# Anthropogenic changes to tropical & subtropical precipitation and circulation

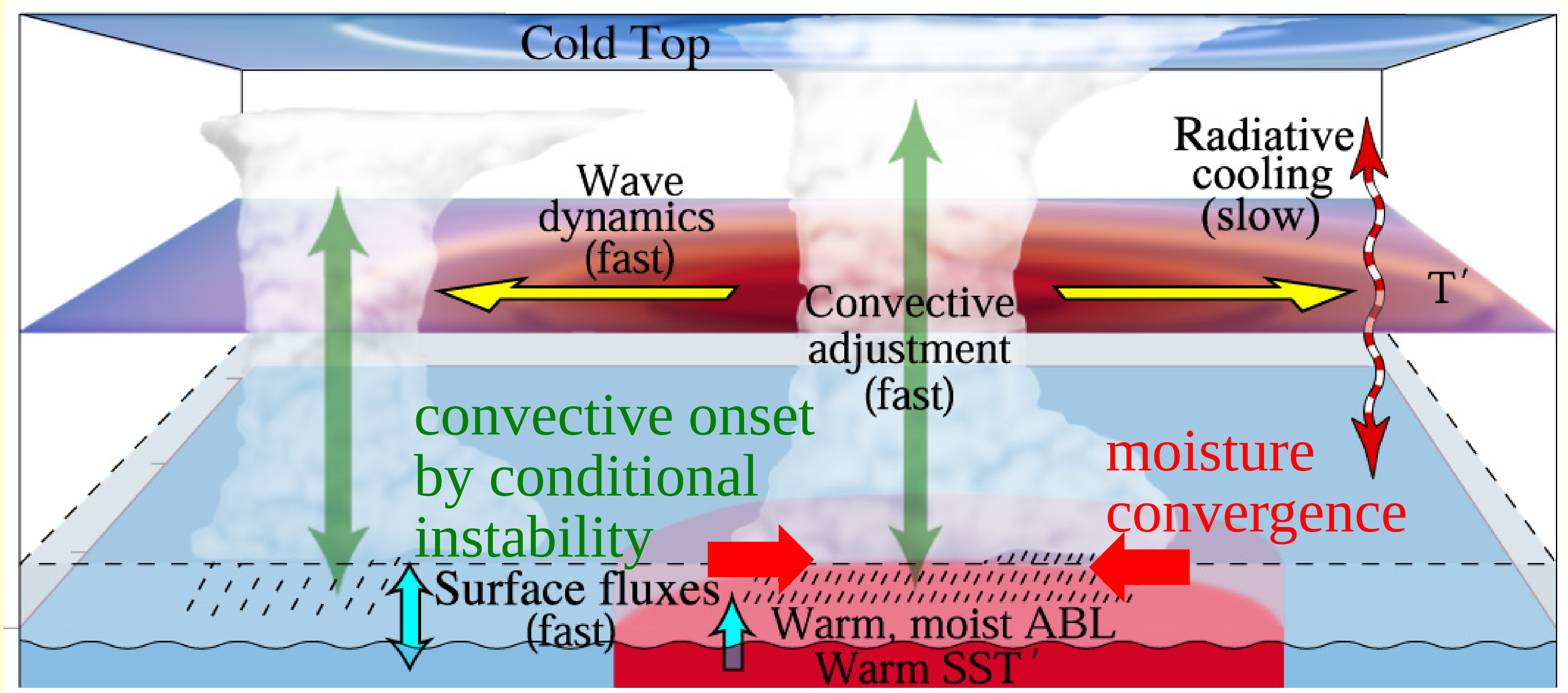
**J. David Neelin[1] + collaborators to be noted**

**[1]Dept. of Atmos. and Ocn. Sci, UCLA**

- **Basics: moisture budget, moist static energy budget, conditions for onset of precipitation, SST, and phrasing of statements of "robust" change**
- **mean versus extremes;**
- **A nagging issue: despite some agreement at large spatial scales, severe problems with model disagreement on precipitation change at regional/seasonal scales**
- **Sensitivity to differences in model parameterizations**

e.g., IPCC WG1 2001, 2007, 2013; Wetherald & Manabe 2002; Trenberth et al 2003; Neelin et al. 2003,2006; Maloney and Hartmann 2001; Chou & Neelin 2004; Held and Soden 2006; Dai 2006; Tost et al. 2006; Bretherton 2007, Xie et al 2009; Seager et al. 2010, 2012; Muller & O'Gorman 2011; Trenberth 2011; Tebaldi et al. 2011; Fasullo 2012; Durack et al. 2012; Hsu & Li 2012; Frierson 2012 ; Chou et al. 2009, 2013; Levy et al. 2013; Bony et al. 2013; ...

# Some processes competing in setting Precip pattern

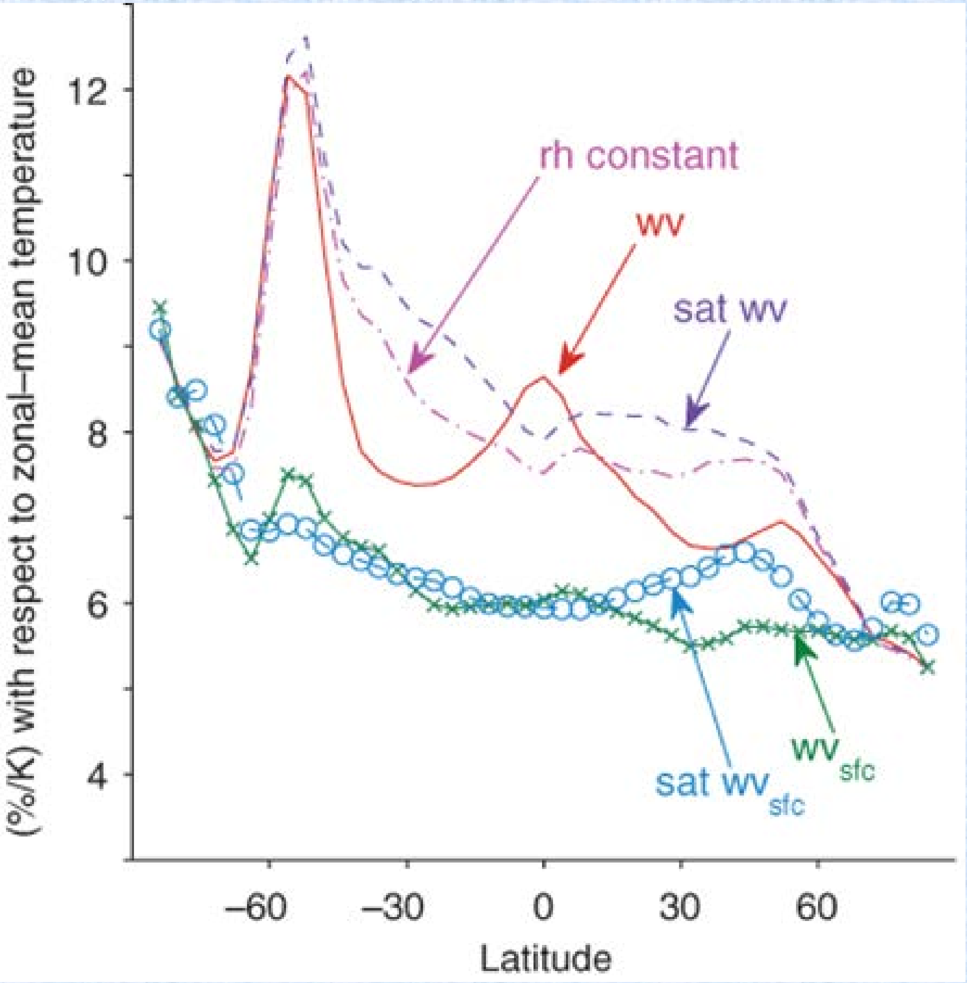



- **convection links tropospheric *T* to atmospheric boundary layer (ABL), moisture, surface fluxes --- imperfect time scale separation**
- **Convection + wave dynamics constrain tropospheric *T* profile**
- **implications of (rough) convective quasi-equilibrium (QE) + wave dynamics implies weak temperature pressure gradients in tropics**

Neelin & Held 1987; Yu & Neelin 1994; Emanuel et al 1994; Neelin 1997; Raymond 2000; N & Zeng 2000; Chiang et al 2001; Chiang & Sobel 2002; Su & Neelin 2002; Bretherton and Sobel 2002, 2003;…

# Most basic: Clausius-Clapeyron saturation temperature dependence

- **Clausius-Clapeyron increase typical numbers: 7.3-7.5% per °C (O'G&M2010, Held & Soden 2006, global mean rel to global surface air temp), 7% (Trenberth et al. 2003 lower free troposphere)**
- **8.2%/°C for 3°C mild nonlinearity**
- **Surface specific humidity 5.7%**
- **Percent increase per °C temperature increase rel. to zonal average surface air temperature of column water vapor (red), column water vapor with an invariant distribution of relative humidity (pink), saturation column water vapor (purple), surface specific humidity (green), and surface saturation specific humidity (blue).**




A recent quantification:
O'Gorman & Muller, 2010, Fig. 1

# Temperature *T* and Moisture *q* equations

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

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

*convective heating*

*vertical velocity*

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

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

*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$\rangle$**

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

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

*Net energy flux into column*

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

# Precipitation change: some basics from moisture/energy budgets

**Start with changes in mean climate, moisture budget-centric:**

**Moisture budget for perturbations**

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

**Precip** **Wet-Get-Wetter*** **$q'$ advection** **Convergence feedback** **Evap**

**~Rich-get-Richer****

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

early q': e.g., Manabe &Stouffer 1980; Manabe &Wetherald 1980 *JAS*, Mitchell et al. 1987 *QJRMS*;
**Chou & Neelin 2004, incl. MSE & onset; Trenberth 2011, Durack et al. 2012,…
*Held & Soden 2006; Seager et al 2012, 2014,…
For "warm-get-wetter" Ma et al. 2012; Ma & Xie 2013, see below.

# 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 transp**

$$\underline{M}\,\nabla\cdot v' = -M'\,\nabla\cdot \underline{v} - \langle v\cdot\nabla q\rangle' - F_s^{net'} + F_{top}^{net'} + \langle v\cdot\nabla T\rangle' \ldots$$

**Yields balances constraining dynamical contribution, here focusing on $\nabla\cdot v'$, gives $\langle\, \bar{q}\,\nabla\cdot v'\rangle$ dynamical contribution to Precip change**

$M = \langle \Omega(p)\partial_p h\rangle = \langle V(p)h\rangle = \langle V(p)s\rangle + \langle V(p)q)\rangle = M_s - M_q;$

***V*** **a typical velocity profile, per unit convergence**

**Several contributions can be viewed through this lense, below**

**Connection to talk by B. Boos on MSE diagnostics for monsoons**

# 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 | X-get-Xer** | $q'$ advection | Convergence Fb | Evap

"Thermodynamic contribution*"

Dynamical contribution [Regional differences]

**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**

**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**

early q': e.g., Manabe &Stouffer 1980; Manabe &Wetherald 1980 *JAS*, Mitchell et al. 1987 *QJRMS*; Chou & Neelin 2004, incl. MSE & onset; Chou et al., 2009; Trenberth 2011, Durack et al. 2012,…
*Held & Soden 2006; **X=rich or wet or warm/wet

# Mechanisms & constraints from moisture/energy budgets

## Moisture budget for perturbations

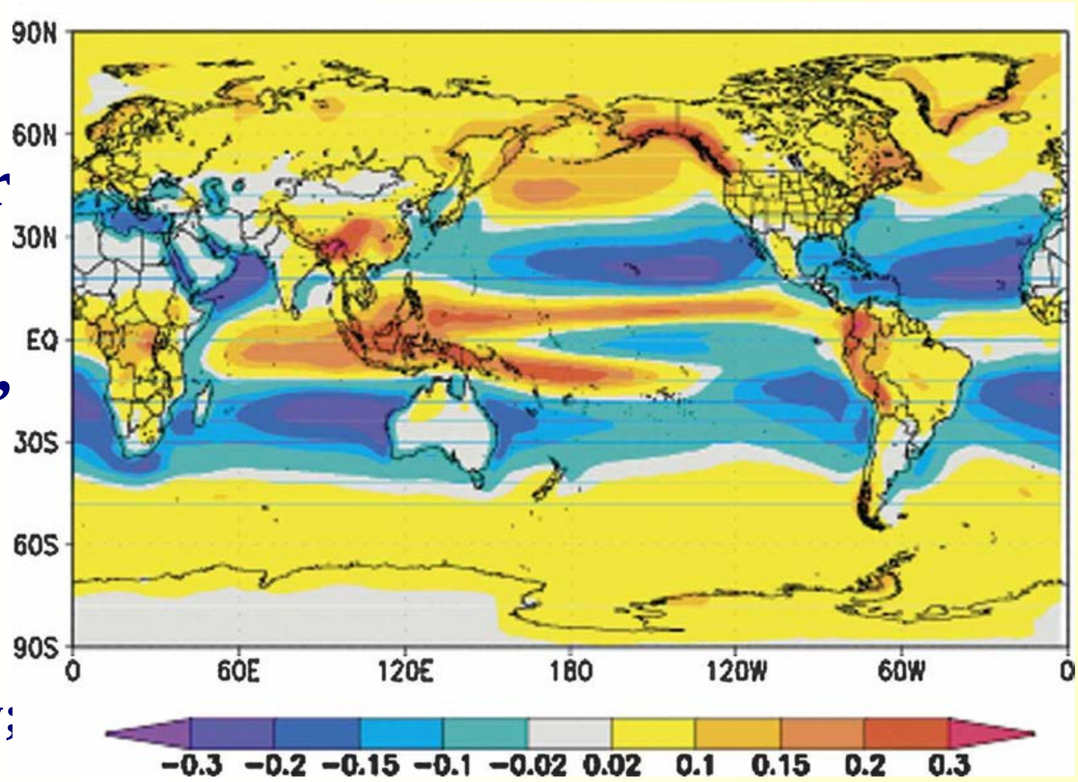
$$P' - E' = 0.07\delta T\,(\overline{P} - \overline{E}) \quad - < \overline{q}\,\nabla\cdot v' > + \ldots$$

* Drop! dynamical contrib.

