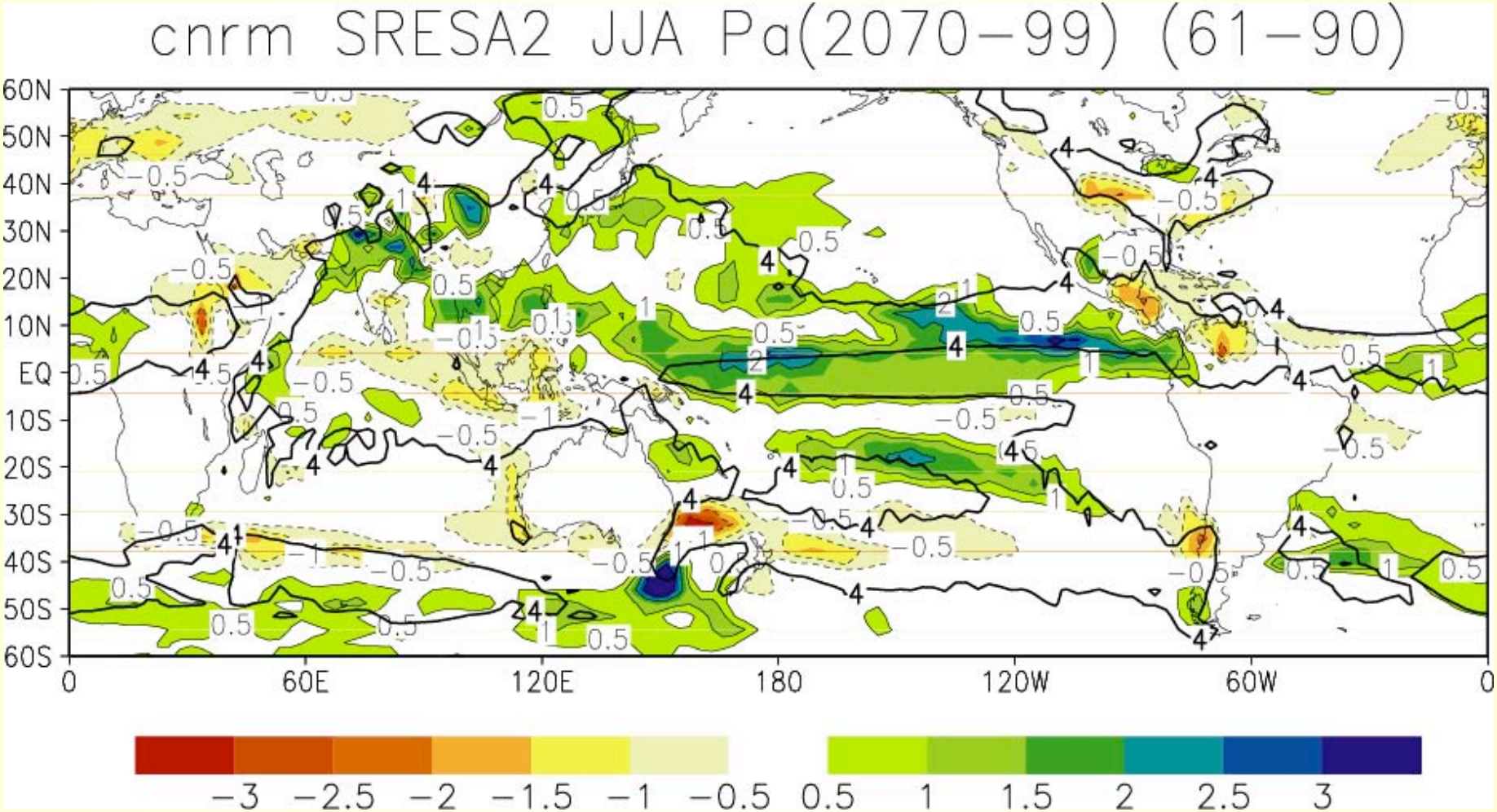
# CCCMA

## JJA Prec. Anom.



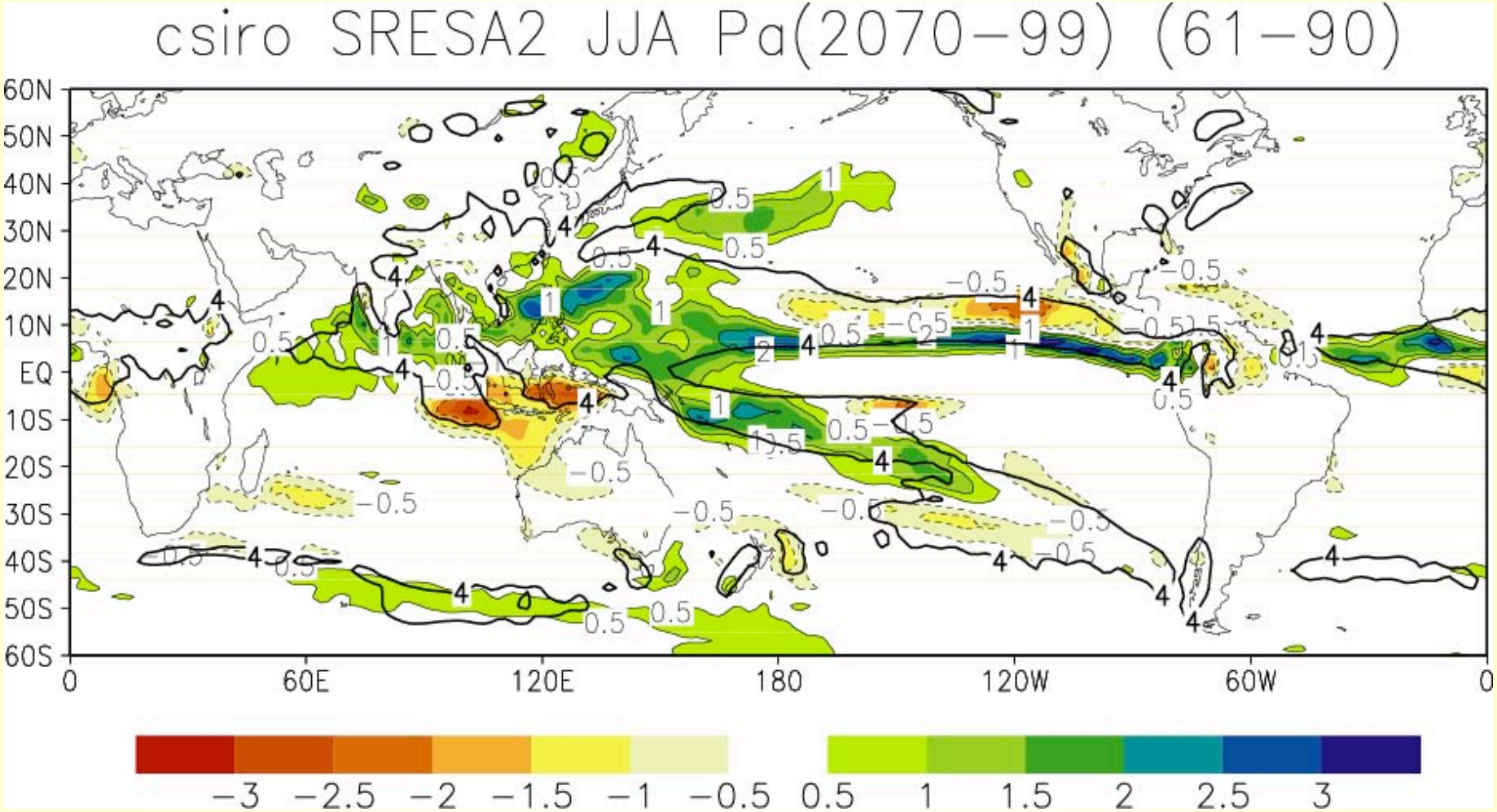
# CNRM_CM3

## JJA Prec. Anom.



# CSIRO_MK3

## JJA Prec. Anom.



# GFDL_CM2.0

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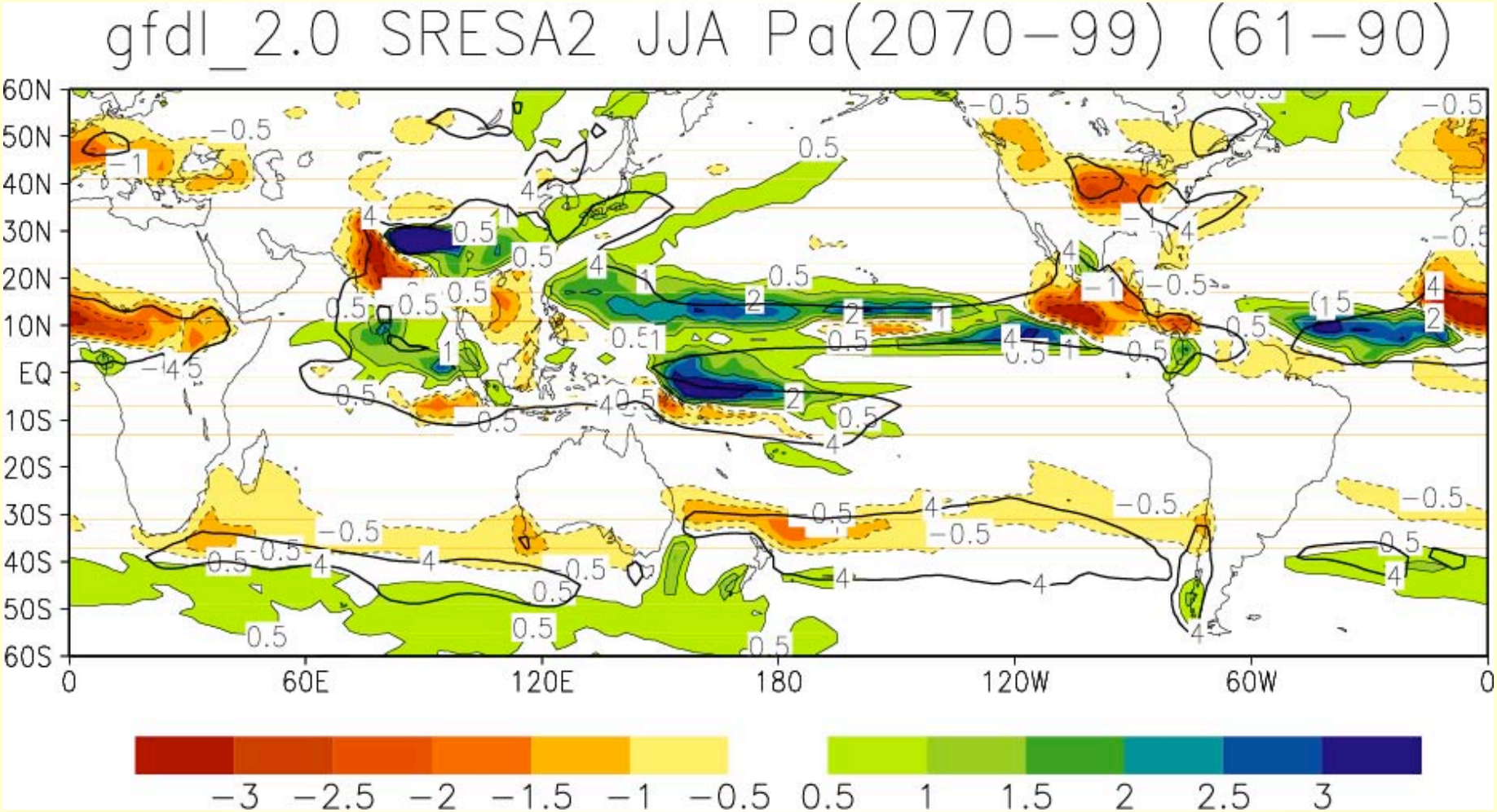
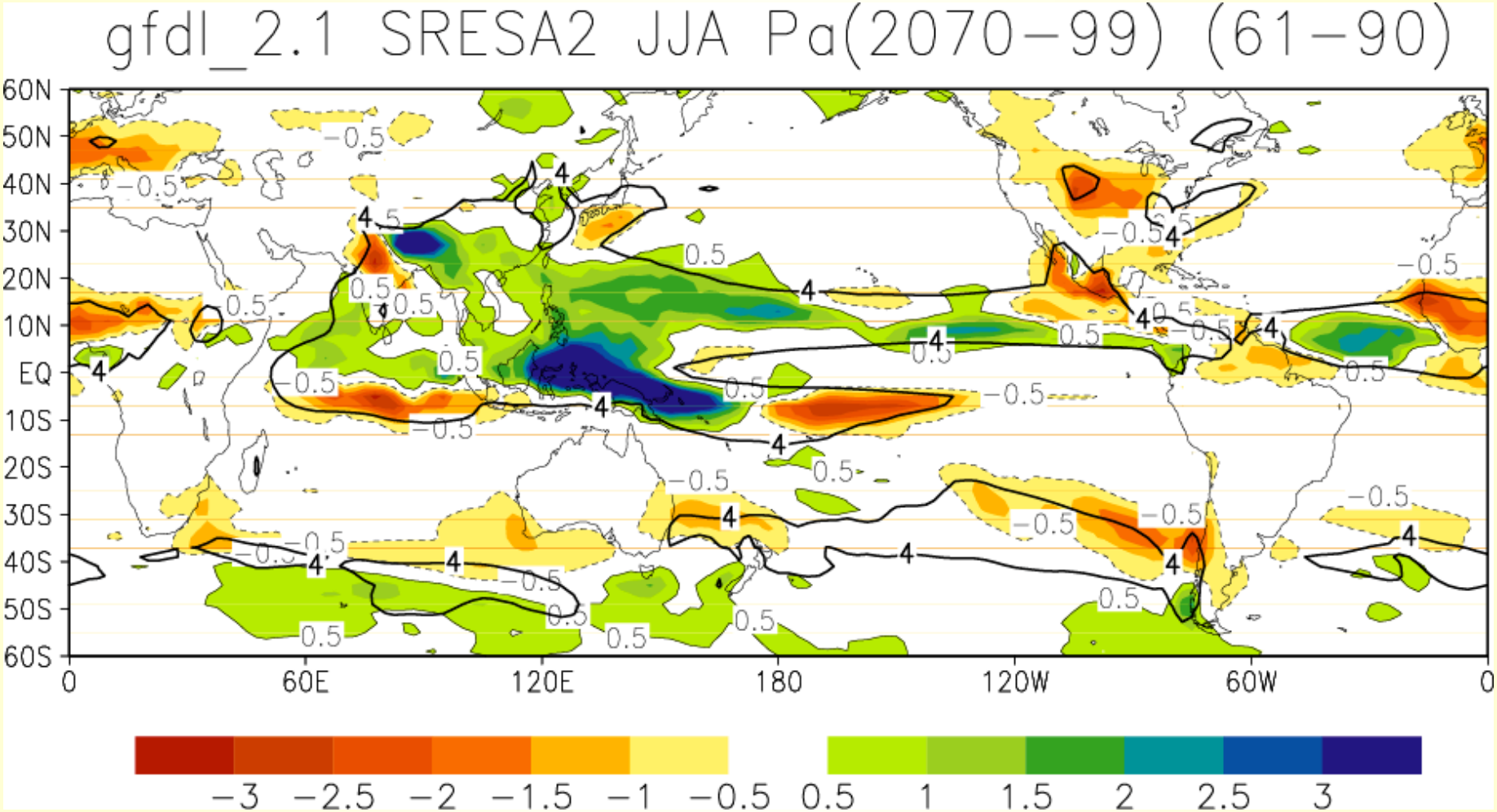