*Rich-get-richer/wet-get-wetter mechanism if don't include thermodynamic eq or onset conditions

Orig. "direct moisture effect"

Now: "thermodynamic component"




Held & Soden 2006, Fig. 7b

NB: moisture budget diagnostic only; if thermodynamic eq is included, drive convergence feedback

# Mechanisms & constraints from moisture/energy budgets

**Moisture budget for perturbations**

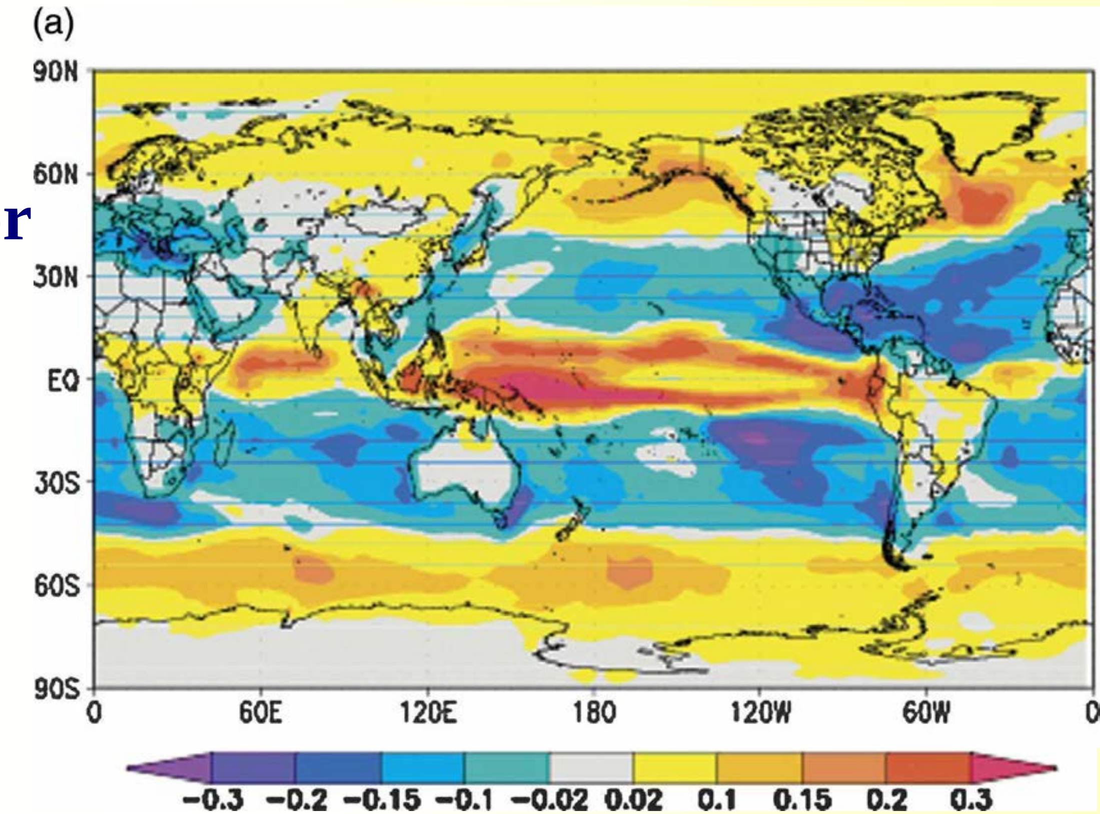
$$P' - E' = 0.07\delta T\,(\bar{P} - \bar{E})$$
*

$$-< \bar{q}\,\nabla\cdot v' > \text{ etc.}$$

**Drop! dynamic contributions**

***Rich-get-richer/wet-get-wetter mechanism if don't include thermodynamic eq or onset conditions**

**Comparison to multi-model ensemble mean depends on spatial scale & multi-model average to reduce circulation change contribution**




Held & Soden 2006, Fig. 7a

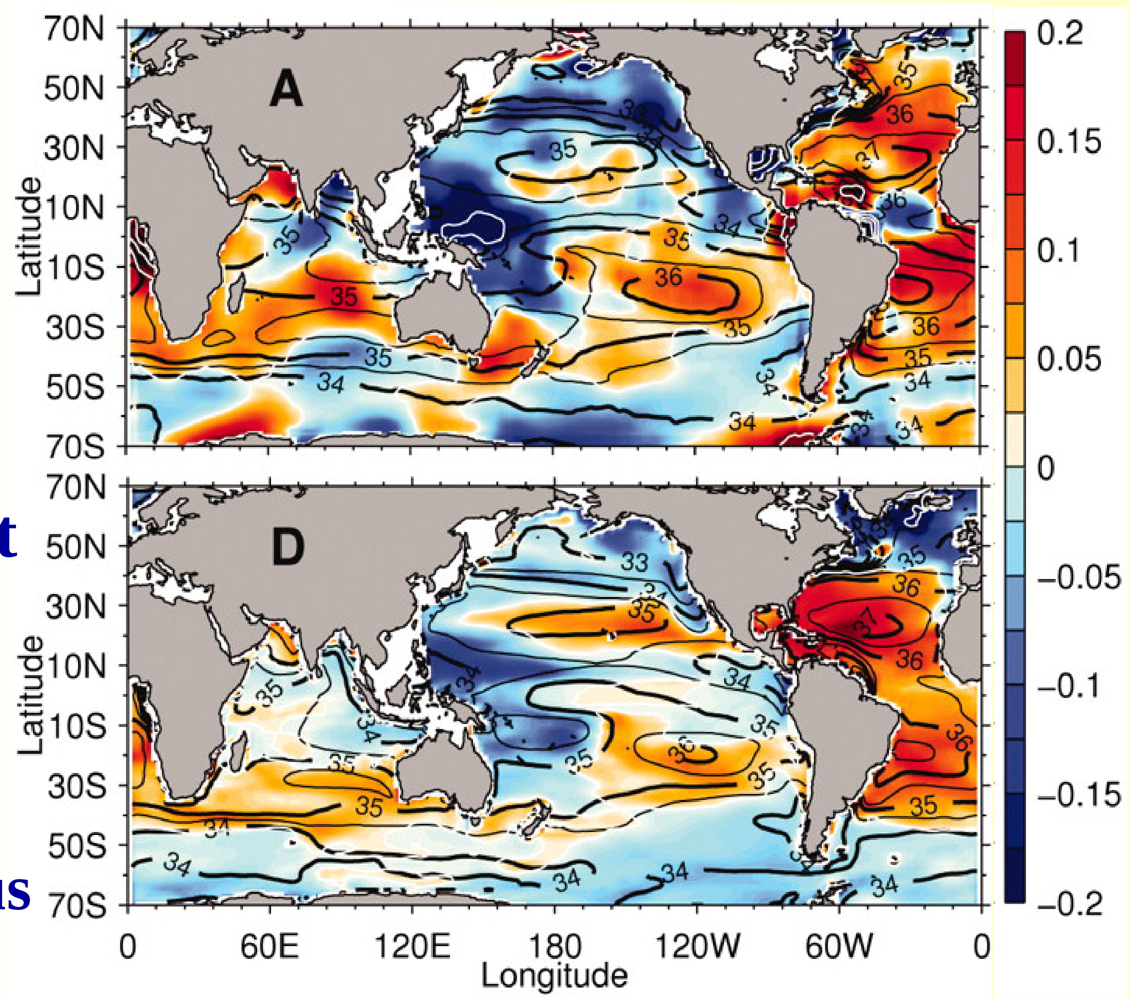
# Rich-get-richer inferred from obs. salinity changes

## works well at ocean basin scale

- **50-year surface salinity trends (PSU per 50 yr)**
- **(A) Observational estimate**
- **(D) Ensemble mean from of the CMIP3 20C3M simulations that warm >0.5°C**

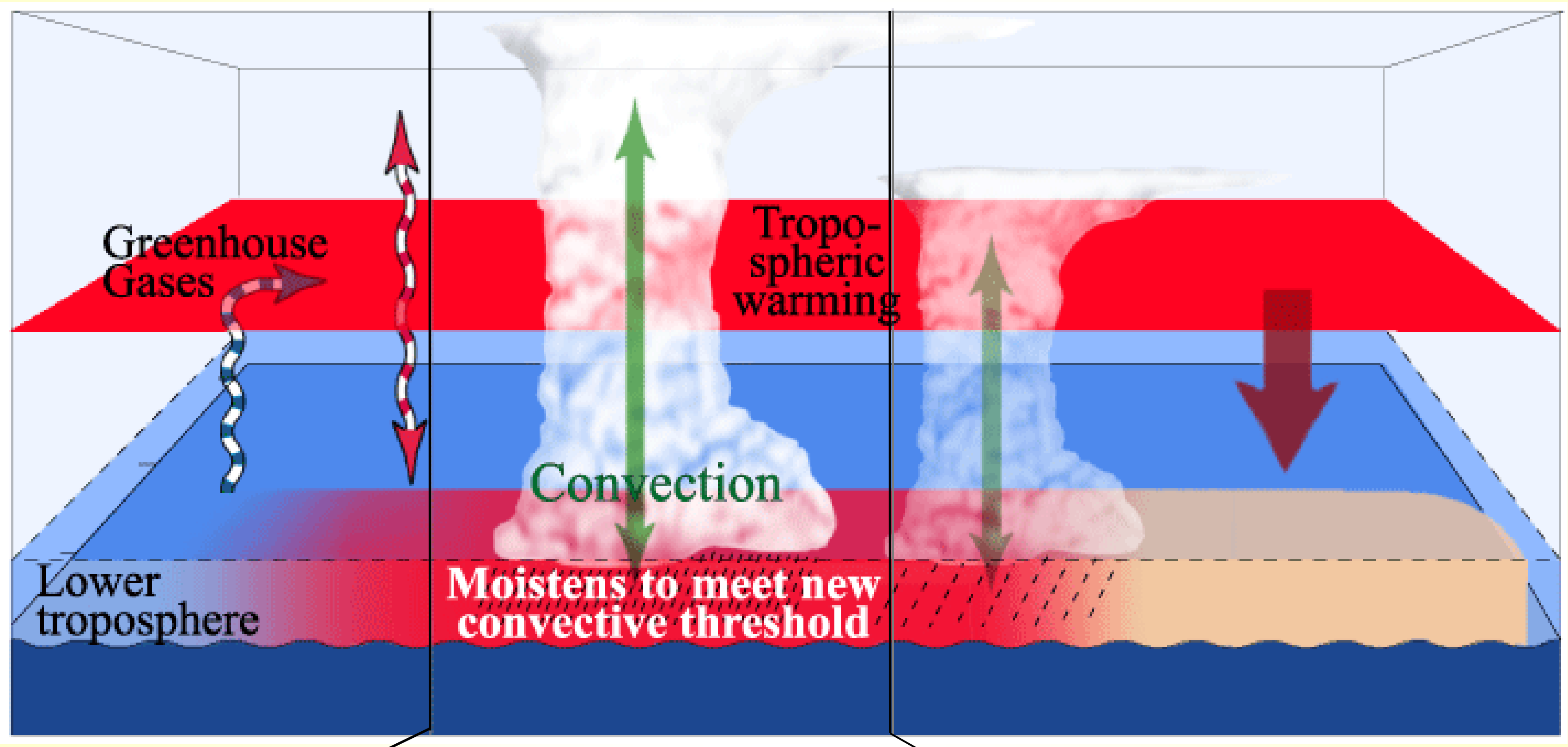
**(Black contours: mean salinity; thick lines every PSU)**

- **est. increase of evap minus precip pattern ~ 8 ± 5% per degree of surface warming**




**Durack et al. (2012; *Science*)**

# The Rich-get-richer (aka wet-get-wetter) mechanism (tropical portion)




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 2009

# 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 transp

$$\underline{M}\,\nabla\cdot v' = -M'\,\nabla\cdot \underline{v} - \langle v\cdot\nabla q\rangle' - F_s^{net'} + F_{top}^{net'} + \ldots$$

Yields balances constraining dynamical contribution, here focusing on $\nabla\cdot v'$, gives $\langle\, \bar{q}\,\nabla\cdot v'\rangle$ dynamical contribution to Precip change

$M' = M_s' - M_q'$; change in lapse rate & in depth of convection increases dry stability contribution; can yield reduced convergence

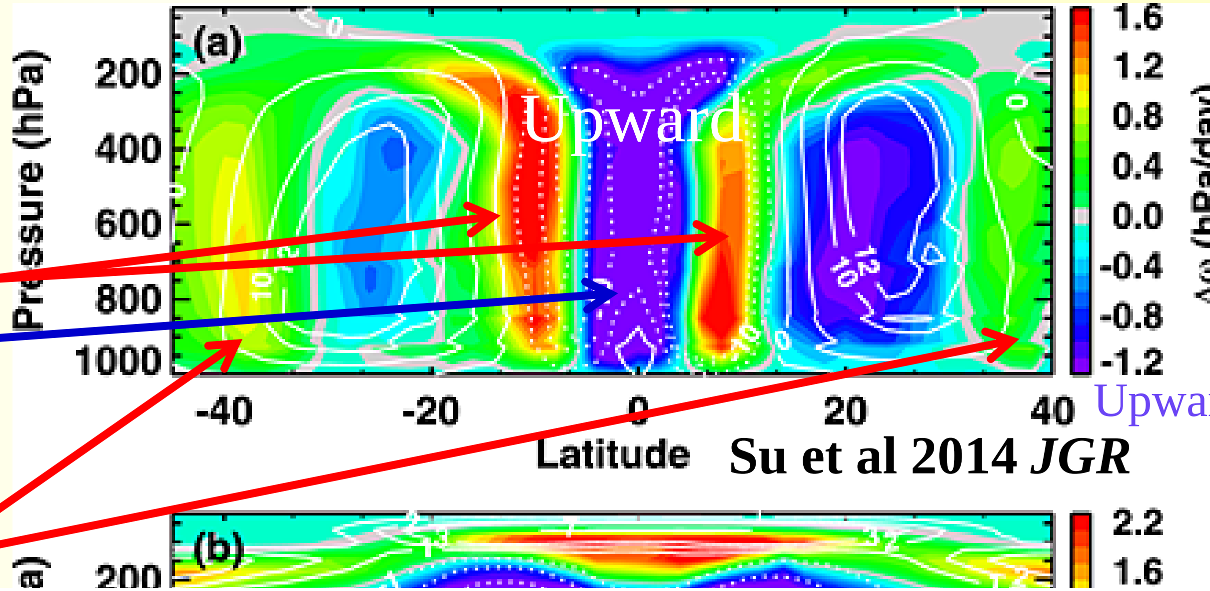
$\langle v\cdot\nabla q\rangle'$ can import low moist static energy air from non-convective regions, making it hard to reach convective onset criterion in warmer atmosphere in convective margins: upped ante mechanism

Balance of radiative vs. convective heating used to argue for slowing circulation holds for large averages: can meet with local reduction

# Example of Hadley circulation changes

**Changes in $\omega$ (colors), $\omega$ climatology (white contours; dashed = up)**

**Reductions at flanks,**
**intensification in core**
**of upward branch;**
**downward branch**
**extends poleward**

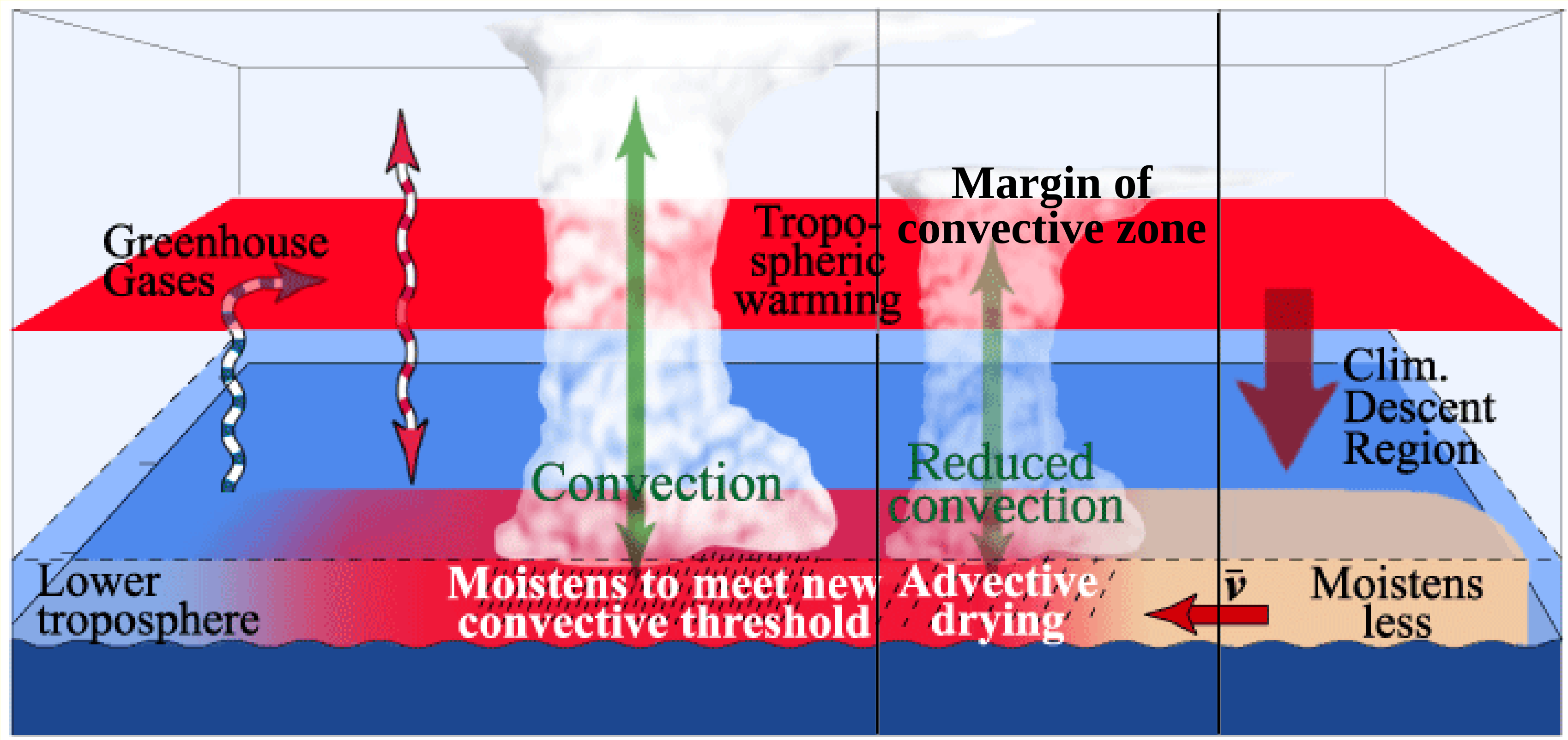



Su et al 2014 *JGR*

Increased width (& depth): e.g., Mitas and Clement, 2006; Frierson et al., 2007; Lu et al., 2007; Lu et al., 2008, Seidel and Randel, 2007; Seidel et al., 2008; Scheff and Frierson, 2012.
Overall weakening of mass flux: Held & Soden 2006; Vecchi & Soden 2007
Impacts at flanks: Chou et al. 2009; upped ante mechanism, convective margin theory (see next)
Relation to SST: Ma et al. 2012; Ma & Xie 2013; Seasonal: Huang et al. 2013

multimodel-mean (CMIP5 subset) zonal-mean vertical pressure velocity ($\omega$), cloud fraction (CF), relative humidity (RH); changes 2074–2098 in RCP 4.5 scenario relative to historical 1980–2004.

# The "upped-ante" mechanism/convective margin theory:
## warmer troposphere increases convective threshold




**A corollary to the rich-get-richer when include convective onset criterion**

**Analogous changes can occur at dry-wet season transition, e.g., extension**

**Teleconnections of remote changes can influence edges of convection zones**

**Neelin, Chou & Su 2003 *GRL;* CN04; Lintner & Neelin 2008, 2009, 2010; Biasutti& Sobel 2009; Lintner et al. 2012; Seth et al., 2011; Chou et al., 2013; Seth et al., 2013; Dwyer et al. 2013; Huang et al. 2013; Kang et al. 2009; Hwang and Frierson 2013; Seo et al. 2014;**

# MSE diagnostics for mechanisms

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

**MSE budget for perturbations $T'$ + ocean transp**

$$\underline{M}\,\nabla\cdot v' = -M'\,\nabla\cdot \underline{v} - (v\cdot\nabla q)' - F_s^{net'} + F_{top}^{net'} + (v\cdot\nabla T)' \ldots$$

**Yields balances constraining dynamical contribution, here focusing on $\nabla\cdot v'$, gives $< \overline{q}\,\nabla\cdot v' >$ dynamical contribution to Precip change**

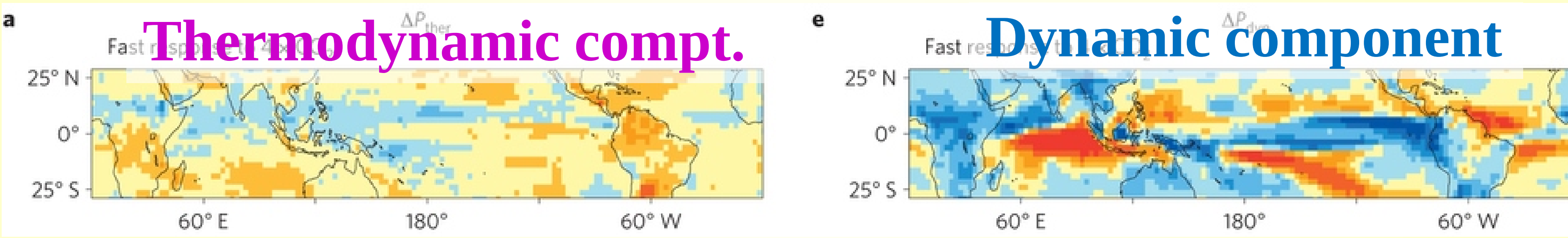
**$F_s^{net'}$ goes to zero/small most places except where ocean transport changes (e.g. equatorial cold tongue). Balance gives SST.**

**$F_{top}^{net'}$ can have spatial pattern from greenhouse gas increase & climatological cloud pattern: direct forcing of a ‘fast’ response**

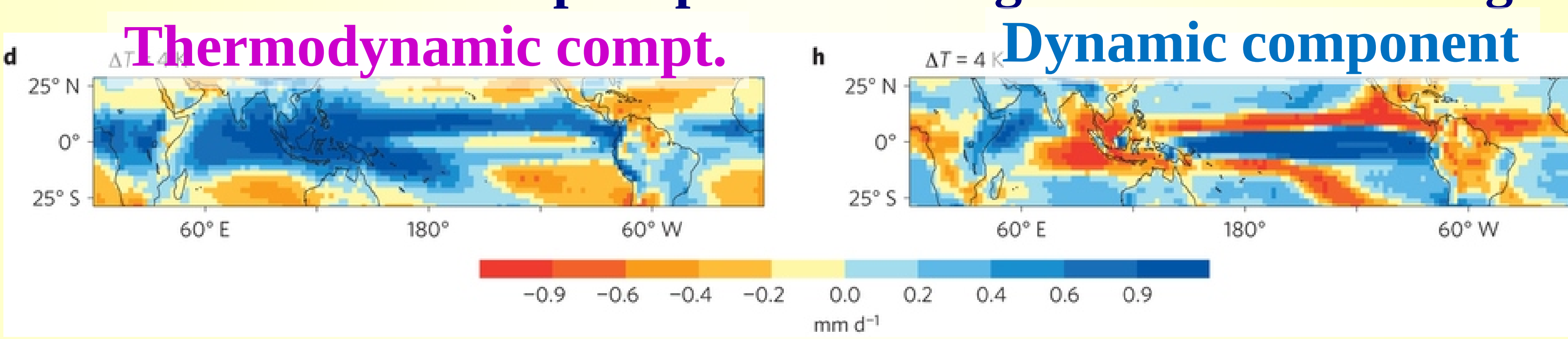
**Smallness of *M* (near-cancellation between convective heating and adiabatic cooling) implies small effects can create large $\nabla\cdot v'$, $P'$**

# Mechanisms & constraints from moisture/energy budgets

**Defining a “fast” response: instantaneous 4xCO2 experiment; multi-model mean precipitation change in first year**




**vs. multi-model mean precipitation change after 4°C warming**

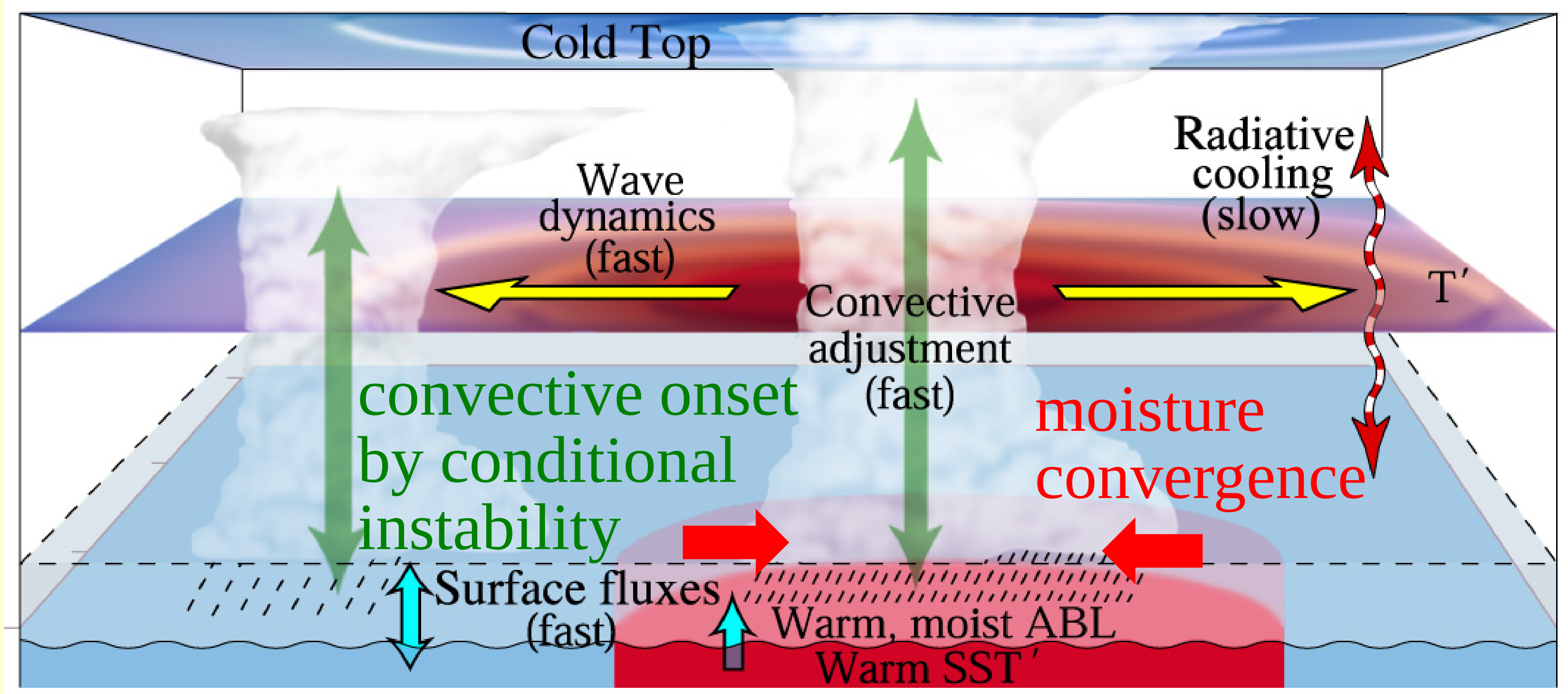



**“fast” dynamic component of response (upper right) not small.**

Bony et al. 2013, Fig. 2a,e,d,h, *Nature Geoscience;* prev. Gregory and Webb 2008, *J. Clim.*