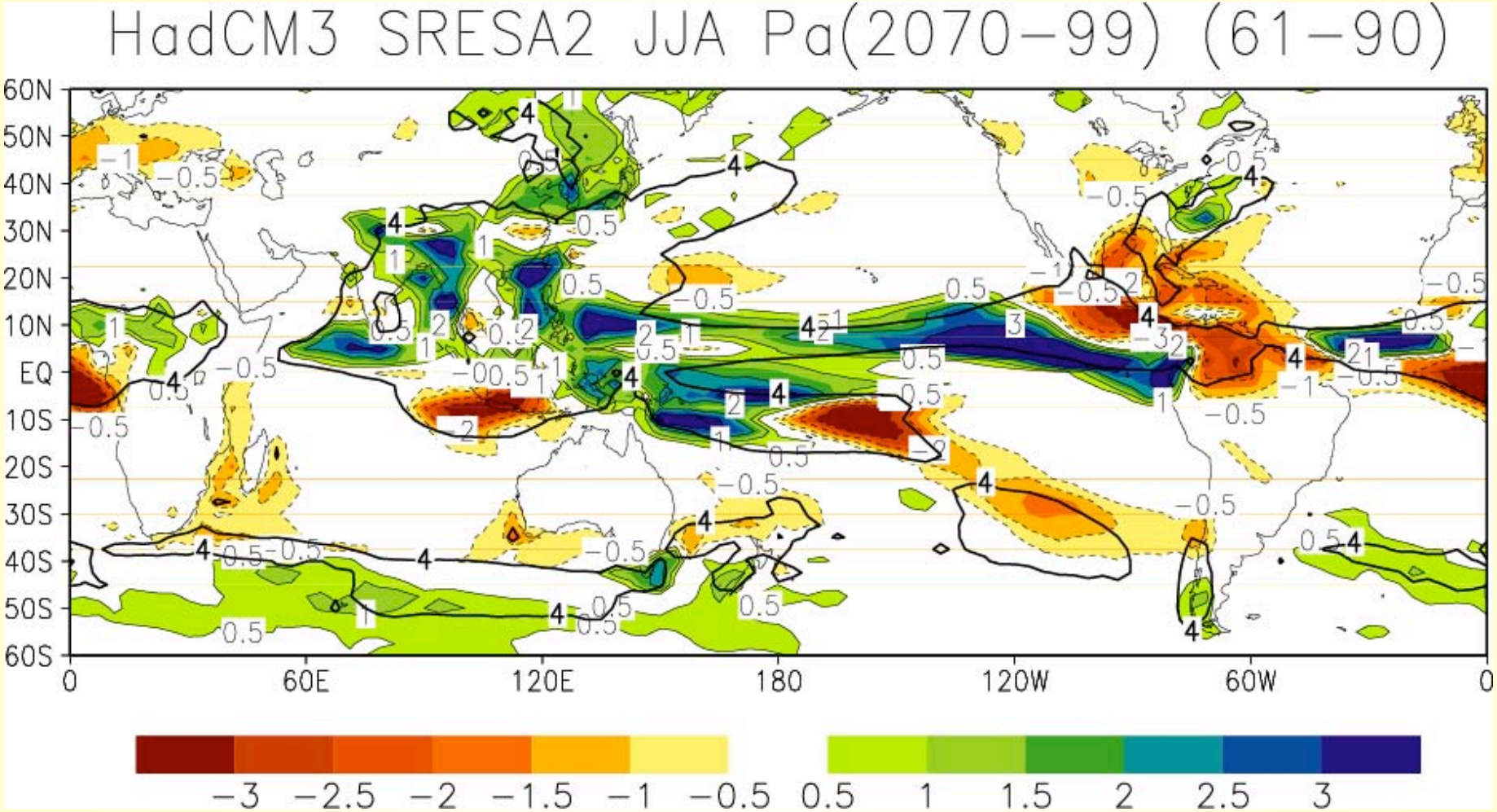
# GFDL_CM2.1

## JJA Prec. Anom.



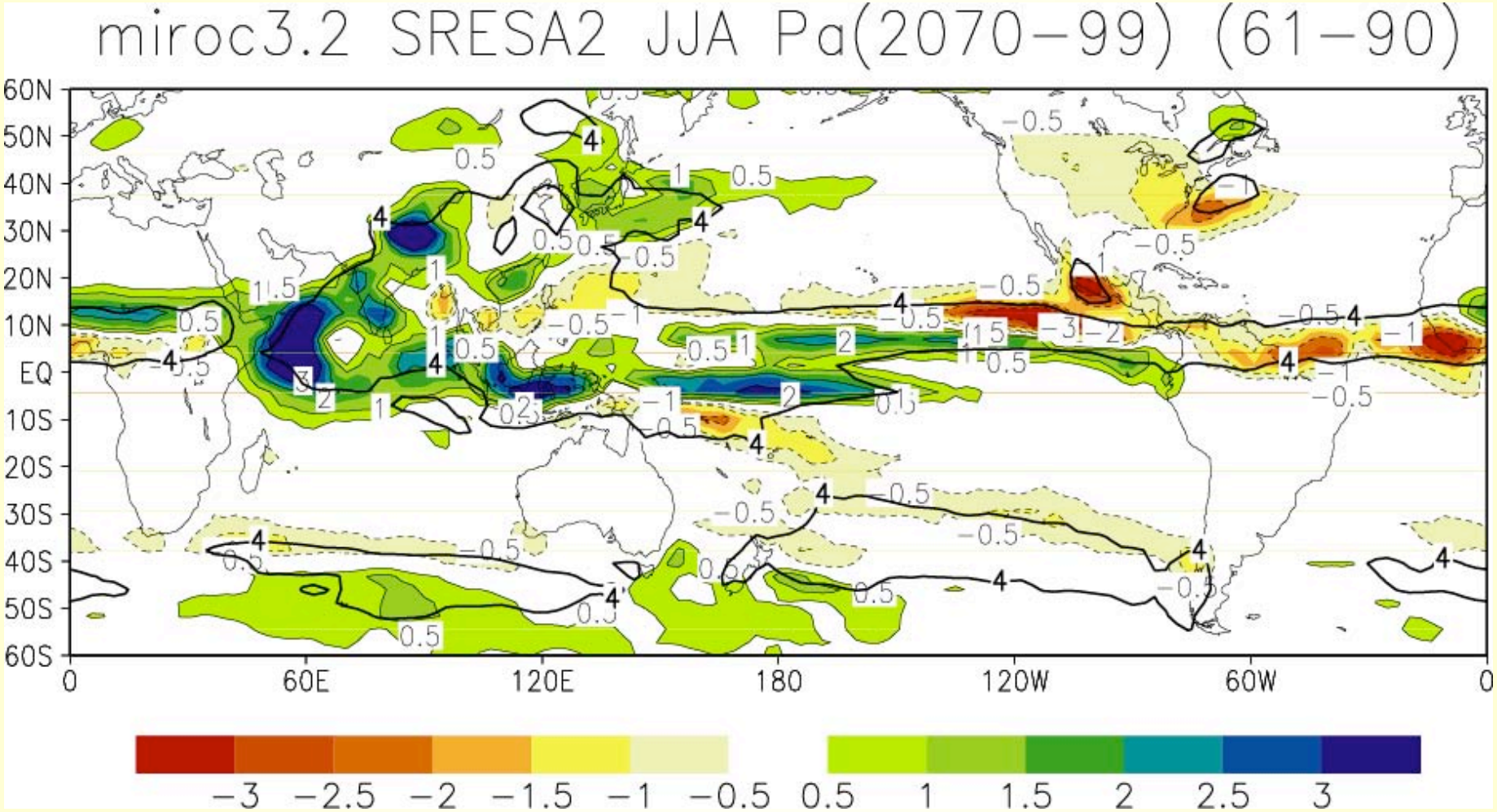
# UKMO_HadCM3

## JJA Prec. Anom.



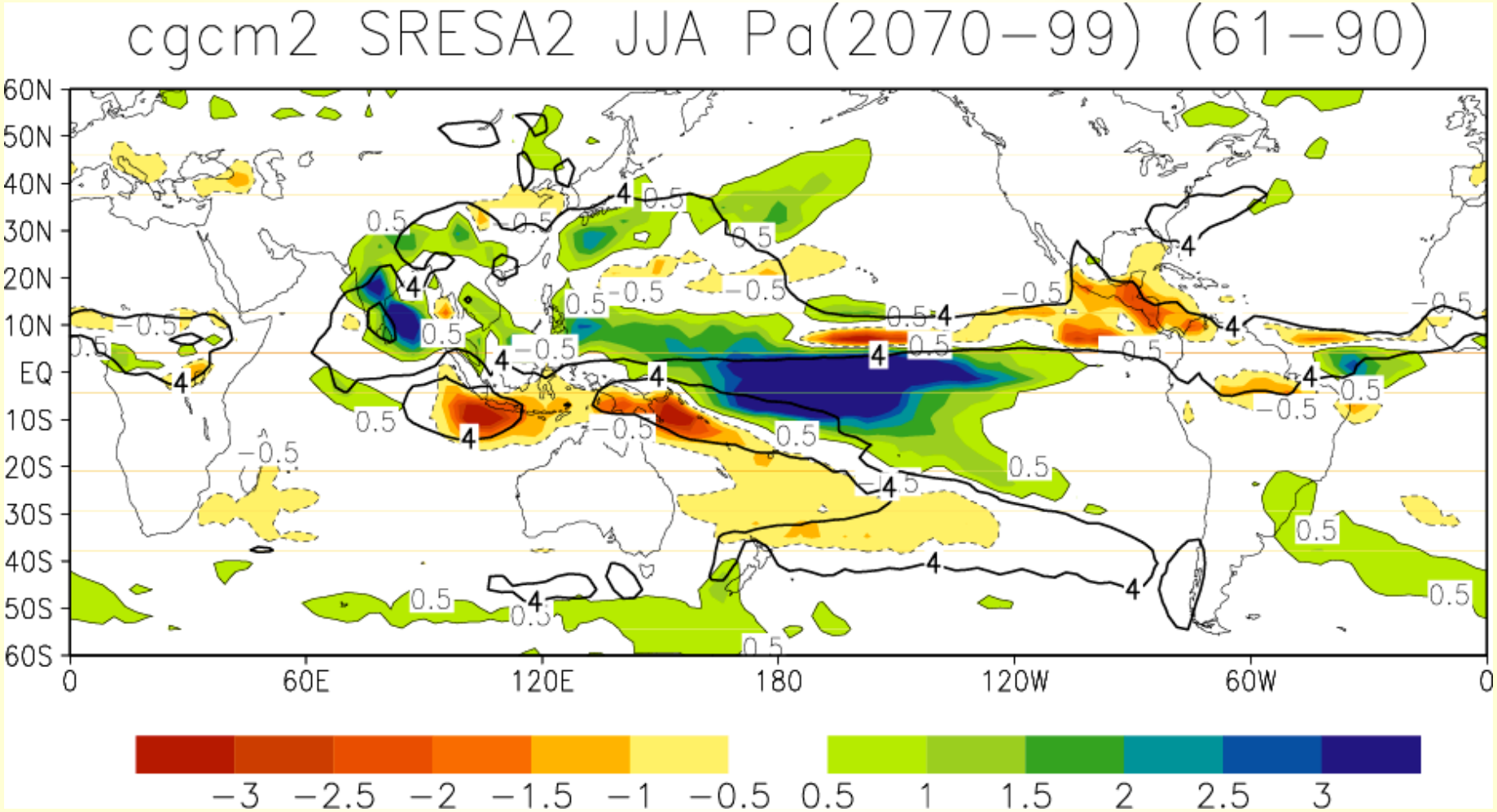
# MIROC_3.2

## JJA Prec. Anom.



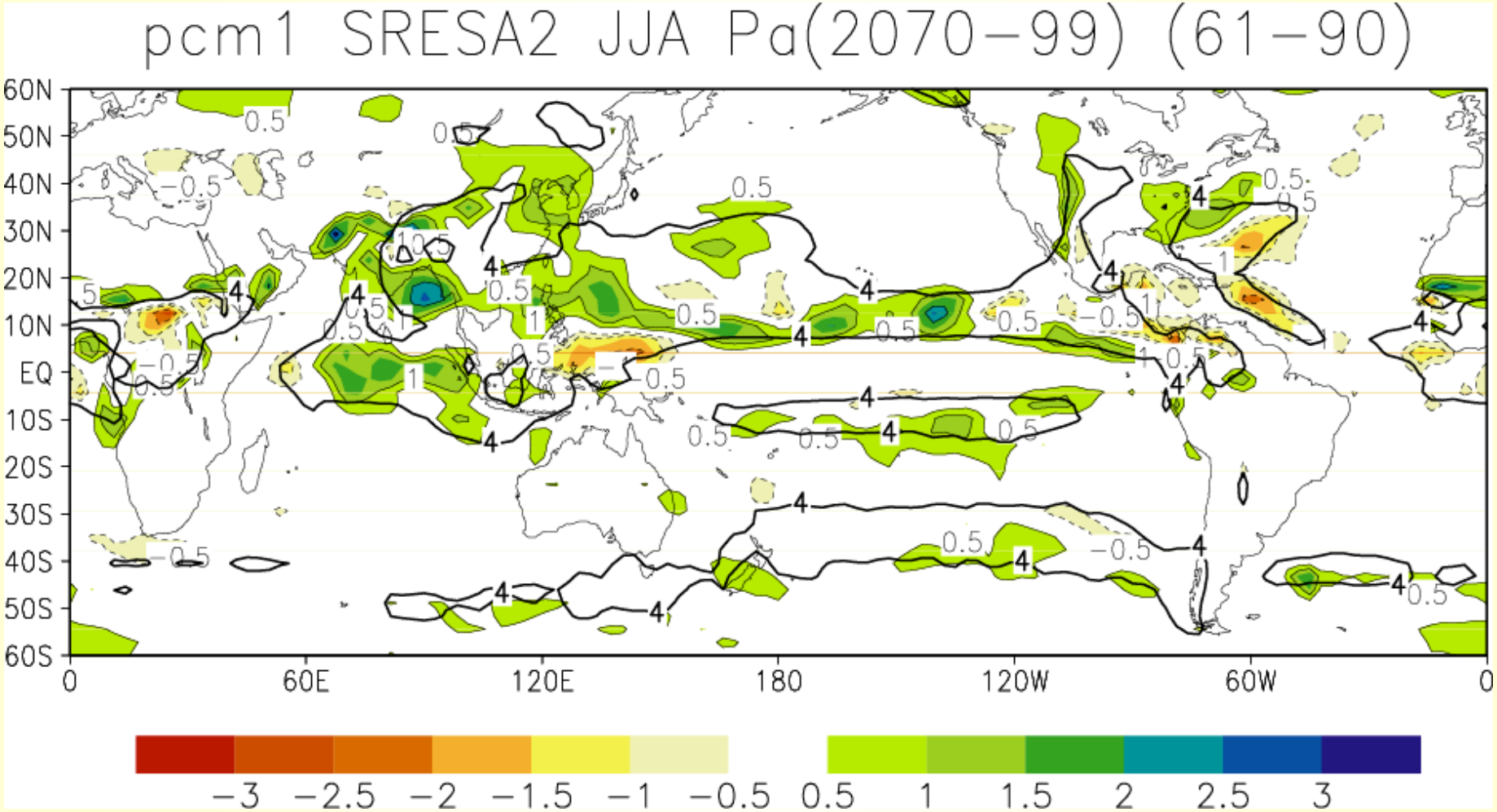
# MRI_CGCM2

## JJA Prec. Anom.



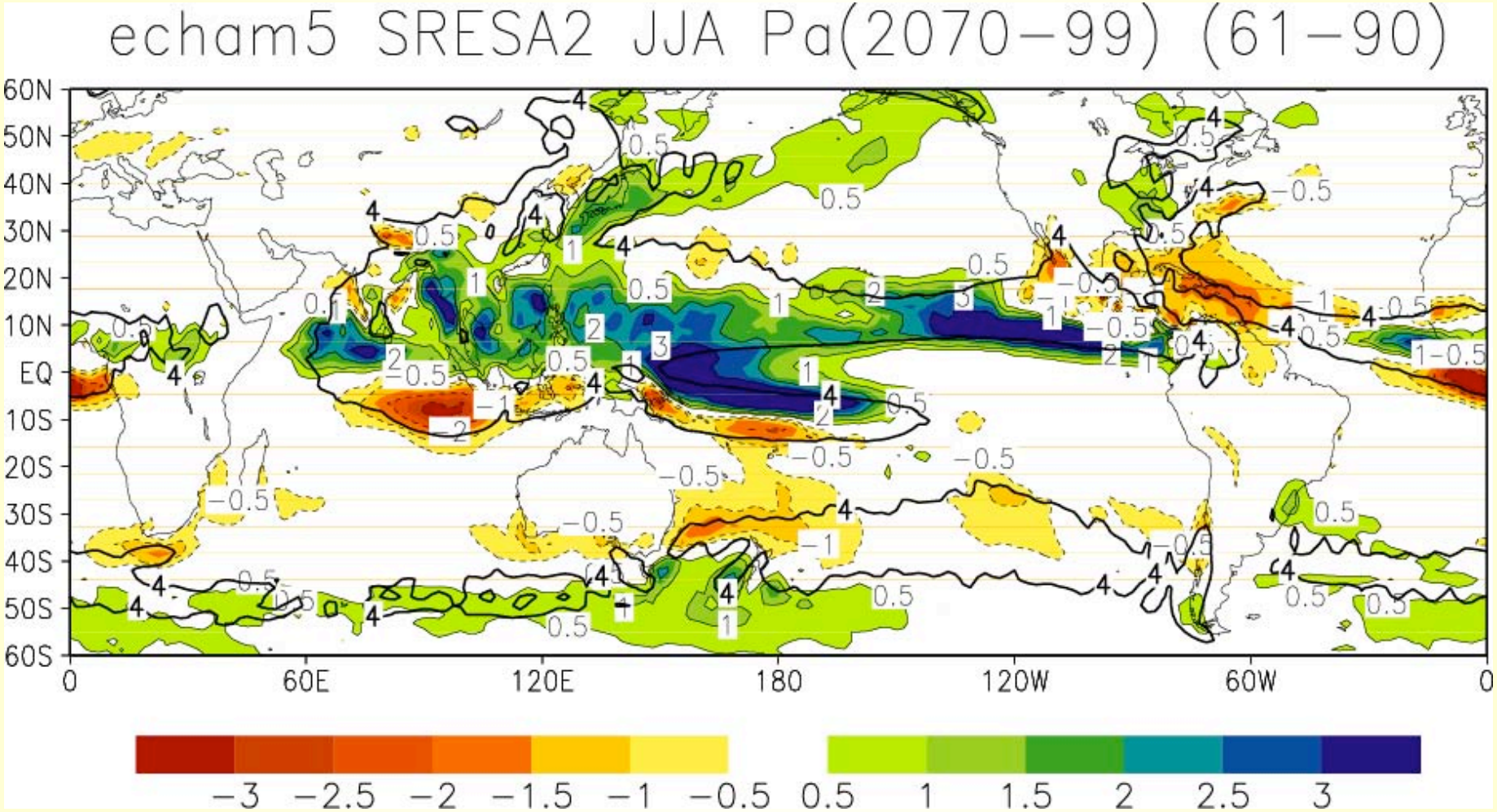
# NCAR_PCM1

## JJA Prec. Anom.



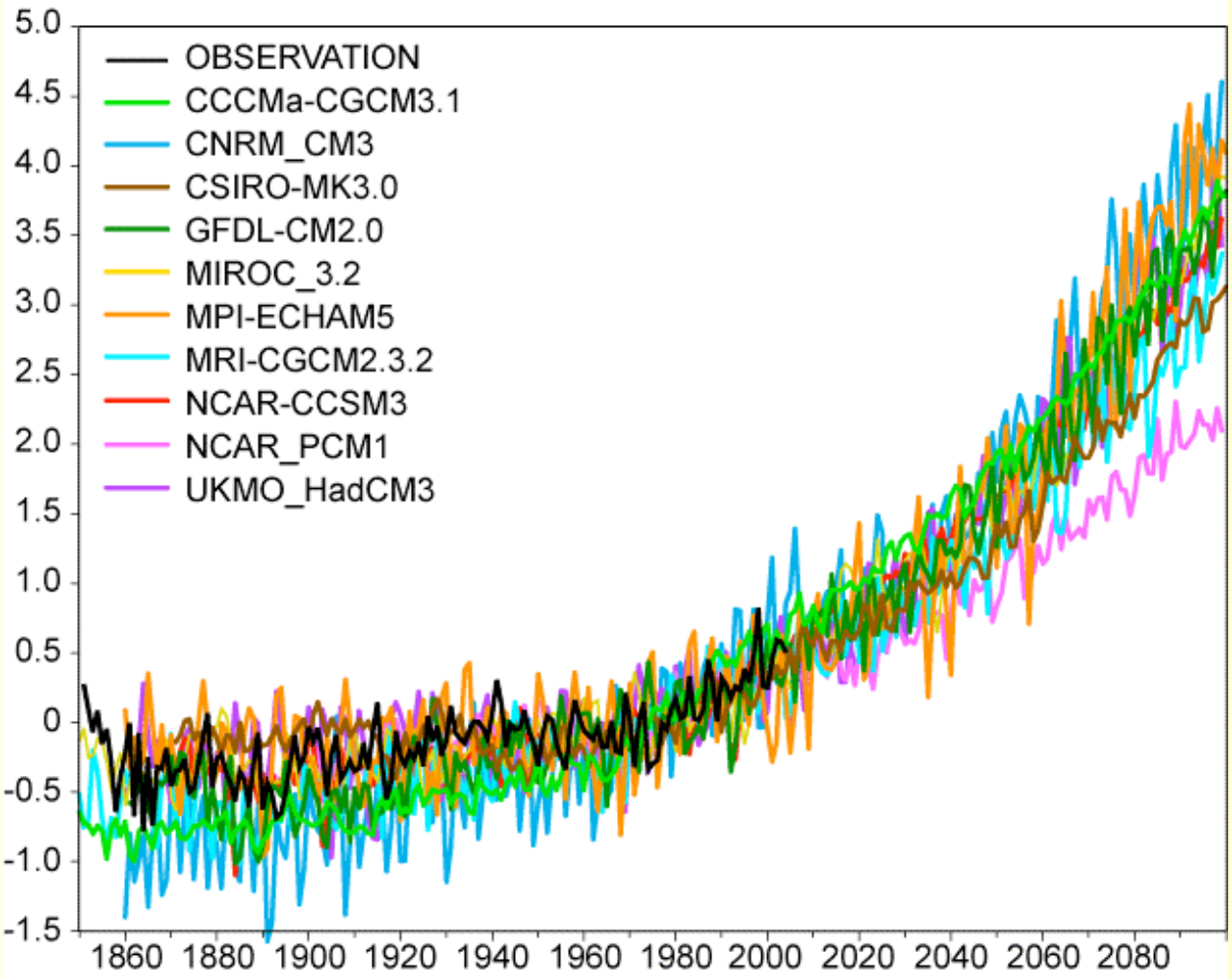