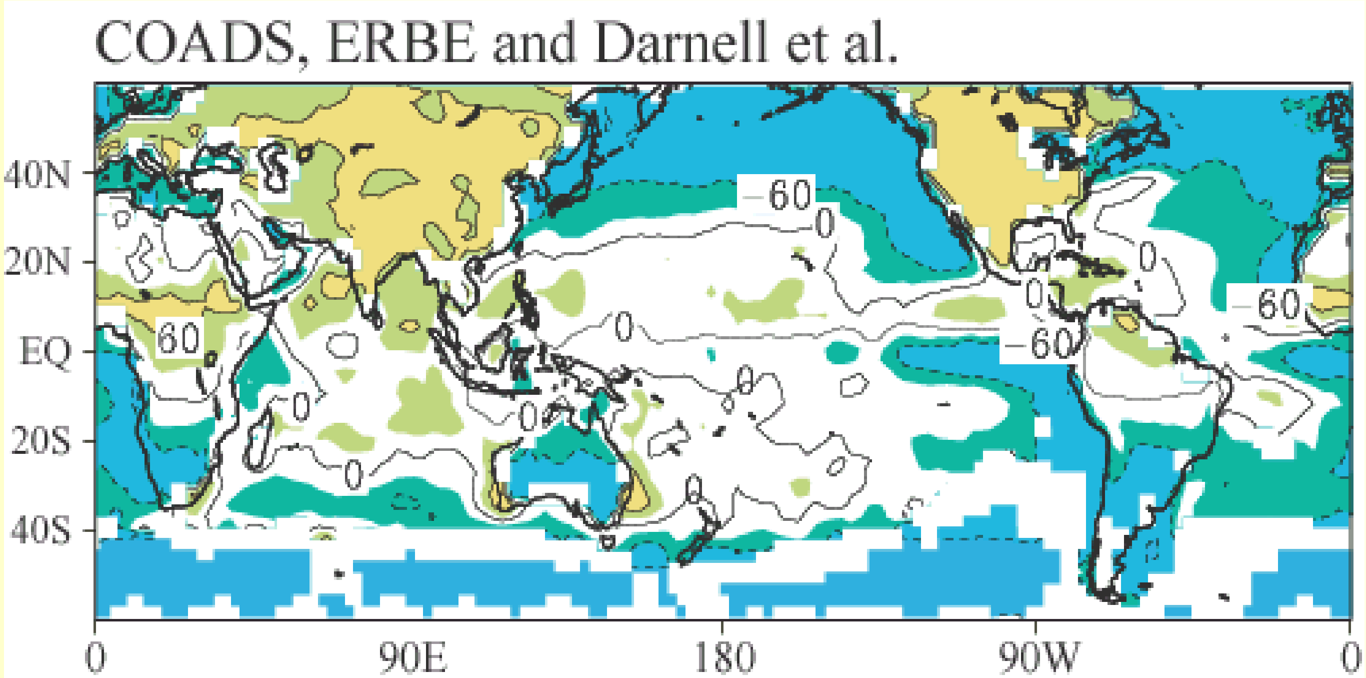
Nomenclature note: ‘fast’ in idealized experiments; time to quadruple CO2 ~2 centuries

# Recall: processes setting Precip pattern




- **In climatology, using moisture budget alone would be odd**
- **Need thermodynamic eq. & convective onset criterion (at minimum)**
- **+ interaction with land or sea surface temperature (SST)**
- **original rich-get-richer discussion included these; restore, and/or**
- **SST provides a variable slaved to column energetic adjustment that has relationship to onset criterion ⇒ potentially useful diagnostic variable (over ocean): see talk by S.-P. Xie this afternoon**

# Observed $F^{net}$ climatology July



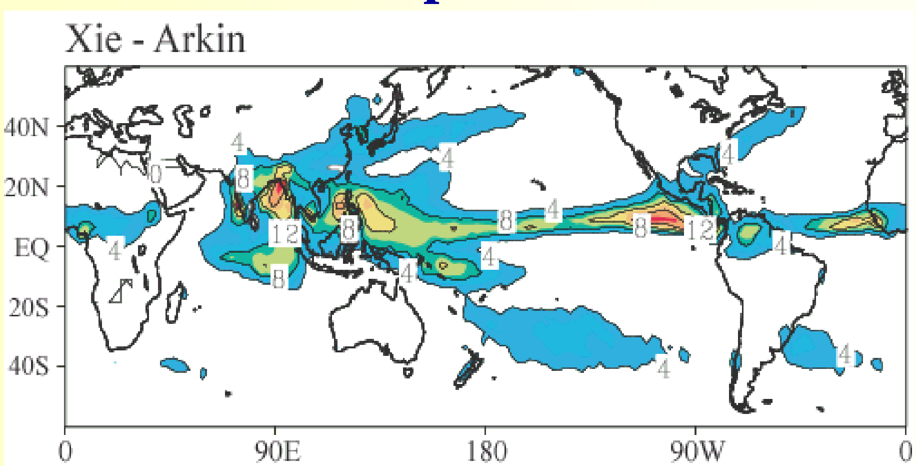

**Net flux into atmosphere**

**Solar, IR, sensible, latent**

**(Net surface flux=0 over land)**

**Shaded over/under +/- 30 W/m$^2$**

**Precipitation**

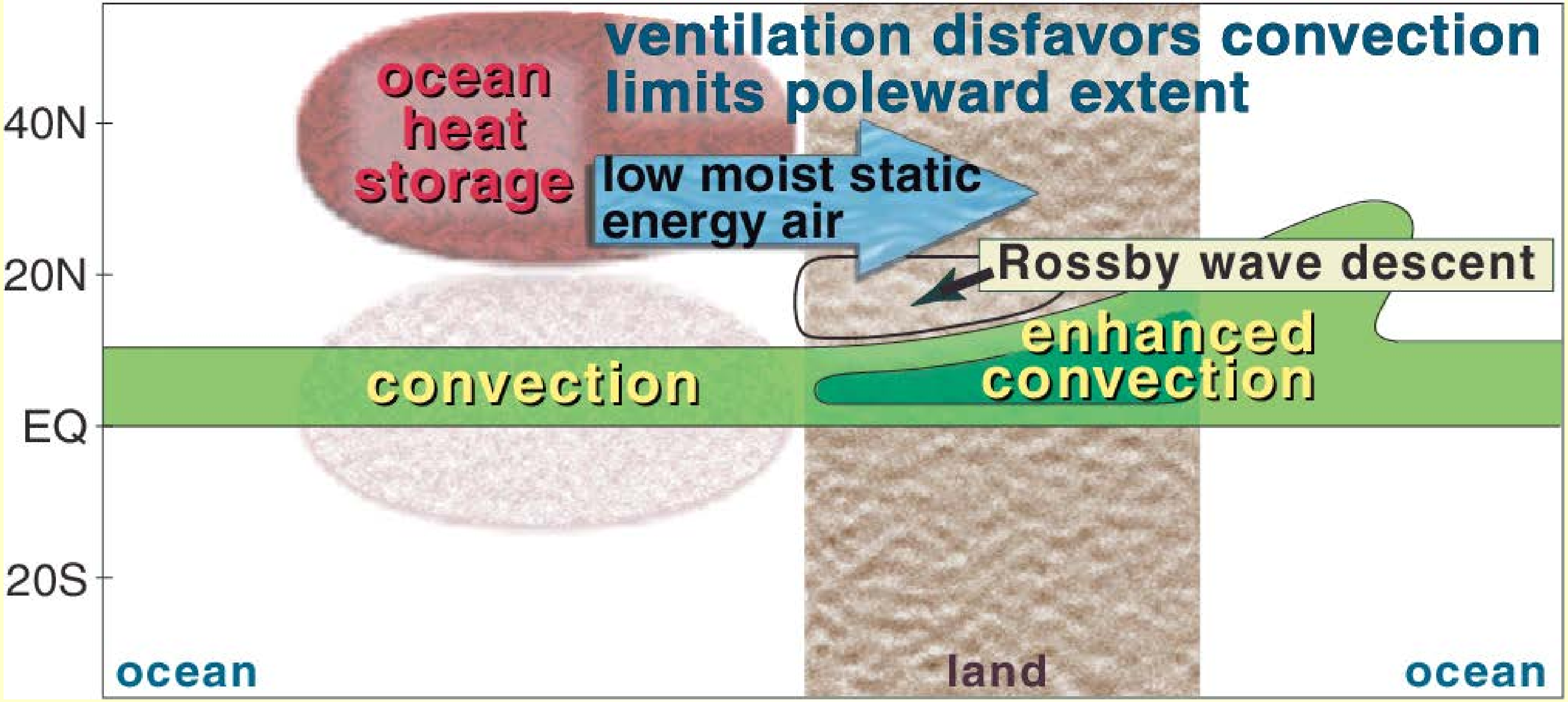



Chou and Neelin 2003, J. Clim.

**Quick note on MSE budget in current climate: Net flux into atm. positive far poleward over land in summer: no surprise that thermodynamic balance must be altered by dynamics**

Quick note on MSE budget in current climate as related to monsoons, cont.

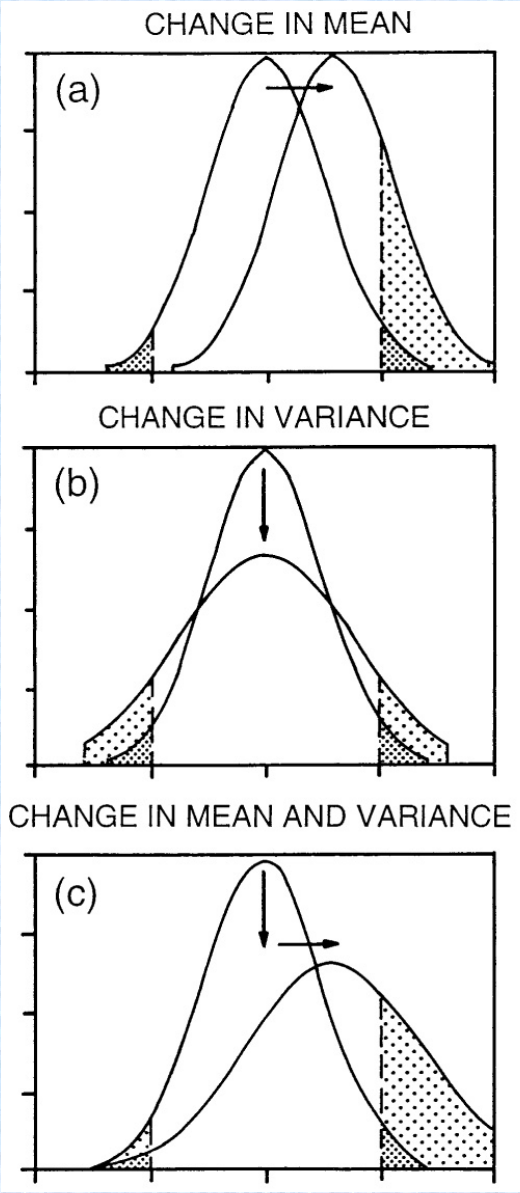
# Ventilation by relatively low moist static energy air from oceanic/nonconvective regions: helps set poleward extent of monsoons




Chou et al 2001 *QJRMS*; Chou and Neelin 2003 *GRL*; 2005 *JClim*

# Precipitation extreme events: basics & background

- Changes in extreme events under global warming have been of concern for some time but getting more quantitative over the last decade
- Still differences between state of understanding for temperature extremes vs precipitation: stages of moving from schematic to quantitative
- e.g., schematic from an early overview:




Meehl et al. 2000, Fig. 1

Meehl, G. A. *et al., 2000:* An introduction to trends in extreme weather and climate events: Observations, socioeconomic impacts, terrestrial ecological impacts, and model projections. *Bull. Amer. Meteor. Soc.* **81**, 413–416.

# Mechanisms from moisture budgets—variability

**Moisture budget for strong events dominated by convergence**

$$P \approx -\langle q \nabla \cdot v \rangle$$

Precip ≈ vert. av. moisture convergence

If moisture tends to increase with approximately constant relative humidity $q \approx (1+\gamma)q_{\mathrm{hist}}$ with $\gamma$ set by Clausius-Clapeyron

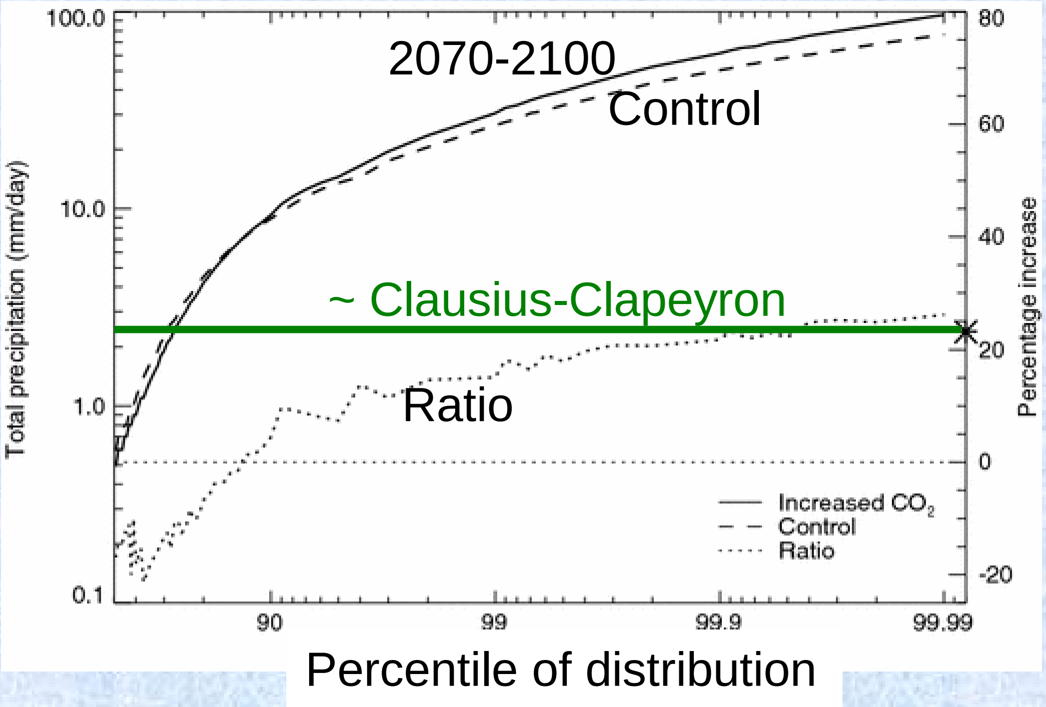
Simplest argument: if factors setting $\nabla \cdot v$ remain approximately the same, precipitation should increase by a factor $(1+\gamma)$ for corresponding situation. (Thermodynamic contribution/Rich-get-richer applied to variability, e.g. Trenberth 2011; Pall et al 2007)

e.g., Chou et al. (2012) argue this should rescale the distribution $p(P)$, i.e., warmer climate has probability $p(P/(1+\gamma))$ from the thermodynamic contribution

Dynamic contribution would be associated with changes in convergence distribution, e.g. weakening of the tropical circulation

# Changes in daily average precipitation intensity

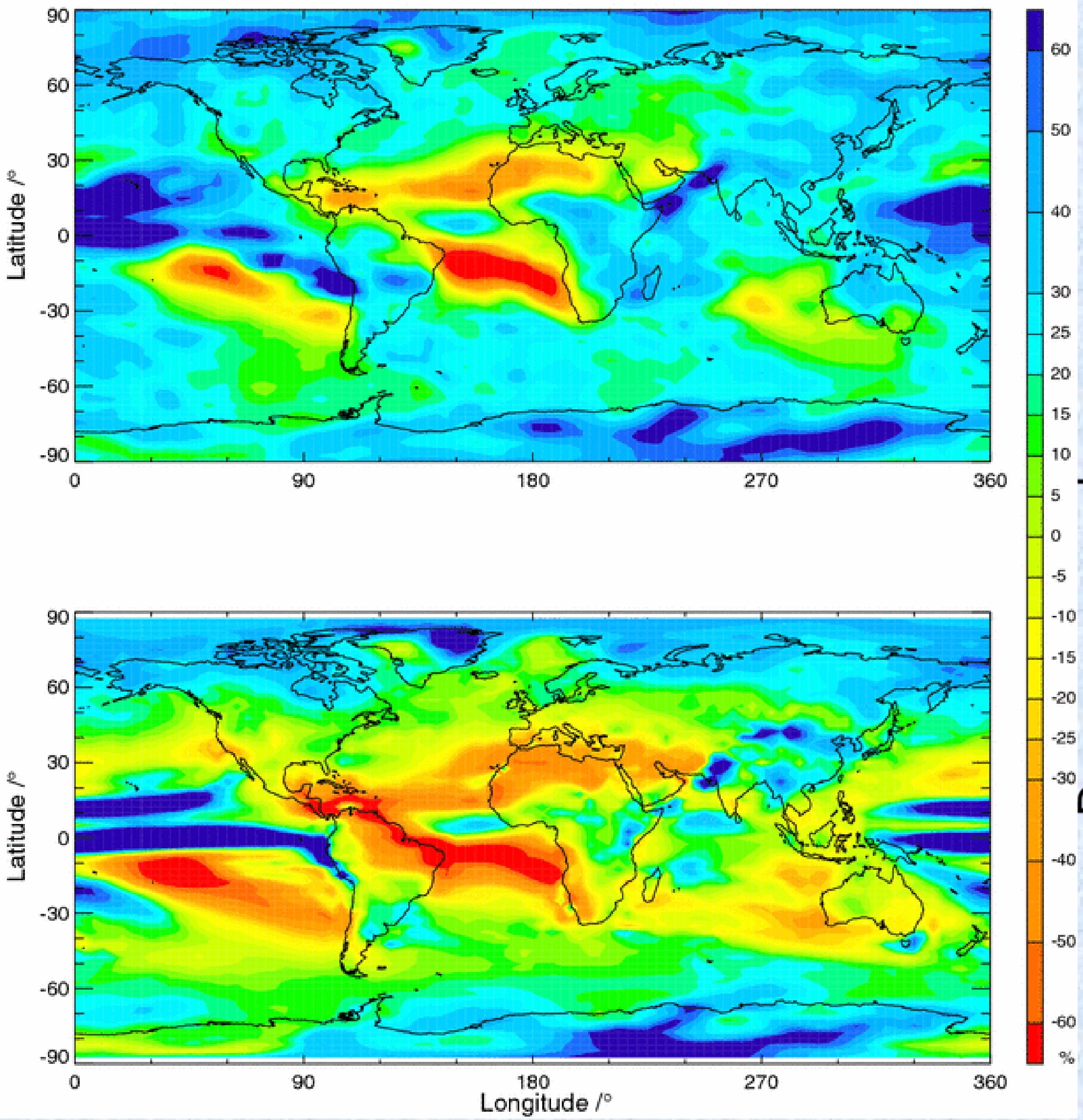
- **Log-log plot of distribution of daily precipitation (millimeter/day), i.e. an averaged intensity, of all grid points from HadCM3**
- **Solid: for 2070-2100 of a transient climate change simulation (avg CO2 x 2.7)**
- **Dashed: control simulation**
- **Dotted : ratio. * & line show 23% increase corresponding to approx. Clausius-Clapeyron increase (for 3.6°C global avg, 3.3°C tropical warming)**
- **~ rule of thumb for upper intensities**




Pall et al. 2007, Fig. 1

# Changes in daily average precipitation intensity

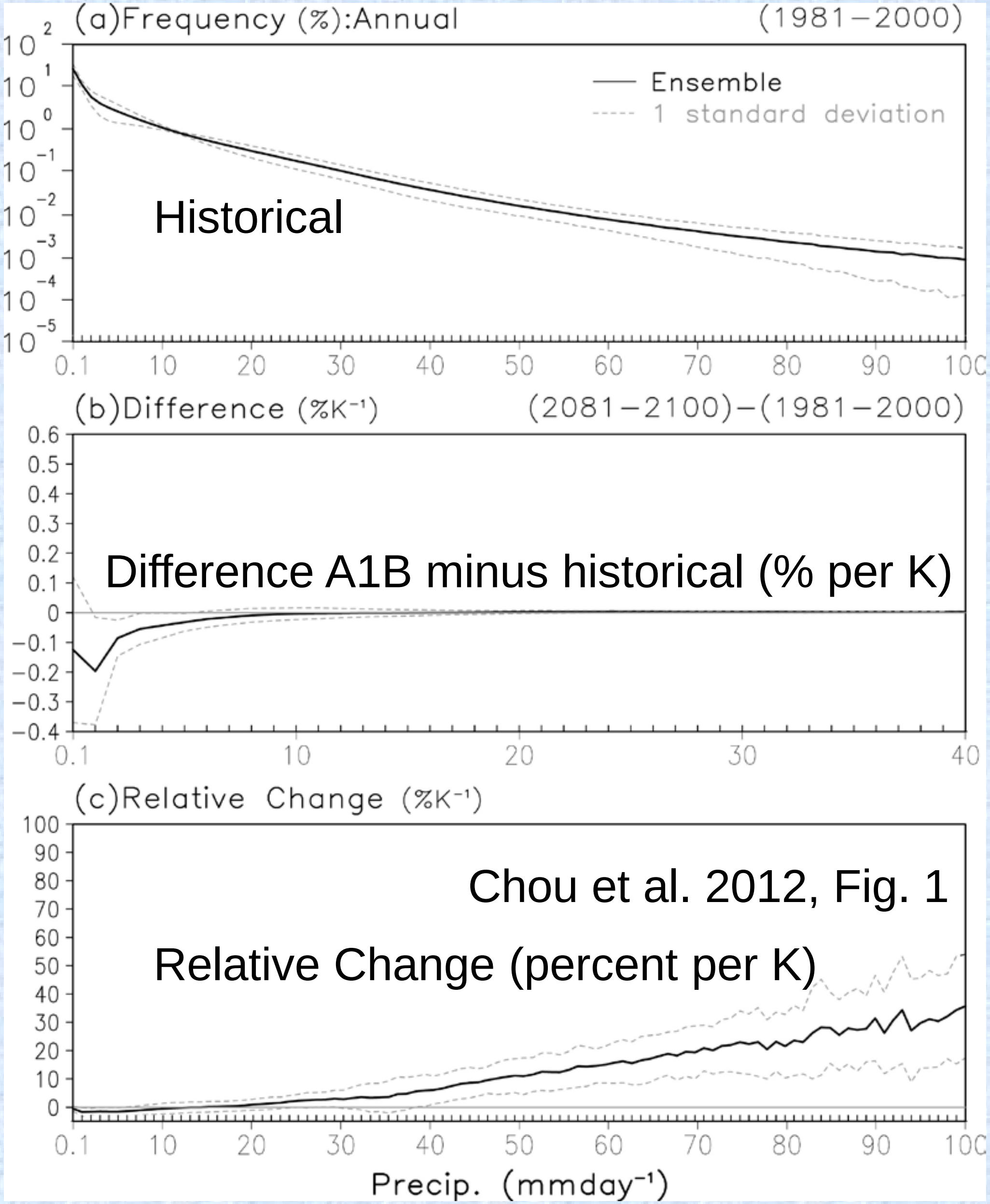
- **Percent change in daily precipitation at the 99.9th percentile (1 in 1000 day event) from HadCM3 for 2070-2100 vs. control (smoothed ~7x11°)**
- **Bottom: percent change in mean precipitation**
- **Note not evenly distributed in space; decreases in 99.9 percentile tend to be within regions of decreased mean in subtropics;**
- **widespread light blue regions ~ Clausius-Clapeyron expectations**
- **Max ~60%**




Pall, Allen, Stone, 2007, Clim. Dyn., Fig. 4

# Changes in daily average precipitation intensity

- **Log-linear plot of distribution of daily precipitation: Percent of days with precip (rel to all days) vs mm/day daily intensity), of all grid points from 10 CMIP3 models** (A1B scenario vs historical)
- **Relative increase larger in upper intensities, up to 20-30% per K**
- **decreases at lower intensities**

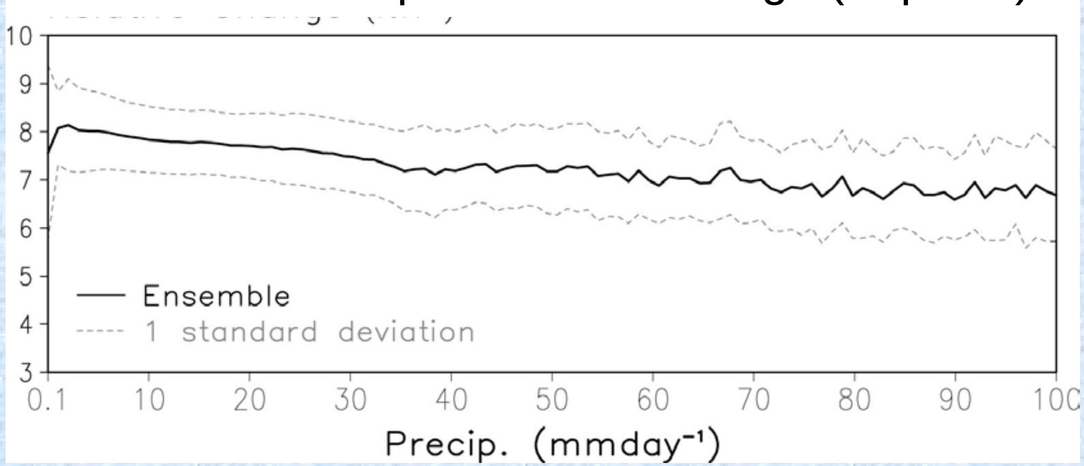



Chia Chou, C.-An.Chen, P.-H.Tan, and K. T. Chen, 2012: Mechanisms for Global Warming Impacts on Precipitation Frequency and Intensity. *J. Climate*, **25**, 3291–3306. .

# Changes in daily average precipitation intensity distribution

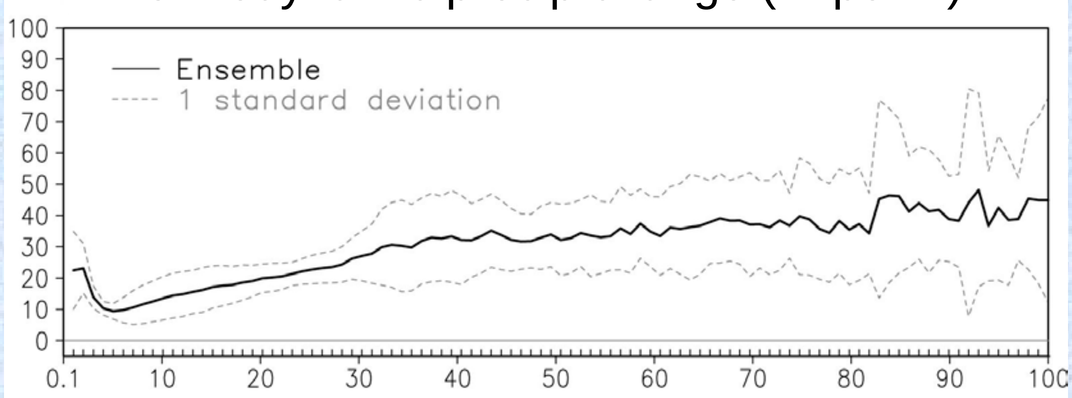
- **Change in column water vapor as a function of daily precip intensity, from 10 CMIP3 models** (A1B scenario vs historical)
- **Roughly Clausius-Clapeyron**
- **Log-linear plot of "thermodynamic component" of change in distribution of daily precipitation:**
- $[p(P/(1+\gamma)) - p(P)]/\,p(P)$
- **$p(P)$ =historical distribution—percent of days with precip (rel to all days)**
- **~30-40% increase**

Column water vapor relative Change (% per K)




Chou et al. 2012, Fig. 4c

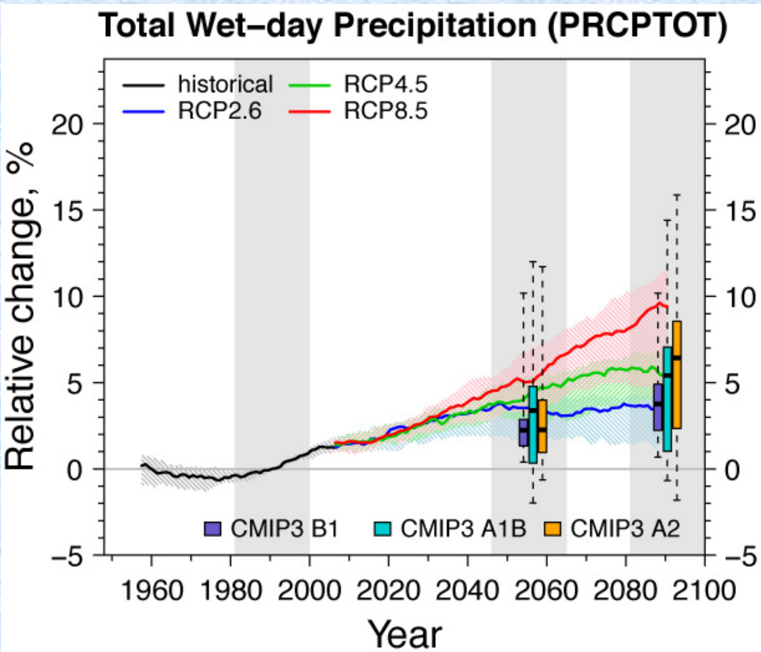
Thermodynamic precip change (% per K)

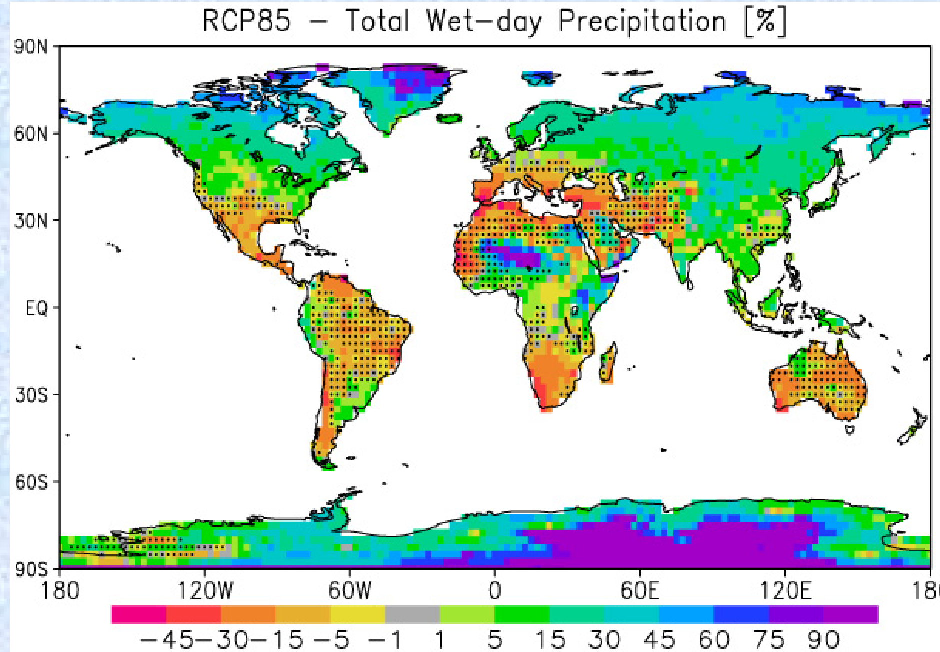



Chou et al. 2012, Fig. 5a

Chia Chou, C.-An.Chen, P.-H.Tan, and K. T. Chen, 2012: Mechanisms for Global Warming Impacts on Precipitation Frequency and Intensity. *J. Climate*, **25**, 3291–3306. .