# MPI_ECHAM5

## JJA Prec. Anom.



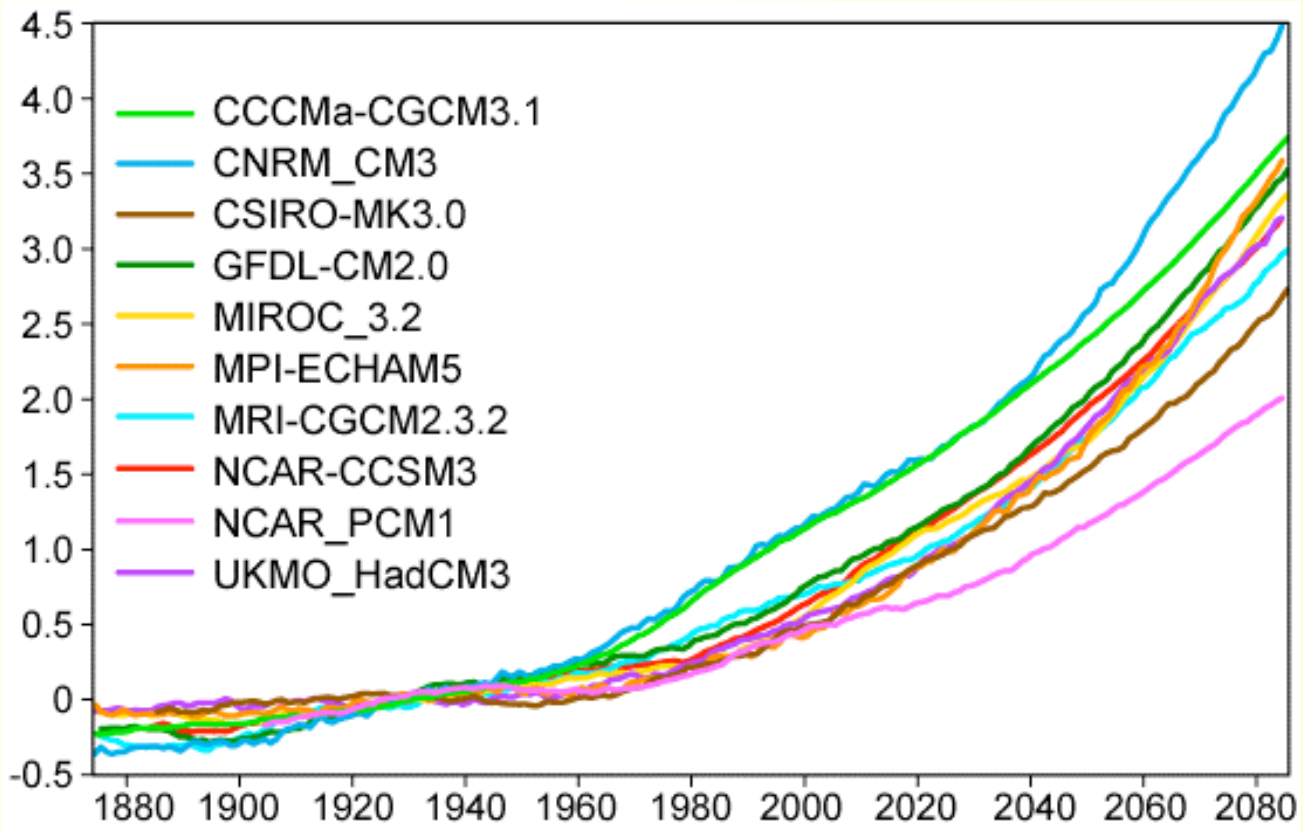
# Tropical surface warming (10 models+obs)

- Tropical avg. (23S-23N) surface air temperature (Annual avg)
- SRES A2 scenario forcings
- Note large interannual variability (El Nino, etc.)



# Tropical surface warming (10 models)

- Tropical avg. (23S-23N) surface air temperature For June-Aug. (30 yr avgs.)
- SRES A2 scenario forcings

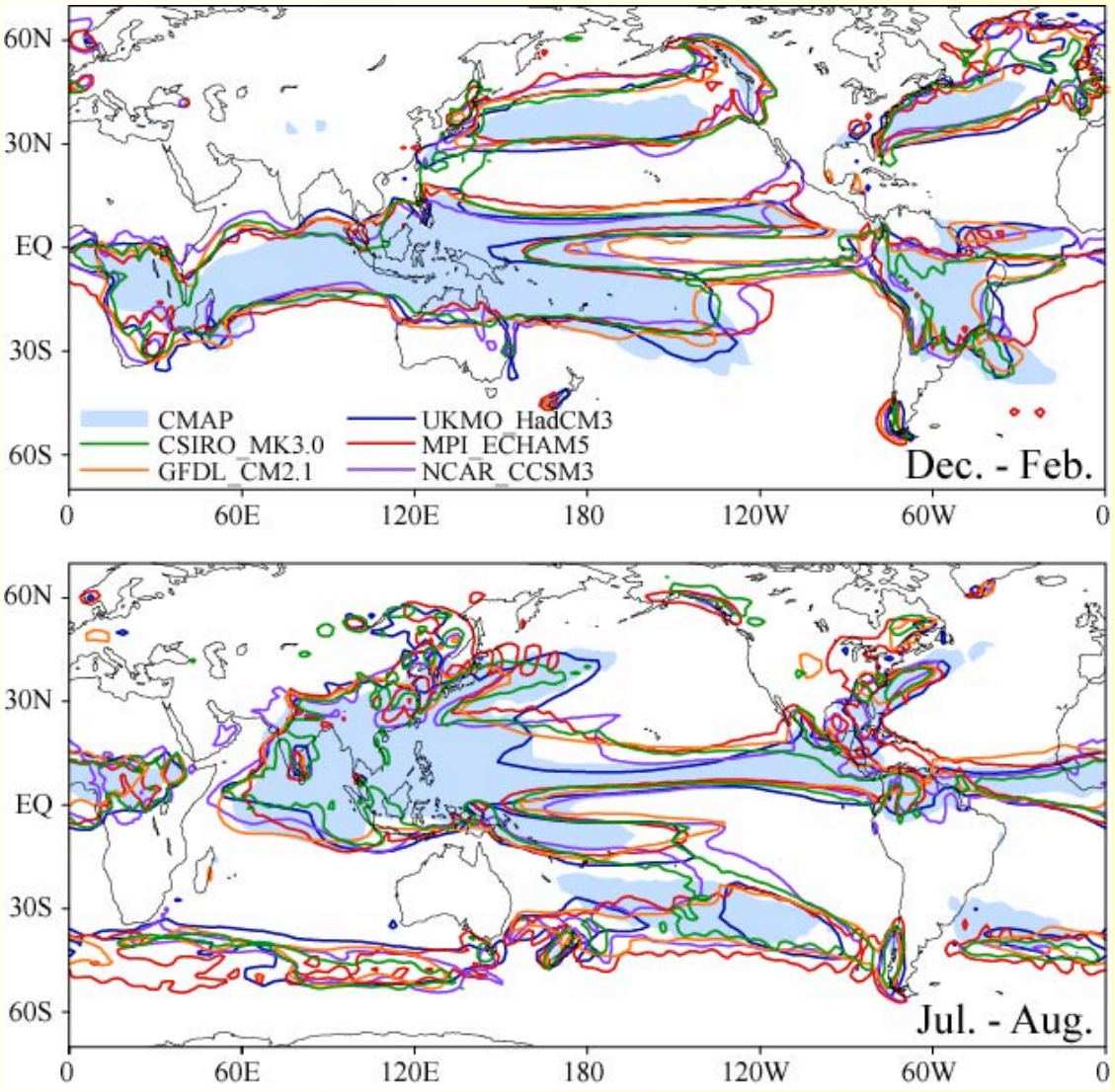


# Observed (CMAP) and 5 coupled models 4 mm/day precip. contour

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

December-February precipitation climatology

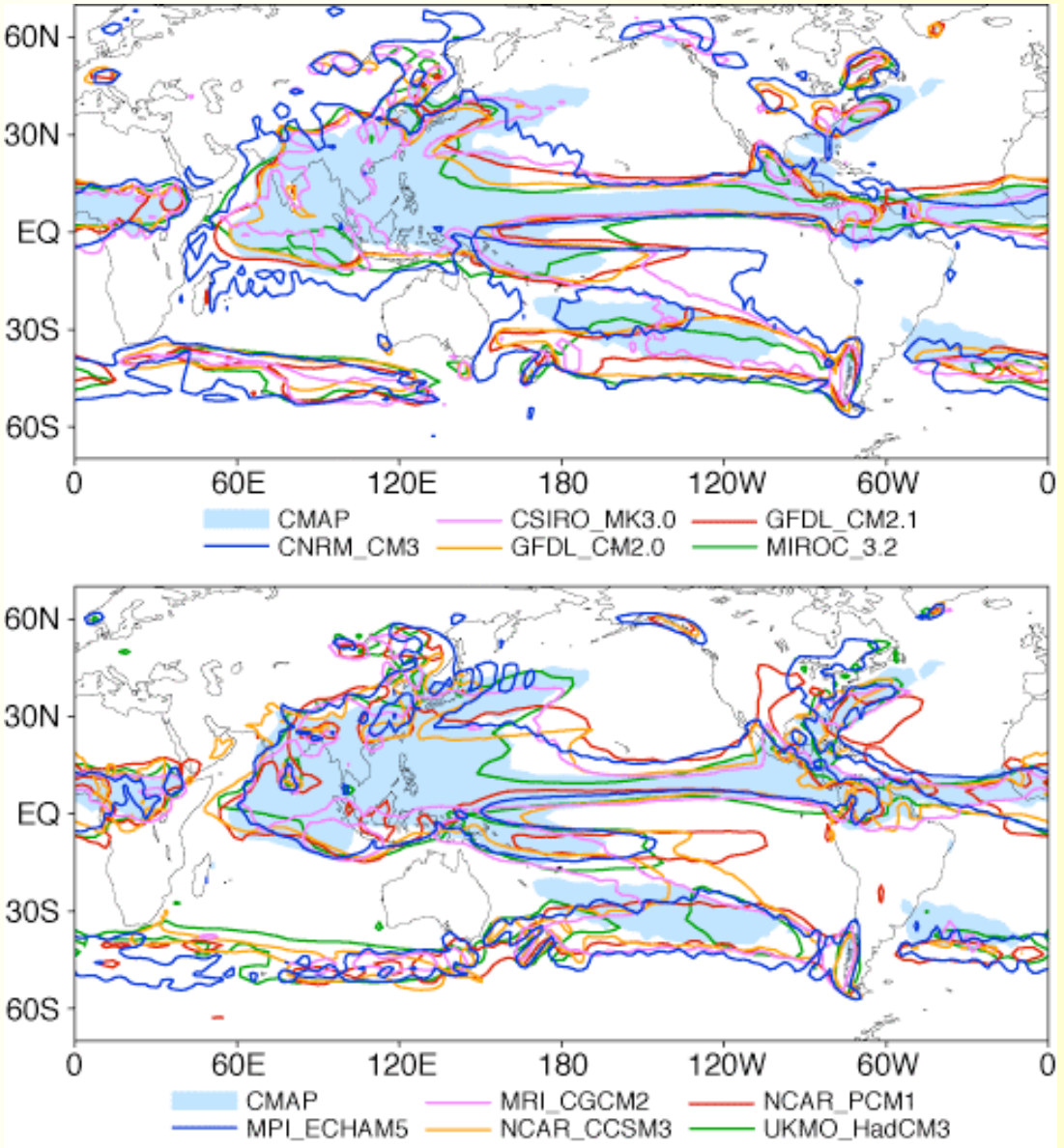
June - August precipitation climatology



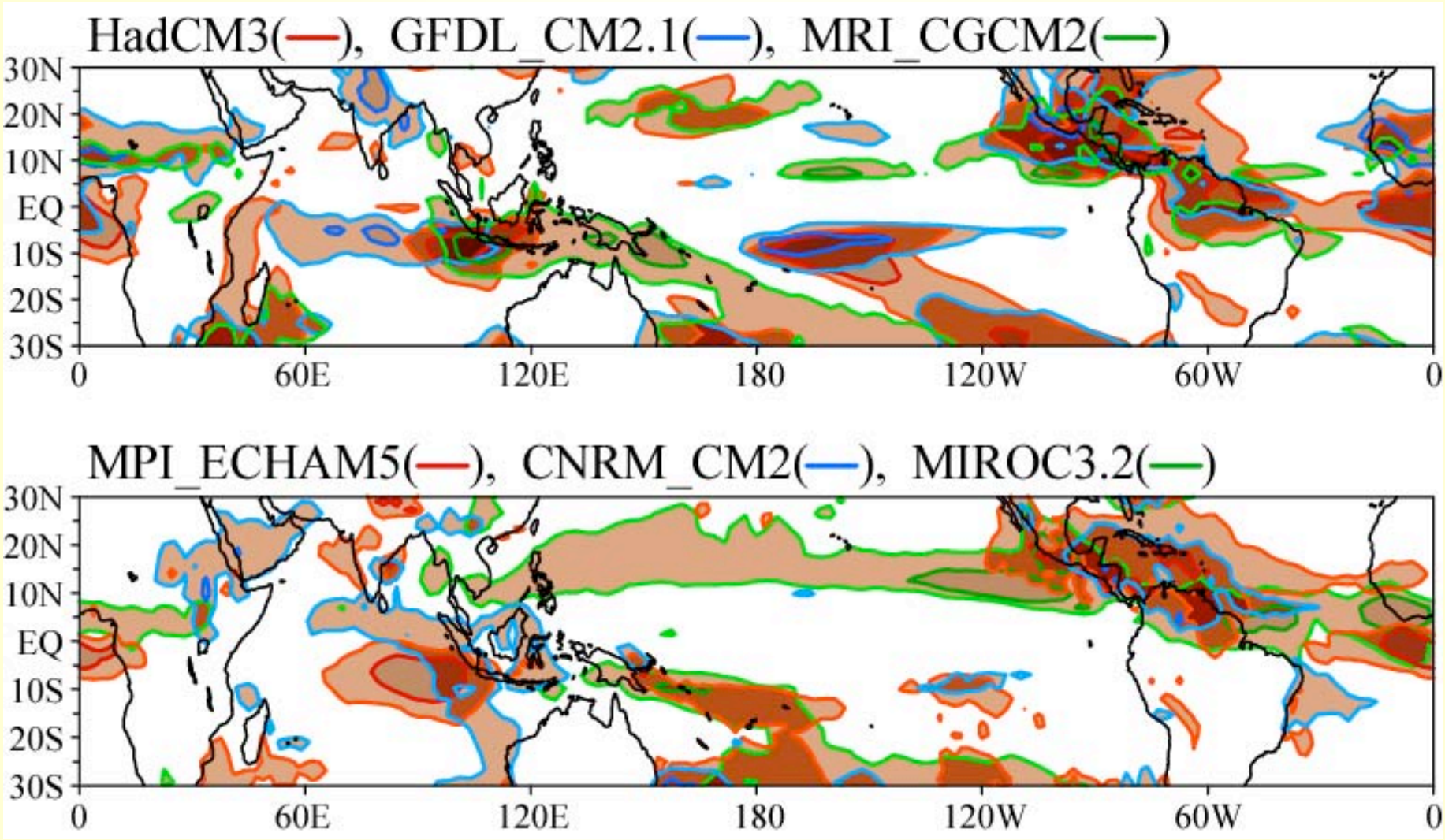
# Climatological precip: Observed vs. 10 coupled models (4 mm/day contour)

**June - August precipitation climatology**

**Coupled simulation clim. (20th century run, 1979-2000); 5 models per panel; observed from CMAP**

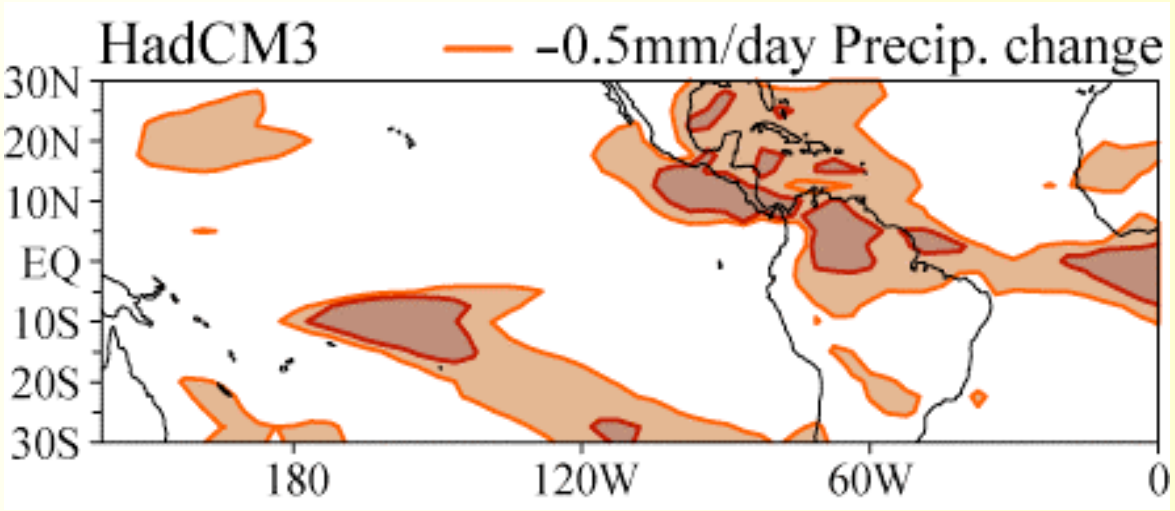


# Global warming (SRES-A2) dry regions: negative precip change (2070-2099 minus 1951-1980) overlaid for 6 models (0.5, 2 mm/day contours)



# Hypothesis for analysis method:

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