# *Changes in precipitation extremes (cont'd)*




Sillmann et al. (2013, *J. Geophys. Res.*)

- **Percent change in: Total wet-day precipitation relative to base period**
- **CMIP5 models; Left: RCP 2.6, 4.5, 8.5 scenarios [also CMIP3 B1, A1B, A2]; Right: RCP8.5 multi-model median 2081-2100 rel to 1981-2000**
- **Tends to track changes in global mean temperature; Change ~10% for RCP8.5**
- **[total annual Precip on days with>1mm; median & 25-75$^{th}$ percentile of model ensemble]**
- **Background on these choices of measures of extremes: set up in Frich et al. (2002); used in the Tebaldi et al. (2006) for CMIP3 models**

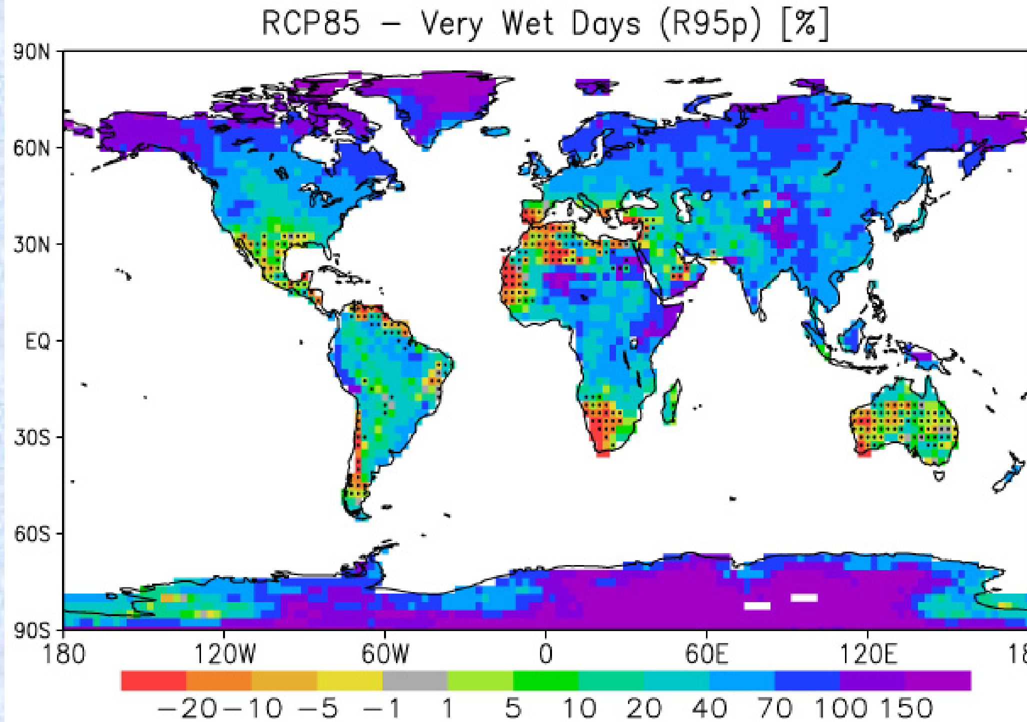

- Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Tank, A. M. G. K. and Peterson, T.: 2002, Observed coherent changes in climatic extremes during the second half of the twentieth century, *Clim. Res.* **19**, 193–212.

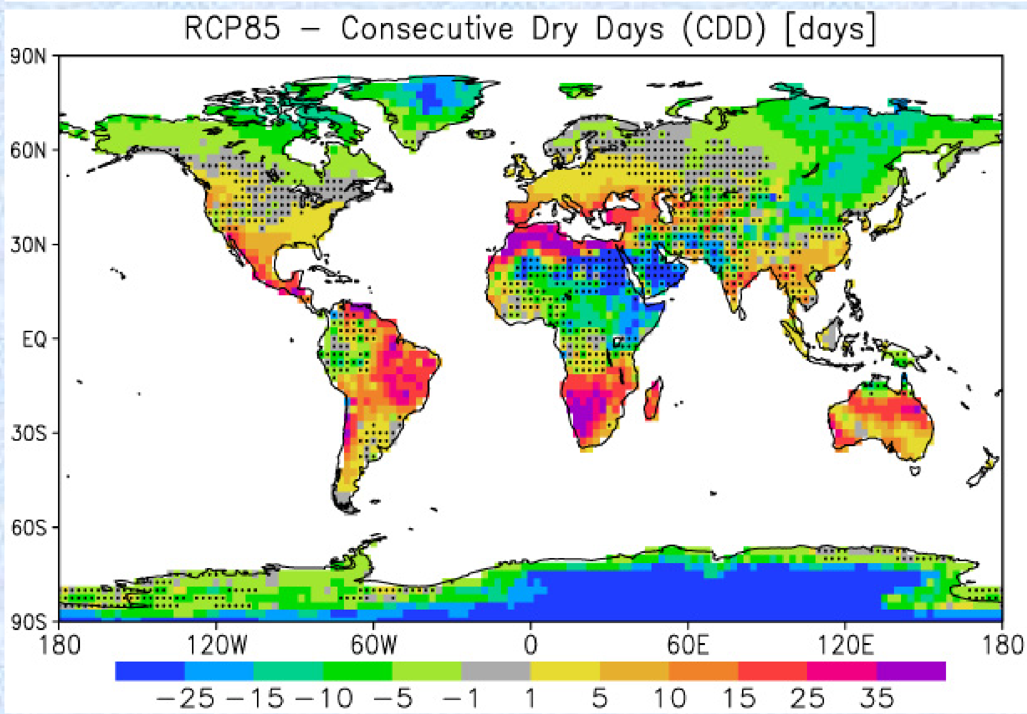
Tebaldi, C., K. Hayhoe, J. Arblaster, and G. Meehl (2006), Going to extremes. An intercomparison of model-simulated historical and future changes in extreme events, Clim. Chang., 79, 185–211..

## Changes in precip. extremes

- **Change in precipitation on "very wet days"**: total precip on days that would qualify as in the 95th percentile of the base period (percent);
- **Change in consecutive dry days** (# days with precip<1mm/day);
- **Percent change** for 2081-2100 relative to 1981-2000
- for median of **CMIP5** models with warming scenario RCP8.5
- [stippled = not significant at 5% level]

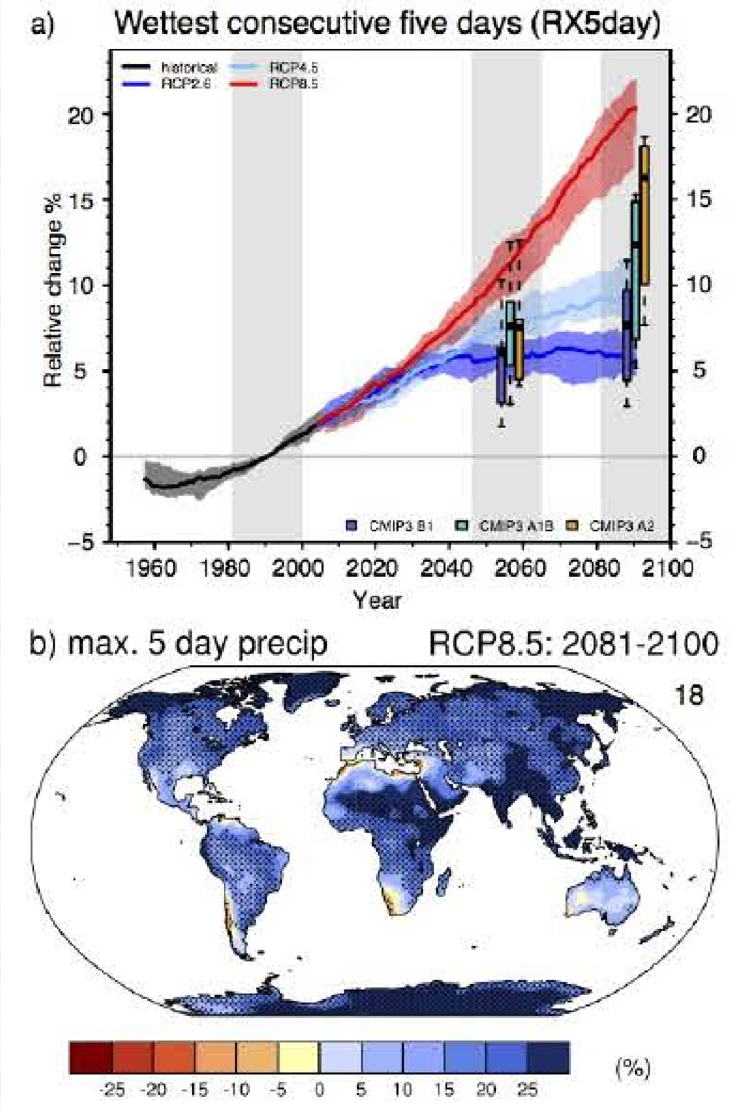
Sillmann et al. (2013, *J. Geophys. Res.*)



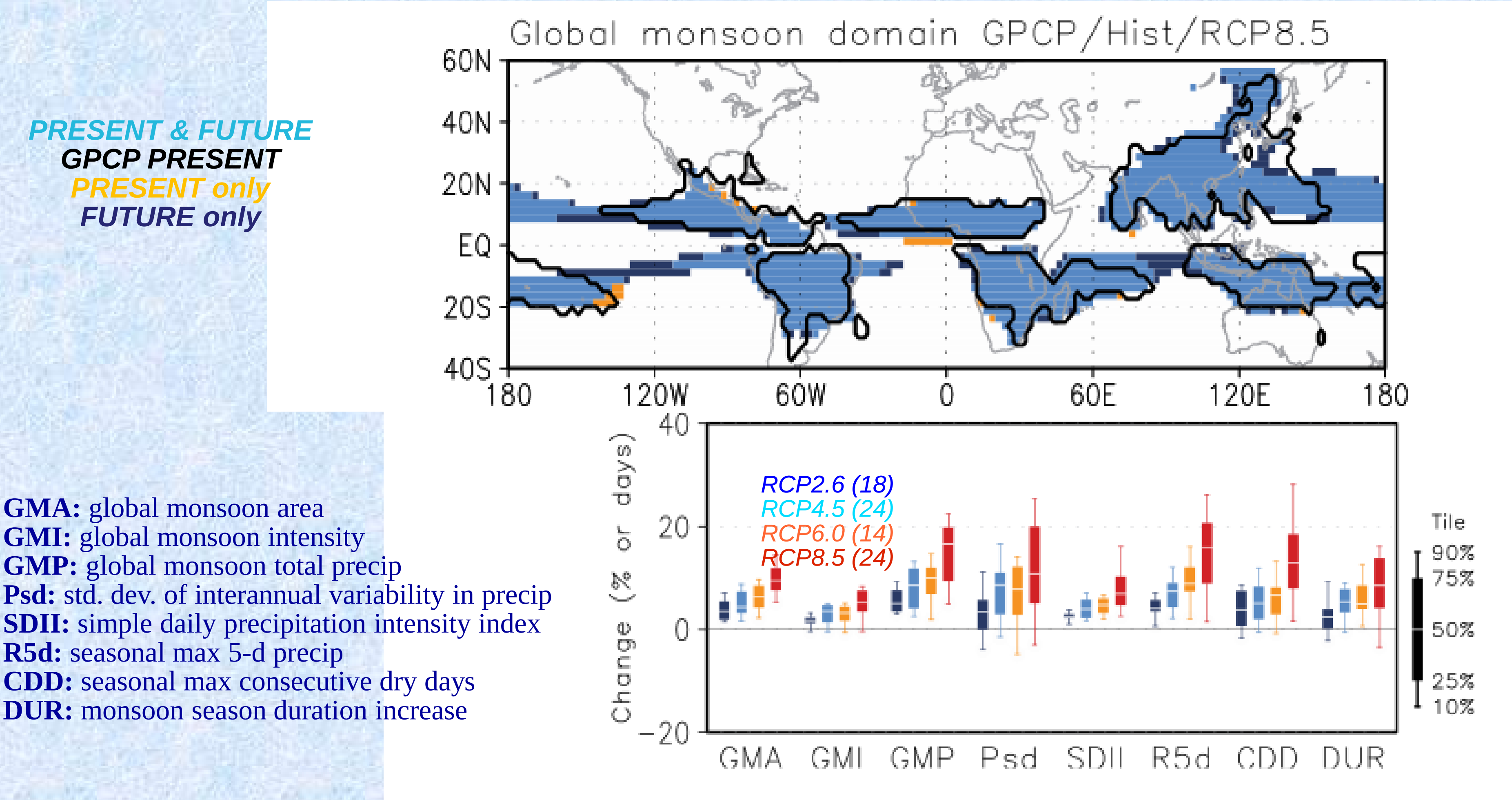
# *Changes in precipitation extremes IPCC WG1 Ch. 12.4.5.5*