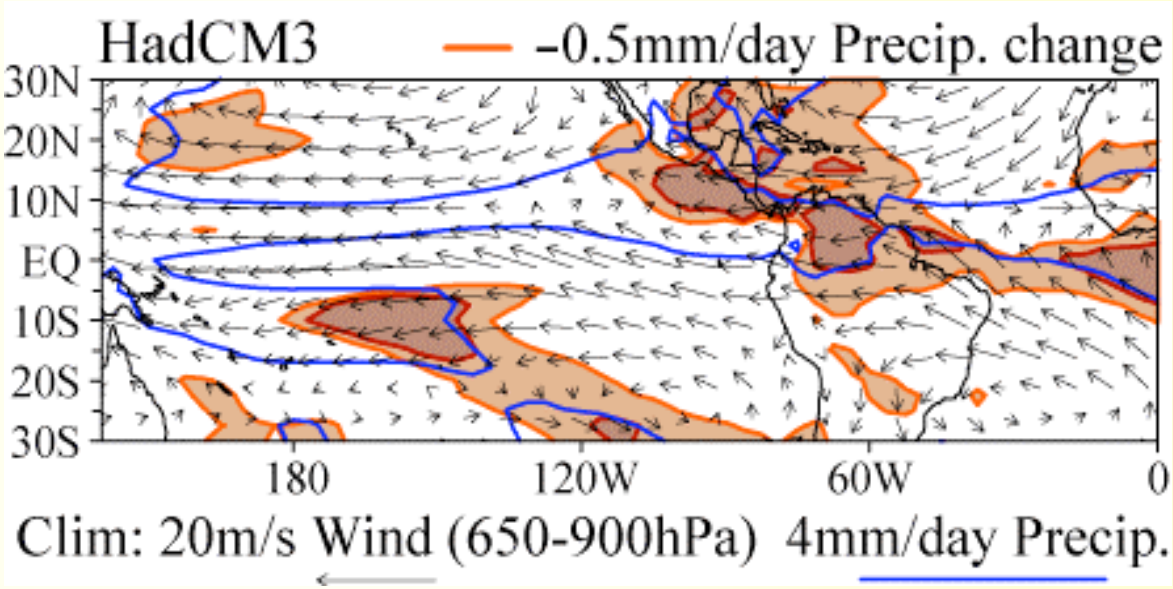



- Check agreement on amplitude measure:
- Spatial projection of precip change for each model on that model's own characteristic pattern of change

# Hypothesis for analysis method:

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

…to differences in model clim. of wind, precip; to variations in the moistening process (shallow convection, moisture closure,…)




- Check agreement on amplitude measure:
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# Hypothesis for analysis method:

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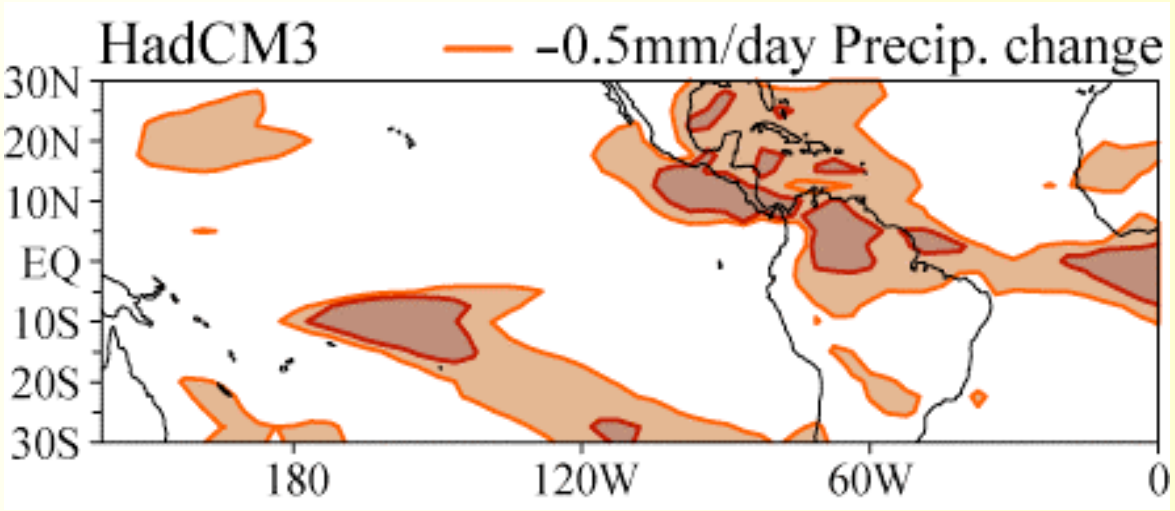
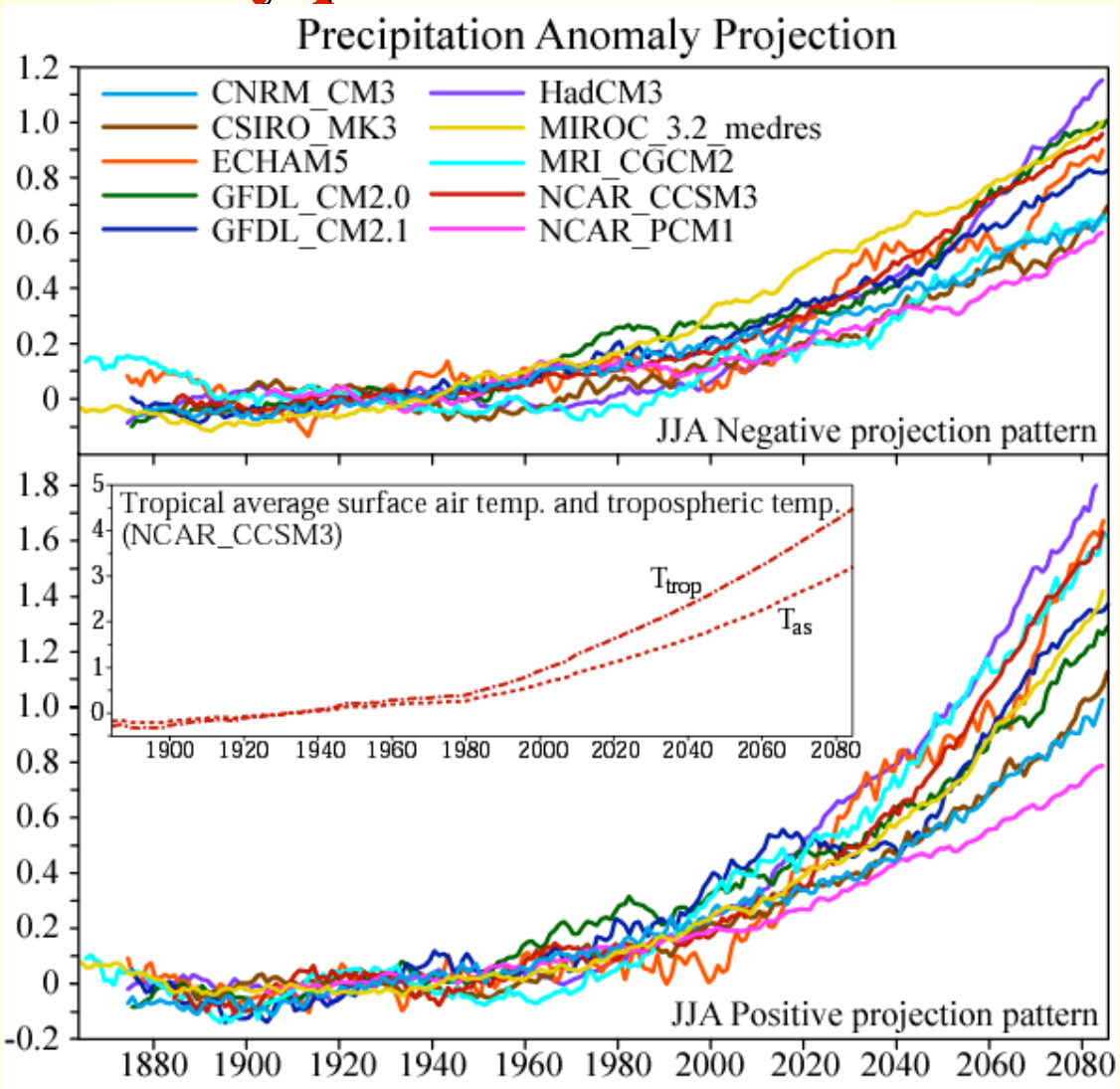



- Check agreement on amplitude measure:
- Spatial projection of precip change for each model on that model's own characteristic pattern of change

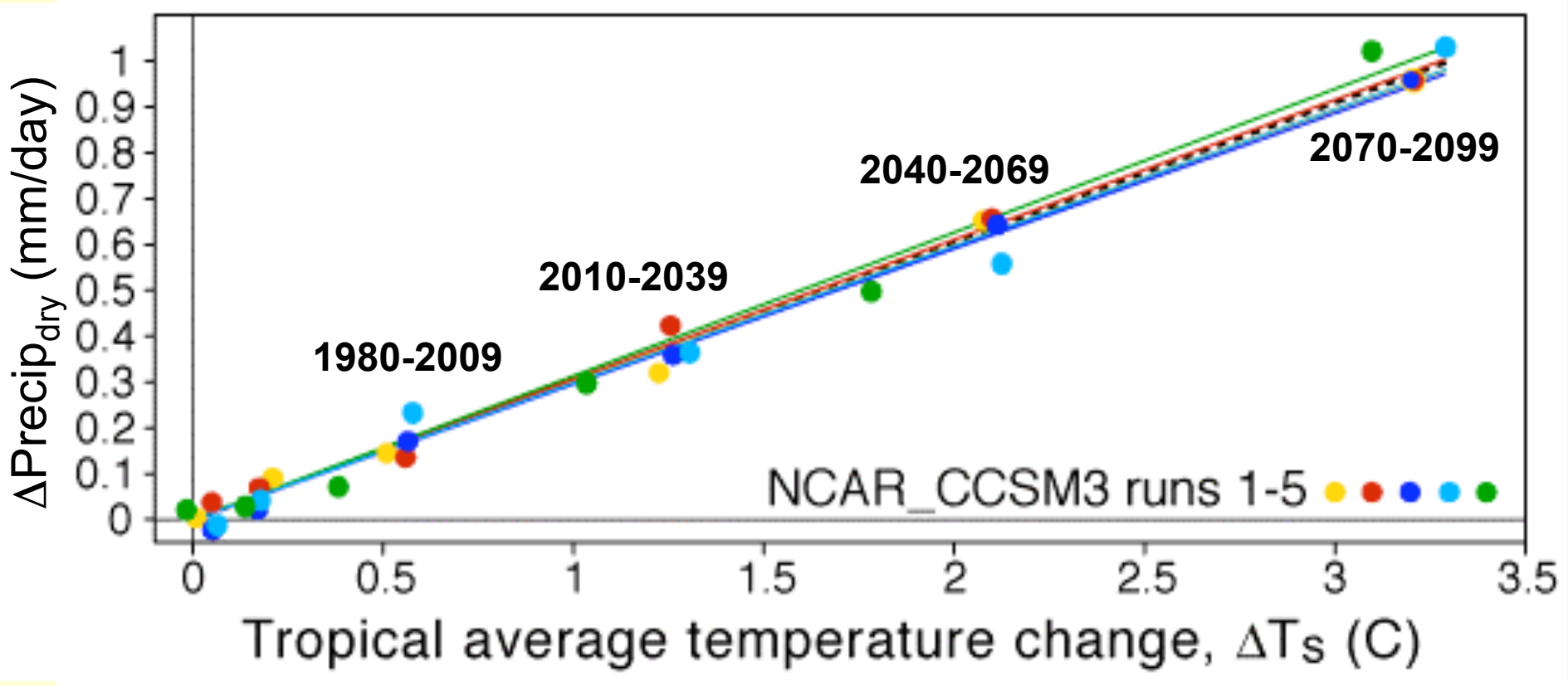
# Projection of JJA (30yr running mean) precip pattern onto normalized positive & negative late-century pattern for each model




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

# Regional precip. anomaly relation to temperature

## Dry region precip. anomaly projection (on late-21st century pattern) $\Delta Precip_{dry}$ versus tropical average surface air temperature




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

# Model agreement on amplitudes of tropical changes

**(June-Aug. 2070-2099 minus 1901-60)**

**Surface air temperature $\Delta T_{as}$**

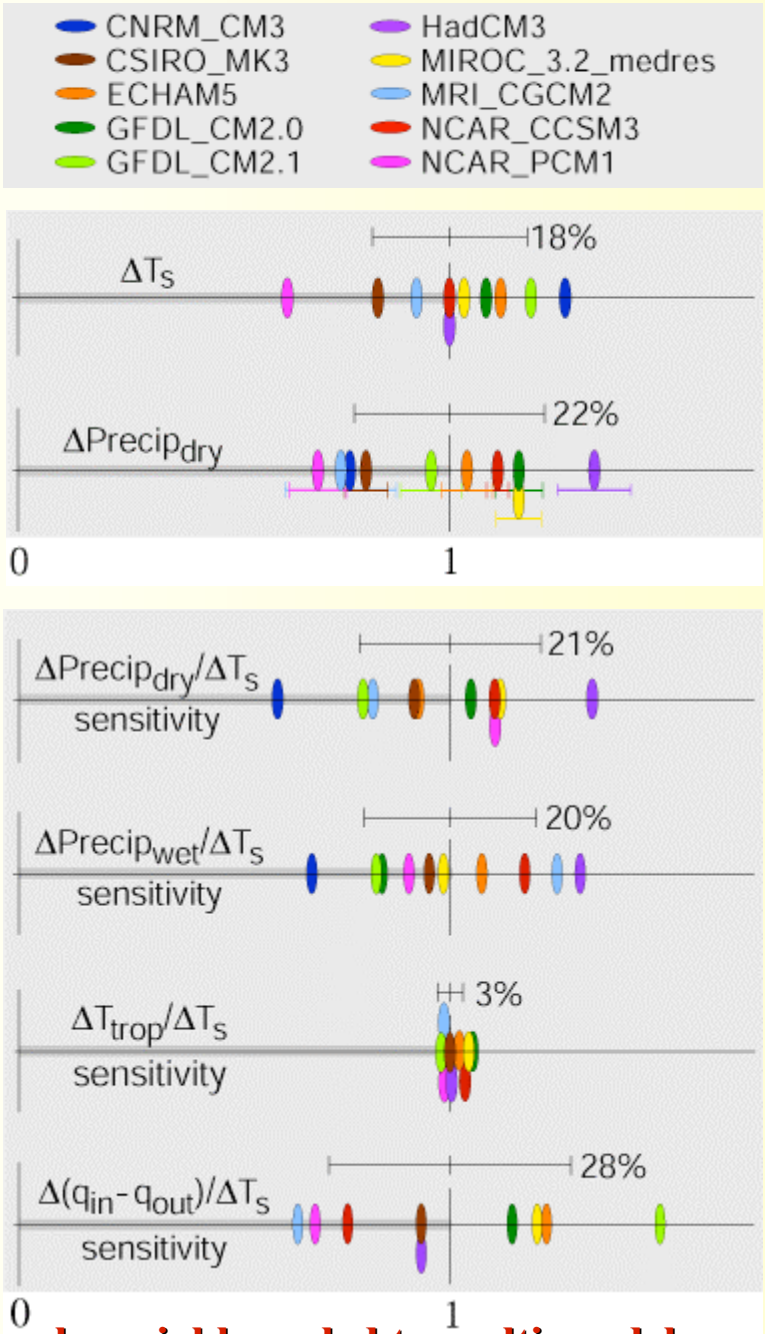
**$\Delta Precip_{dry}$ (dry region projection)**