- **Percent change in: Maximum 5-day precipitation percent change relative to base period for CMIP5 models (See previous slide for details), also consecutive dry days map (prev. slide).**
- **Less than crystal clear discussion of what was termed thermodynamic and dynamic contributions above**
- **"strong agreement across the models over the direction of change"**
- **"future episodes of more intense precipitation in the wet seasons for most of the land areas, especially in the NH and its higher latitudes, and the monsoon regions ... magnitude of the projected change is dependent on the model used"**
- **"These changes produce two seemingly contradictory effects: more intense downpours, … yet longer dry periods"**




**IPCC WG1 Fig. 12.26 straight from Sillmann et al. (2013, *J. Geophys. Res.*)**

# Aggregating over global monsoon area yields reasonable agreement various metrics of change, scaling with radiative forcing




**GMA:** global monsoon area
**GMI:** global monsoon intensity
**GMP:** global monsoon total precip
**Psd:** std. dev. of interannual variability in precip
**SDII:** simple daily precipitation intensity index
**R5d:** seasonal max 5-d precip
**CDD:** seasonal max consecutive dry days
**DUR:** monsoon season duration increase

Monsoon area Definition (Wang et al. 2011): where the local summer-minus-winter precipitation rate exceeds 2.5 mm/day and the local summer precipitation exceeds 55% of the annual total

Ch. 14 IPCC WG1 Figure 14.1

# Regional Precipitation uncertainty

- **At regional scale, for individual models amplitudes of projected change much larger than the multi-model ensemble mean, but less agreement, associated with dynamical feedbacks; examples from multirun RCP8.5**
- **Is there some fundamental issue like rough parameter dependence? small change in model yields large change?**
- **Combine parameter uncertainty studies to identify sensitive processes with independent constraints on those processes, e.g. fast process diagnostics**
- **(coordinate for current climate and global change)**
- **Examples of 2 global warming cases: ICTP* & CESM****

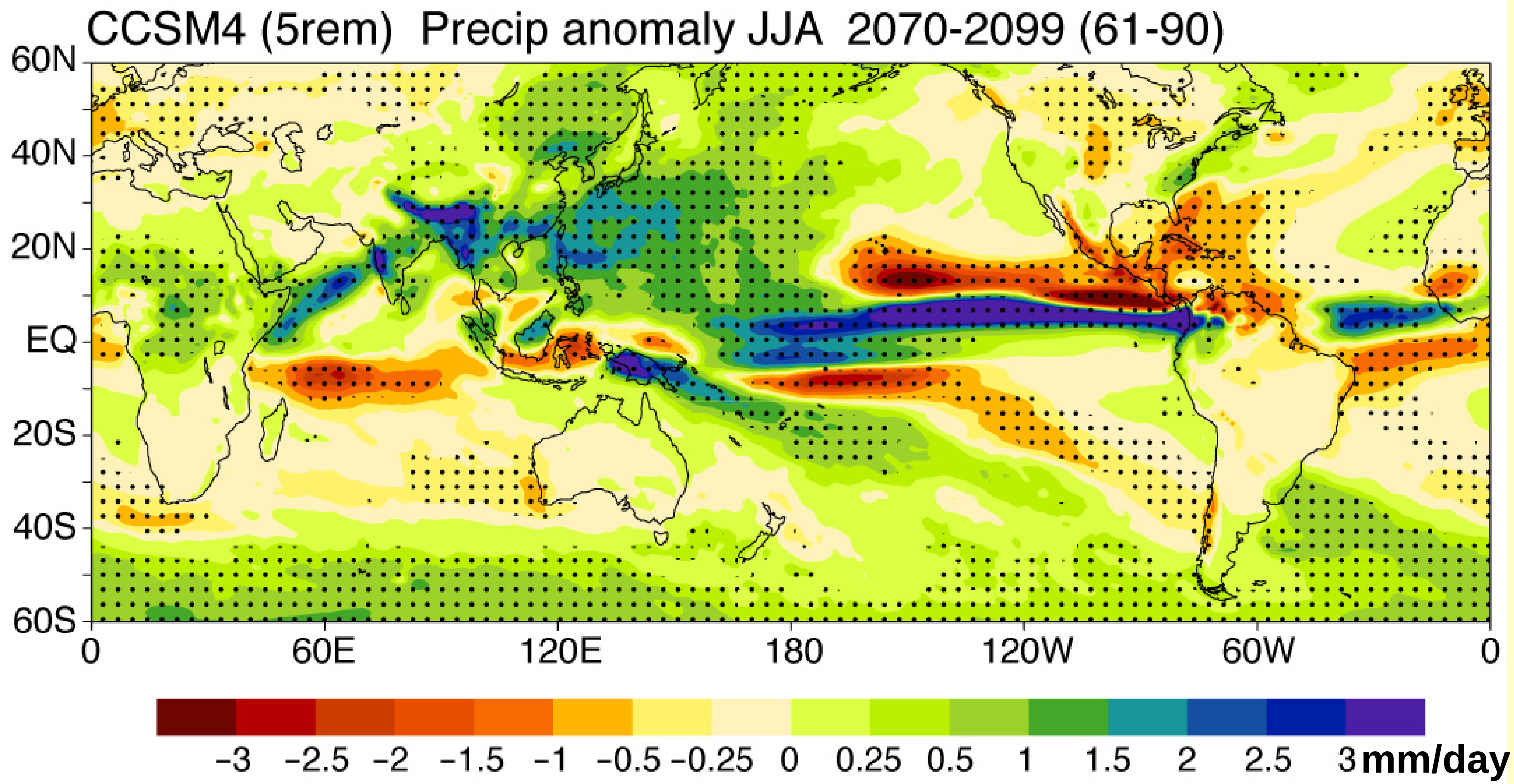
*International Centre for Theoretical Physics atmospheric general circulation model: ICTP AGCM; Molteni F., 2003; Bracco et al. 2004**).**

******National Center for Atmospheric Research Committee Earth System Model

# CMIP5 examples of individual model precip change

## Representative Concentration Pathway RCP* 8.5 CCSM4

**Precipitation change June-Aug., 2070-2099 avg minus 1961-90 avg.**




**Analysis: J. Meyerson**

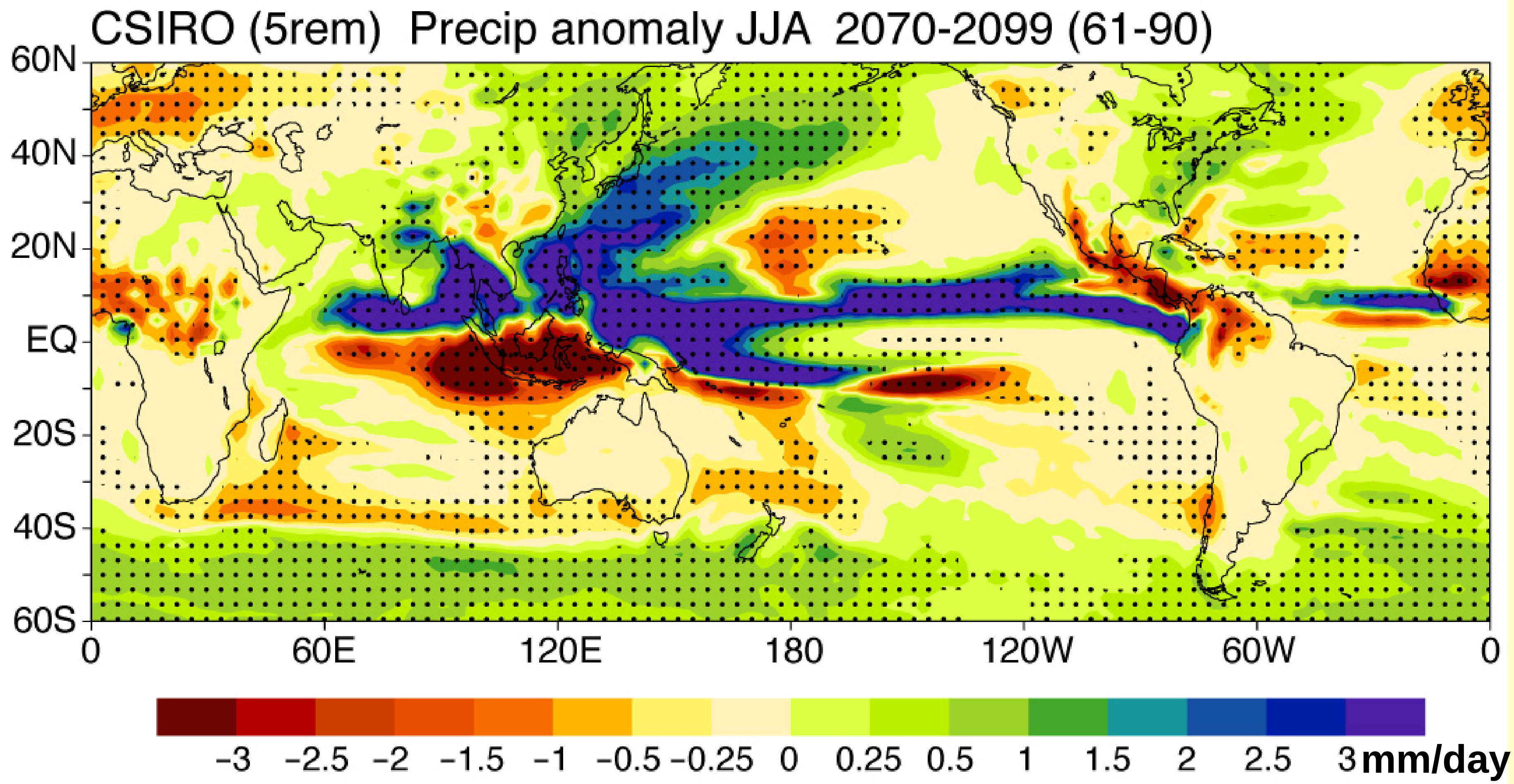
NCAR Community Climate System Model; *Representative Concentration Pathway

**CMIP5**

# CMIP5 examples of individual model precip change

## Representative Concentration Pathway RCP 8.5 CSIRO-Mk3.6

**Precipitation change June-Aug., 2070-2099 avg minus 1961-90 avg.**




**Analysis: J. Meyerson**

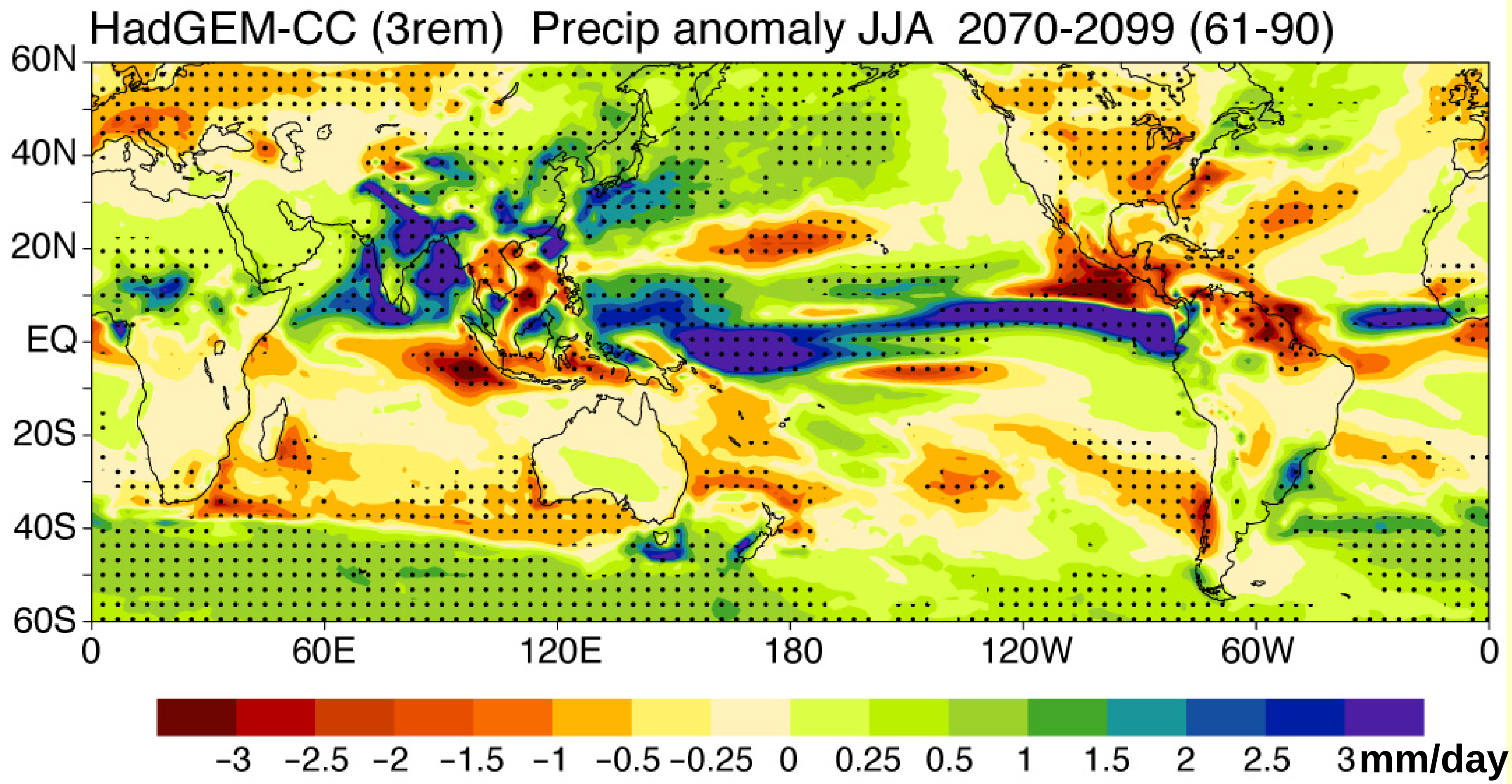
Commonwealth Scientific and Industrial Research Organisation Mark, V3.6.0

**CMIP5**

# CMIP5 examples of individual model precip change

## Representative Concentration Pathway RCP 8.5 HadGEM-CC

Precipitation change June-Aug., 2070-2099 avg minus 1961-90 avg.