**Sensitivity (ratio to $T_{as}$):**
**$\Delta Precip_{dry}/\Delta T_{as}$**

**$\Delta Precip_{wet}/\Delta T_{as}$**

**Vert avg. troposph. temp. $\Delta T_{trop}/\Delta T_{as}$**

**Moisture difference (inside/outside P=4mm/day) $/\Delta T_{as}$**



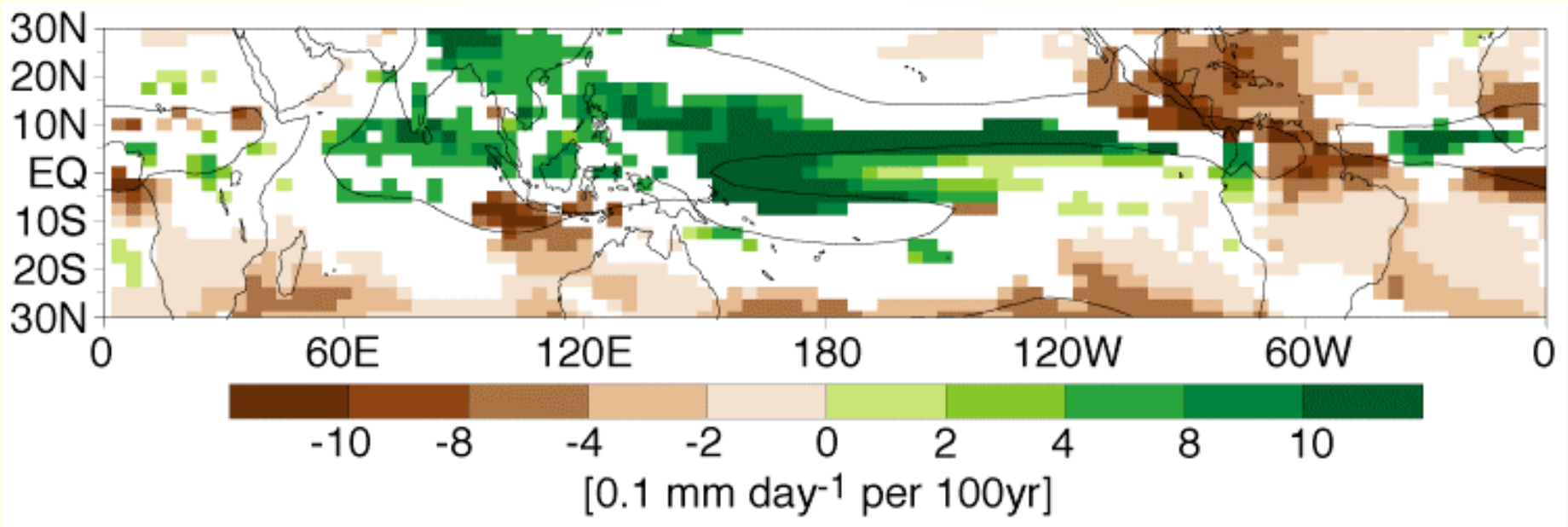

**(each variable scaled to multi-model mean)**

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

# Precipitation change: measures at the local level

## Trend of the 10-model ensemble median

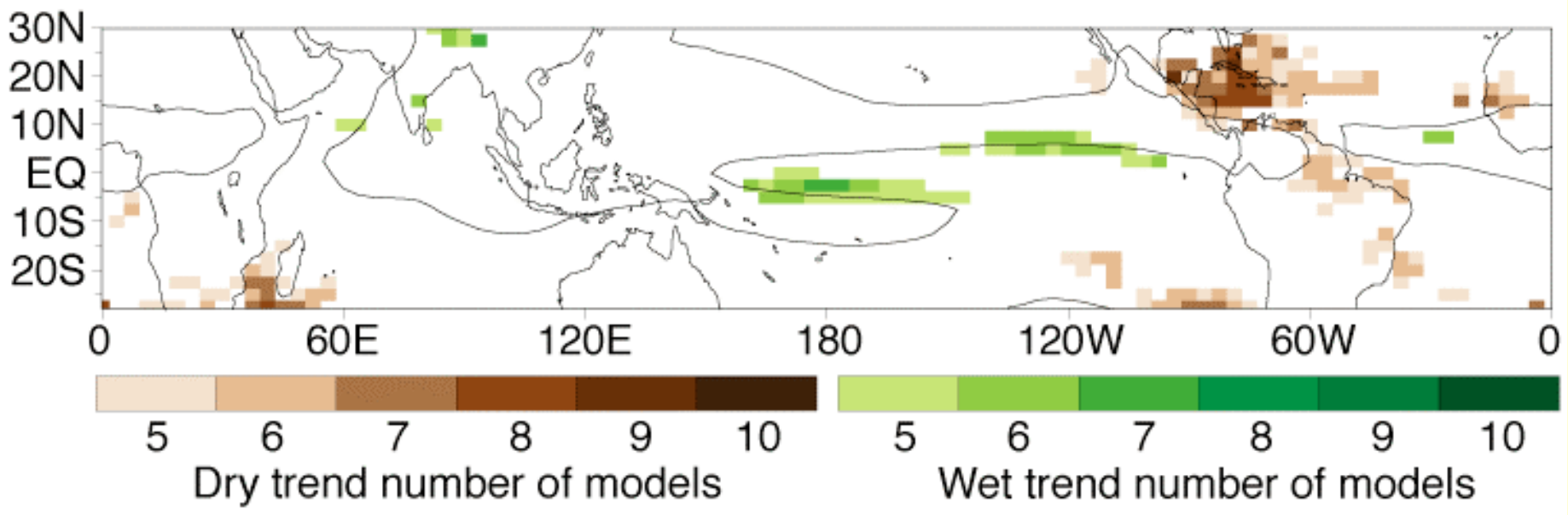
## > 99% significance (1979-2099)




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

# Inter-model precipitation agreement

## Number of models (out of 10) with > 99% significant* dry/wet trend (1979-2099) and exceeding 20% of the median clim./century



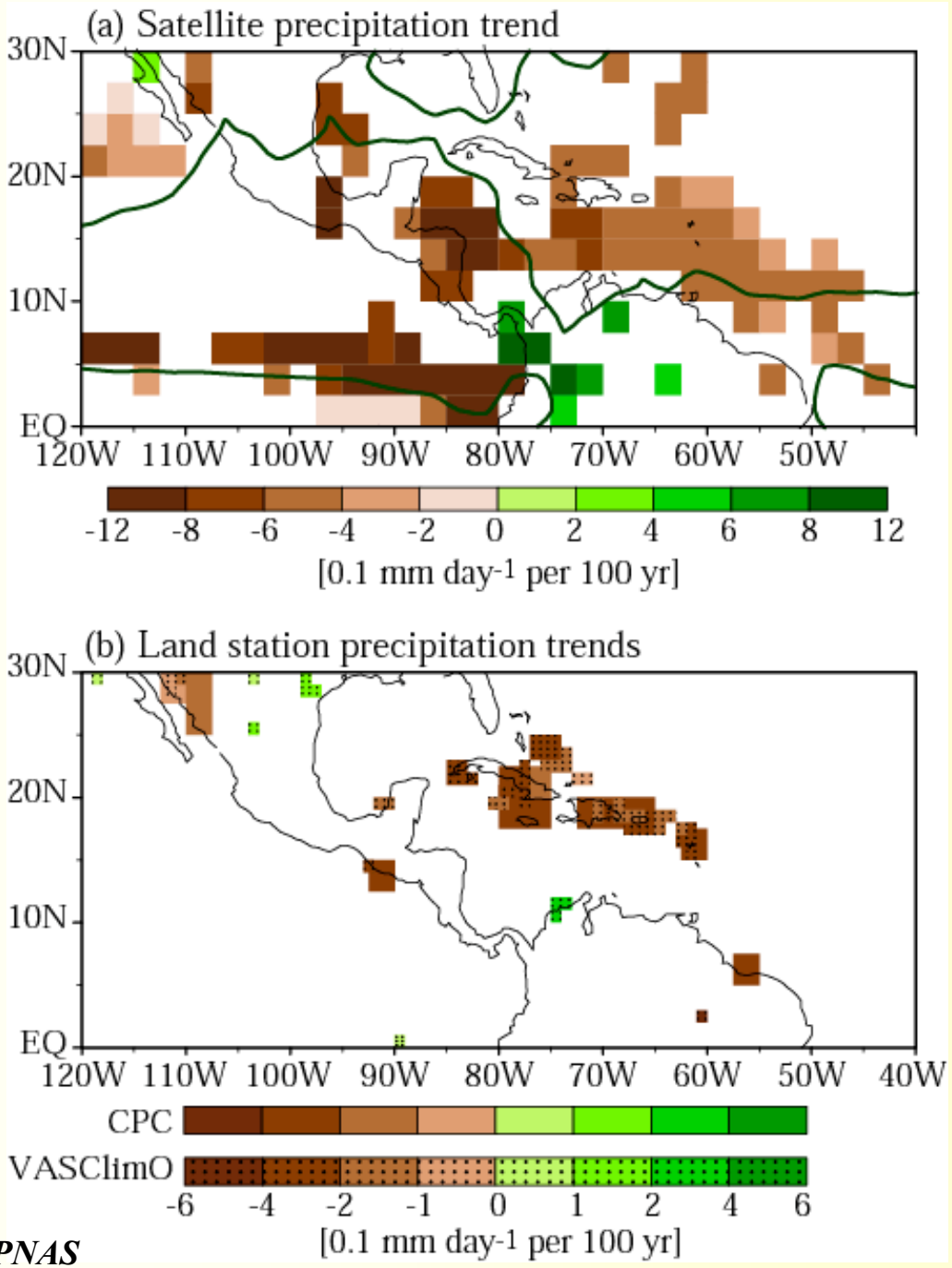

*[Spearman-rho test]

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

# Observed precipitation trend in region of high intermodel agreement

**CMAP satellite data set 1979-2003**

**Land station data:**
**CPC (2.5 degrees, 1950-2002)**
**VASCLIMO (1 deg, 1951-2000)**
**Shaded over 95% significance**



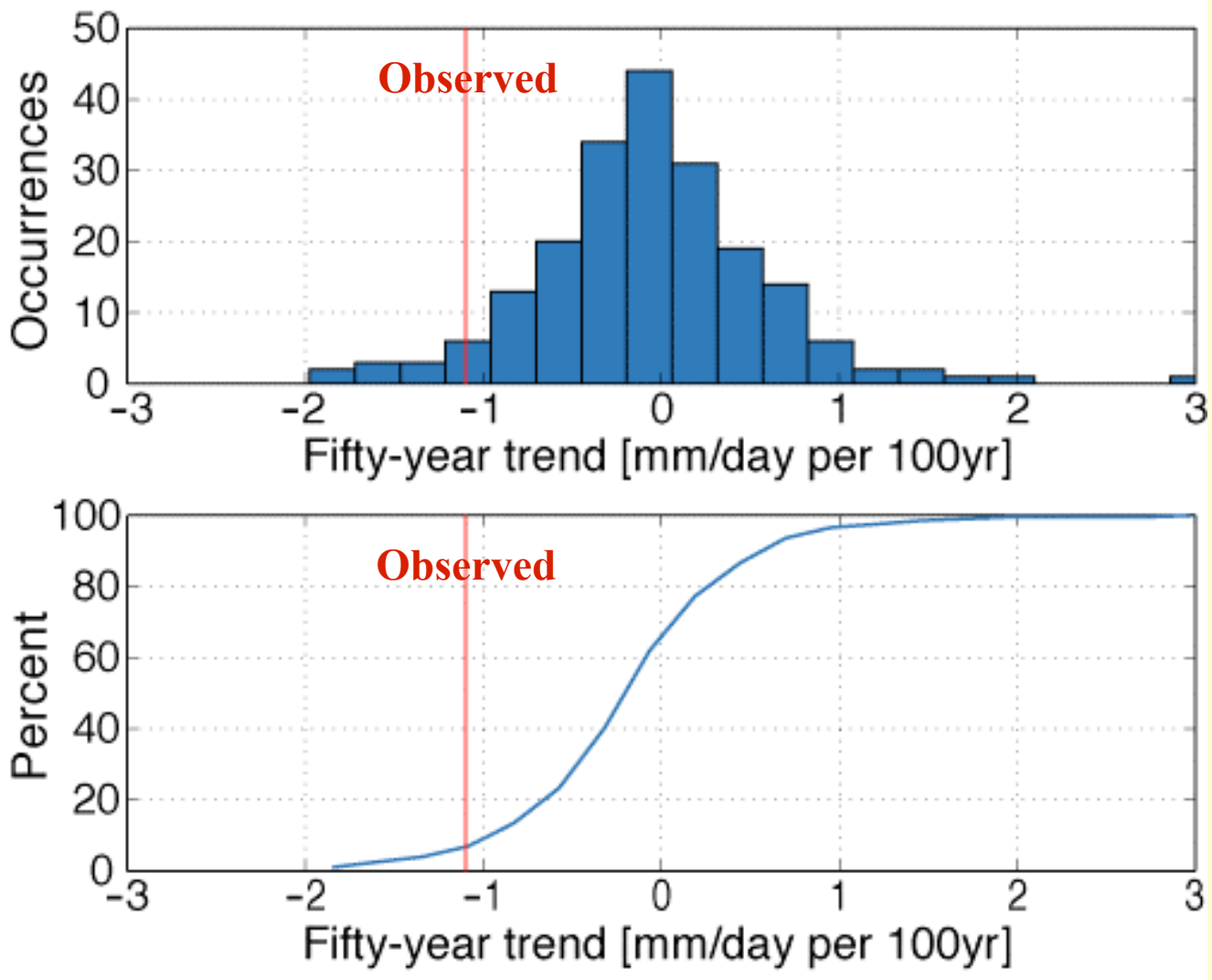

Neelin, Munnich, Su, Meyerson and Holloway , 2006, *PNAS*

# 50-year trend: obs. drying vs. model control runs

**Histogram of occurrences of 50-yr. trends (multi-model)**

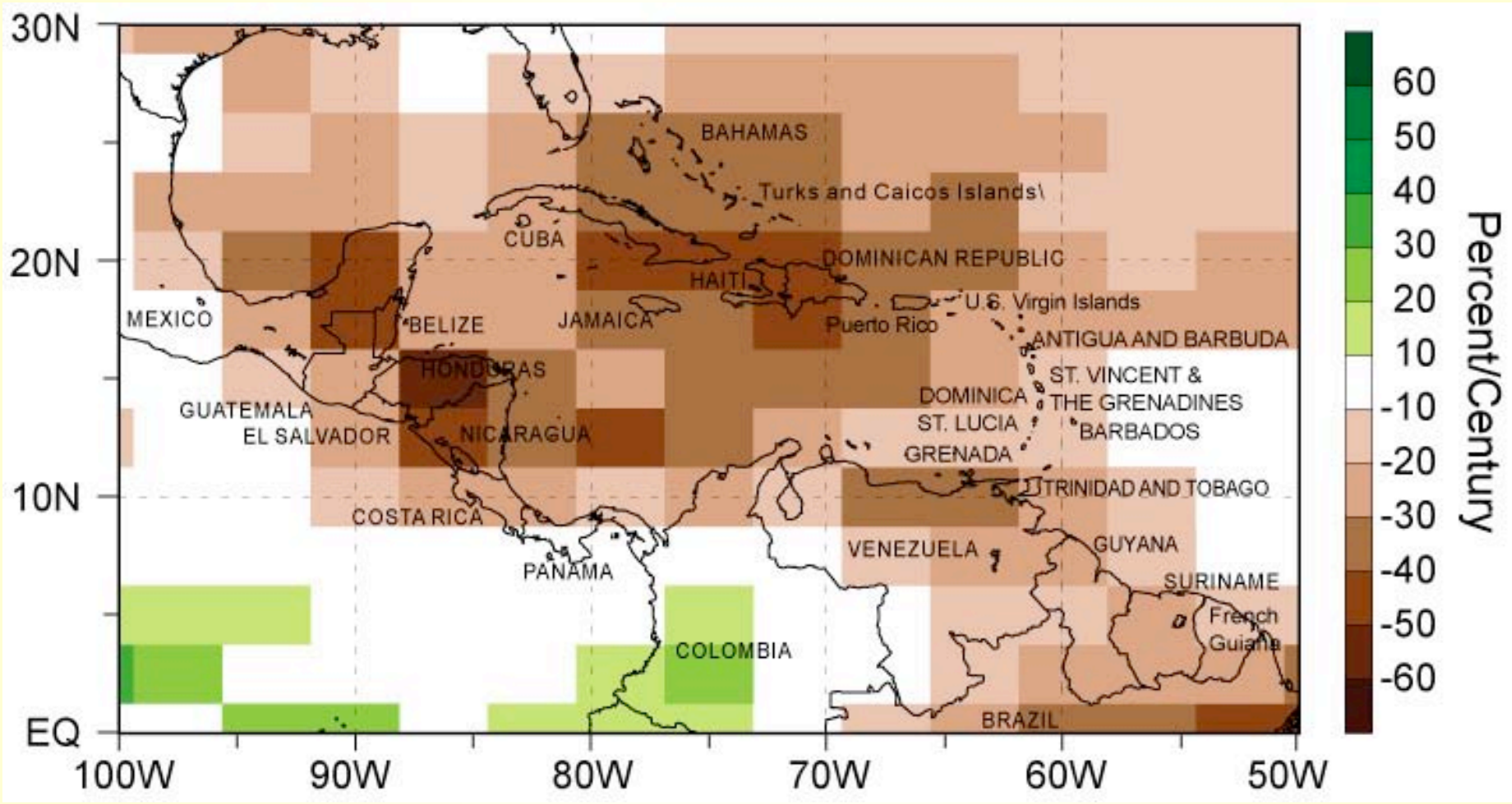
**Caribbean/ C. American region avg. precip.**

**Cumulative dist. for 50-yr trends**



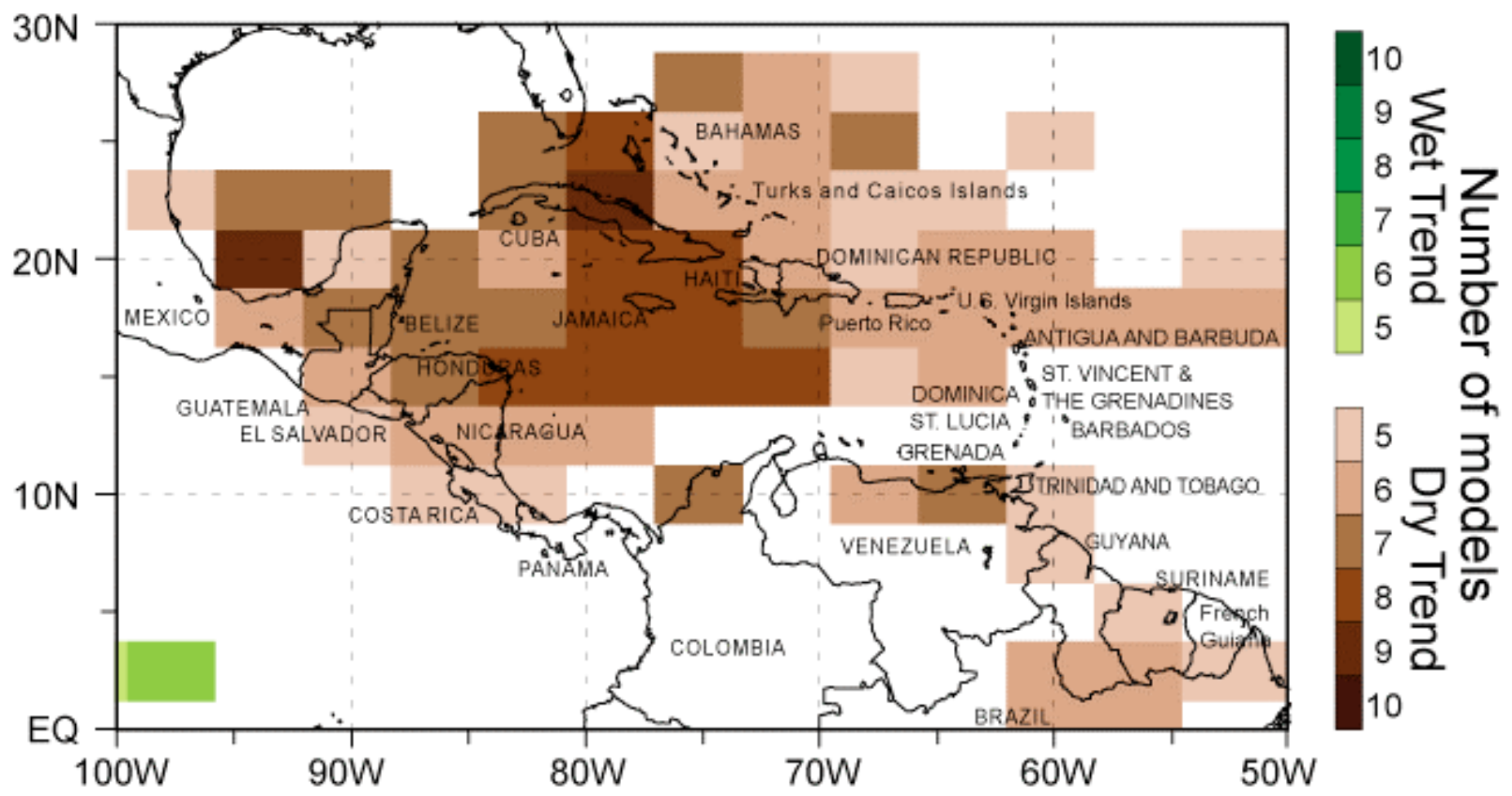

**Estimate of natural variability of 50 year trends in model control runs without anthropogenic forcing**

# Model median June-August precipitation trend as percent of median climatology per century



# Inter-model Dry/Wet trend agreement

## Number of models (out of 10) with > 99% significant trend (1979-2099), exceeding 20% of the median clim./century



# Model names

**cccma_cgcm3.1, Canadian Community Climate Model**

**cnrm_cm3, Meteo-France, Centre National de Recherches Meteorologiques, CM3 Model**

**csiro_mk3.0, CSIRO Atmospheric Research, Australia, Mk3.0 Model**

**gfdl_cm2.0, NOAA Geophysical Fluid Dynamics Laboratory, CM2.0 Model**

**gfdl_cm2.1, NOAA Geophysical Fluid Dynamics Laboratory, CM2.1 Model**

**giss_model_er, NASA Goddard Institute for Space Studies, ModelE20/Russell**

**miroc3.2_medres, CCSR/NIES/FRCGC, MIROC Model V3.2, medium resolution**

**mpi_echam5, Max Planck Institute for Meteorology, Germany, ECHAM5 / MPI OM**

**mri_cgcm2.3.2a, Meteorological Research Institute, Japan, CGCM2.3.2a**

**ncar_ccsm3.0, NCAR Community Climate System Model, CCSM 3.0**

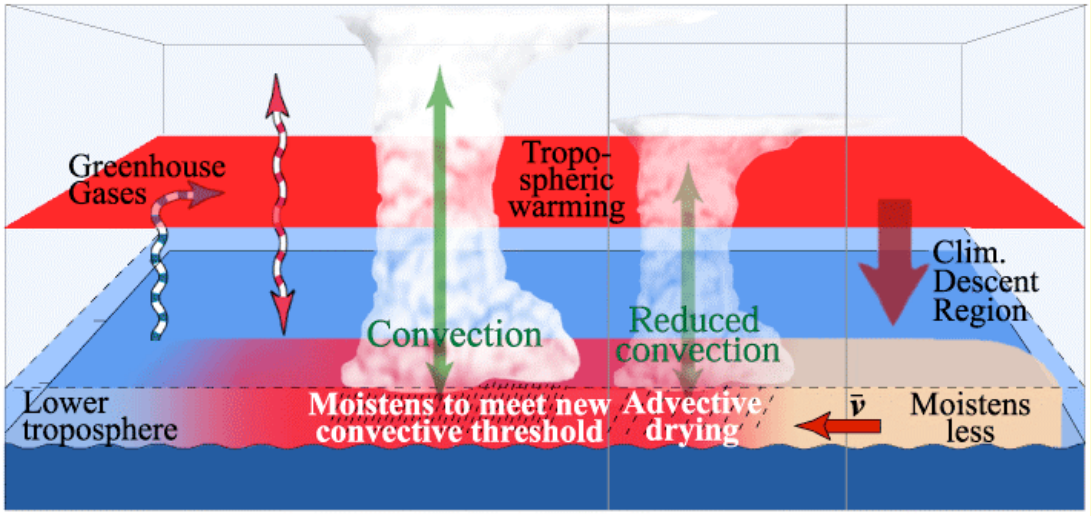
**ncar_pcm1, Parallel Climate Model (Version 1)**

**ukmo_hadcm3, Hadley Centre for Climate Prediction, Met Office, UK, HadCM3 Model**

# Summary: mechanisms

- tropospheric warming increases moisture gradient between convective and non-convective regions

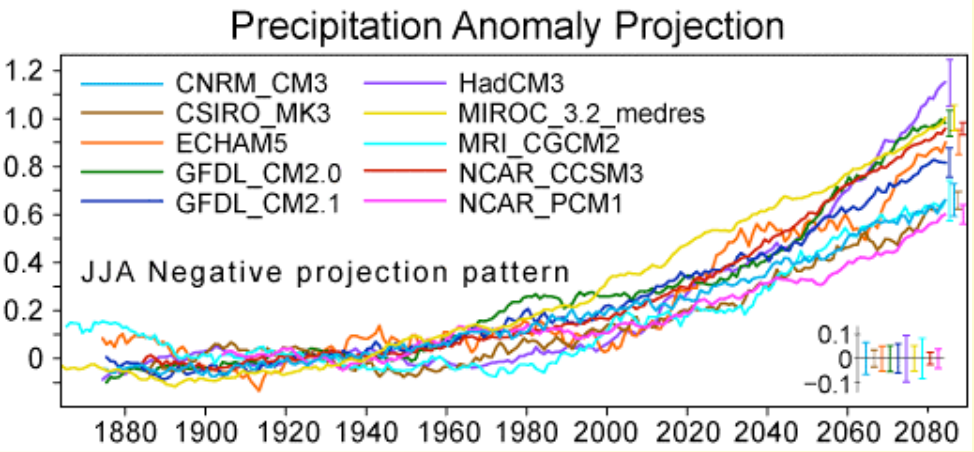
- the "upped-ante mechanism":
  - negative precipitation anomaly regions along margins of convection zones with wind inflow from dry zones




- the "rich-get-richer mechanism" (a.k.a. $M'$ mechanism):
  - Positive/negative precipitation changes in regions of with high/low climatological precipitation
- [+ocean heat transport anomaly in equatorial Pacific]

# Summary: multi-model tropical precipitation change

- agreement on amplitude of wet/dry precip anoms, despite differing spatial patterns
- growth with warming for projected precip. patterns; consistency of spatial pattern with time in each model
- ⇒ take qualitative aspects of these changes seriously




- agreement on Caribbean/Central America summer drying trend
- observed trend in this region; but caution on attribution (poor observational constraints on interdecadal variatiability)