**Analysis: J. Meyerson**

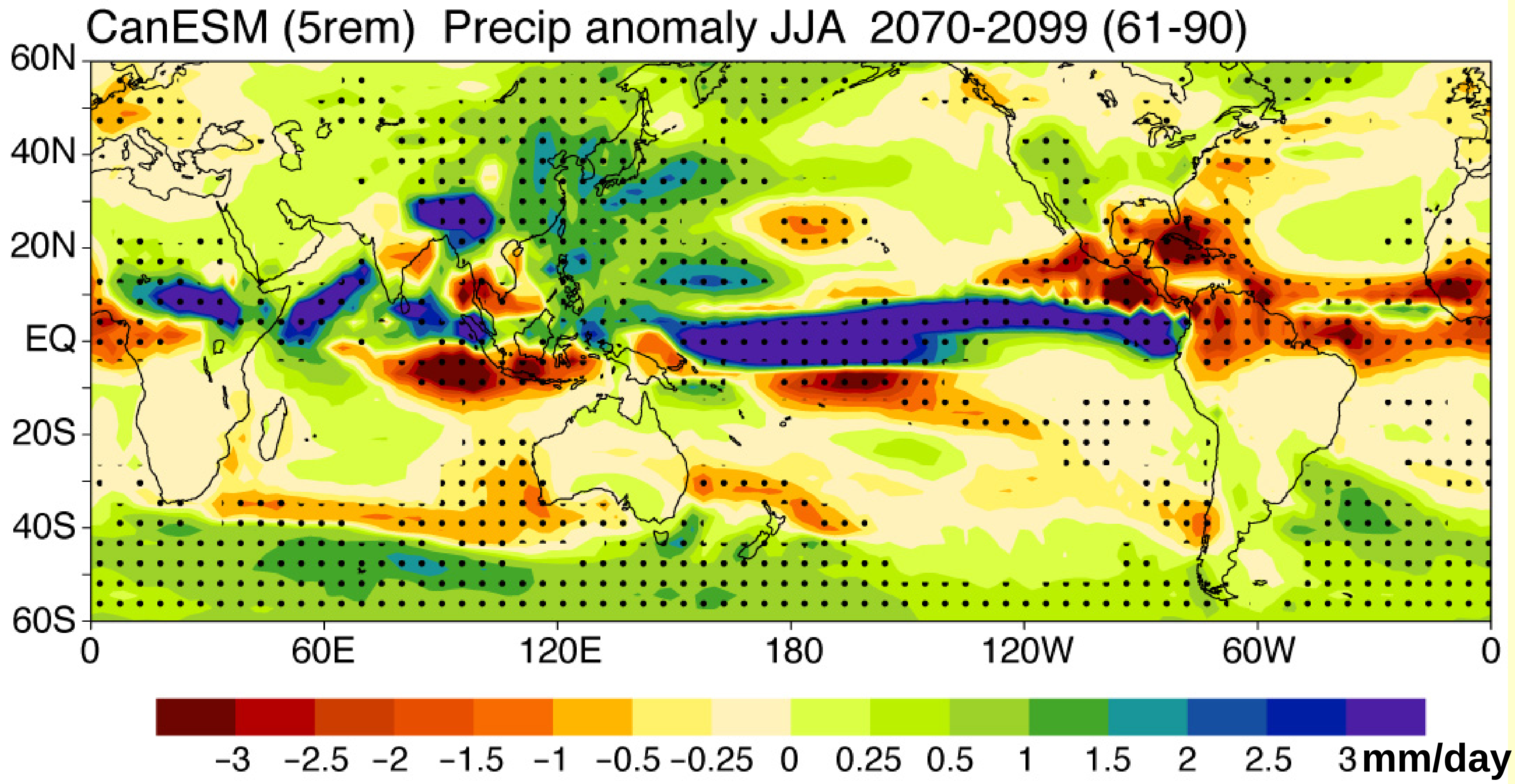
Hadley Centre Global Environment Model, V2–Carbon Cycle

**CMIP5**

# CMIP5 examples of individual model precip change

## Representative Concentration Pathway RCP 8.5 CanESM

**Precipitation change June-Aug., 2070-2099 avg minus 1961-90 avg.**




**Analysis: J. Meyerson**

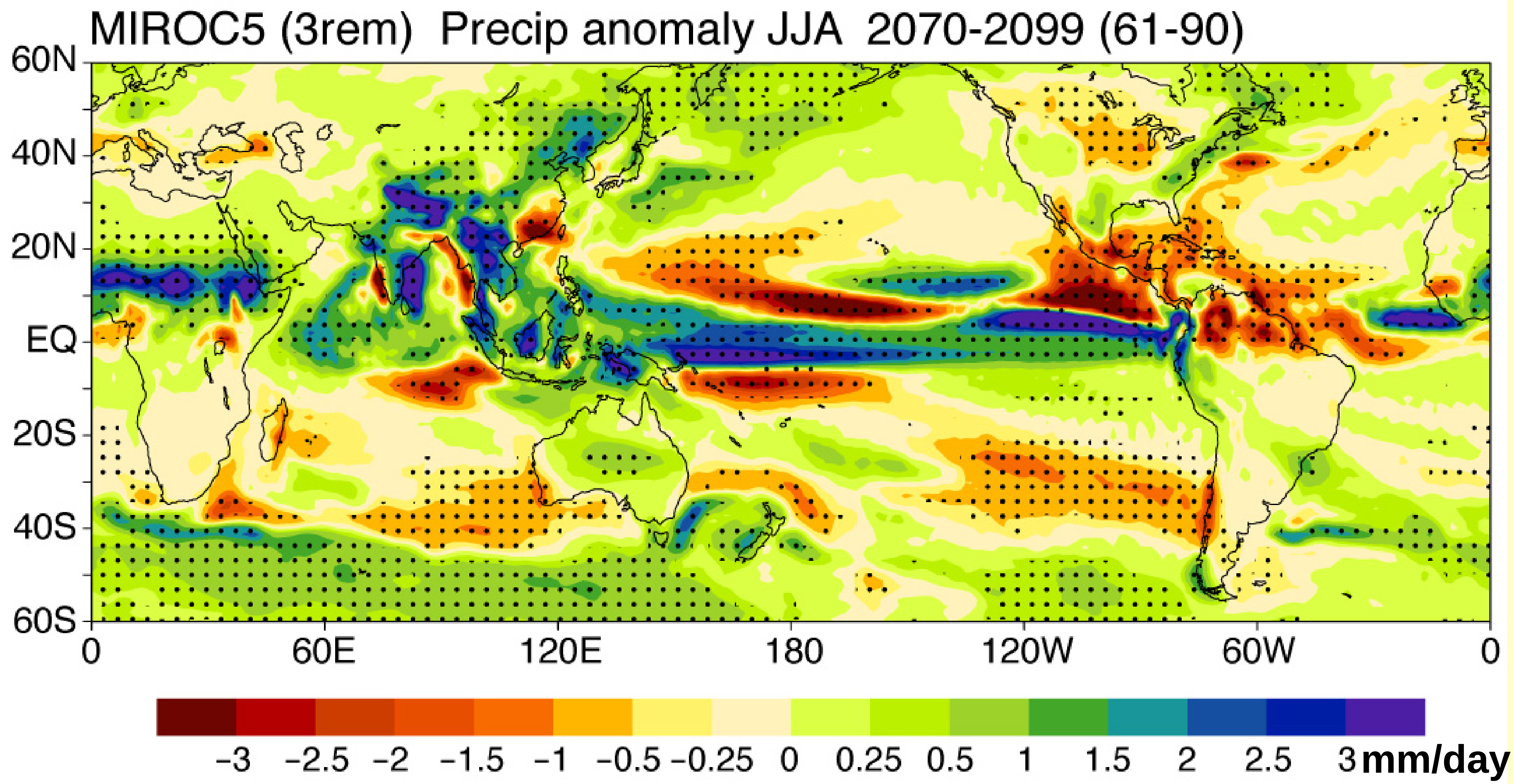
Second Generation Canadian Earth System Model

**CMIP5**

# CMIP5 examples of individual model precip change

## Representative Concentration Pathway RCP 8.5 MIROC5

**Precipitation change June-Aug., 2070-2099 avg minus 1961-90 avg.**




**Analysis: J. Meyerson**

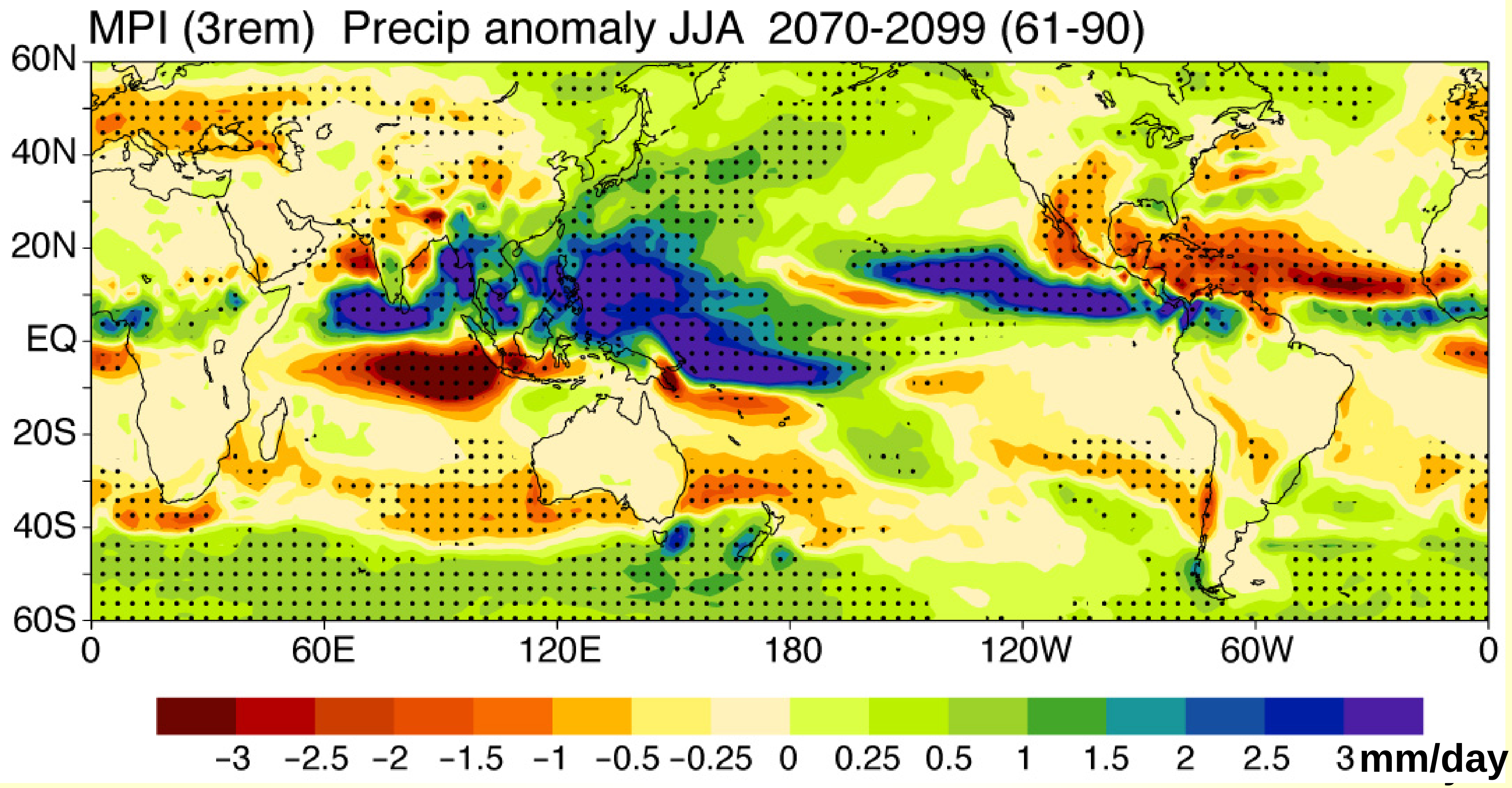
Model for Interdisciplinary Research on Climate, V5

**CMIP5**

# CMIP5 examples of individual model precip change

## Representative Concentration Pathway RCP 8.5 MPI-ESM-LR

### Precipitation change June-Aug., 2070-2099 avg minus 1961-90 avg.




**Analysis: J. Meyerson**

Max Planck Institute Earth System Model, low resolution

**CMIP5**

# Precipitation sensitivity cont'd

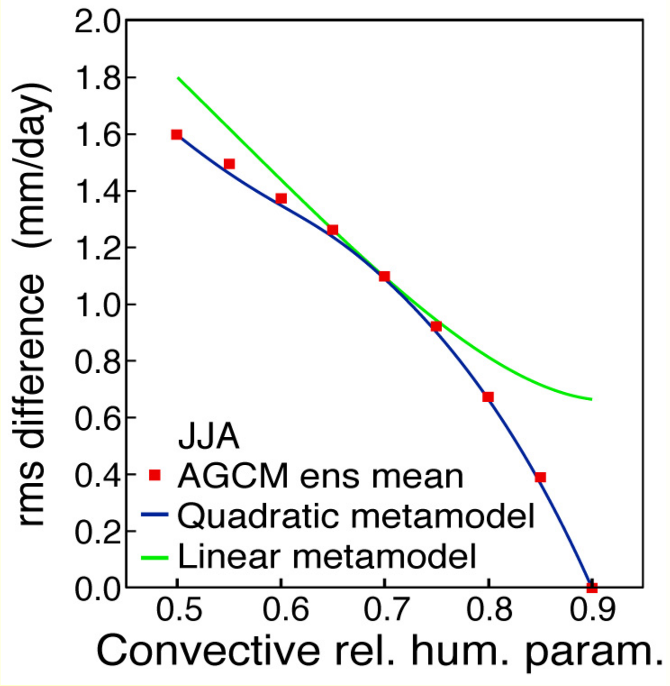
- **Interest in systematic parameter sensitivity (esp. global avg climate sensitivity) and optimization in climate models (Stainforth et al. 2005 *Nat.*, Jones et al. 2005 *Clim. Dyn.*, Knight et al. 2007 *PNAS*, Kunz et al. 2007 *Clim. Dyn.*, Jackson et al. 2008 *J Clim.*, Sanderson et al. 2008, Sanderson 2011 *J Clim*; Rougier et al. 2009 *J. Clim.*, Covey et al. 2012, Shiogama et al. 2012, *Clim. Dyn*. , …)**
- **# parameters $N$ can easily be $>10$**
- **Brute force sampling at density $s$ gives order $s^N$ problem, but e.g. $\sim N^2$ depending on nature of parameter dependence.**

**If smooth: degree of nonlinearity of climate model response as a function of parameter matters to strategy for sampling at identifying important parameter ranges to constrain**

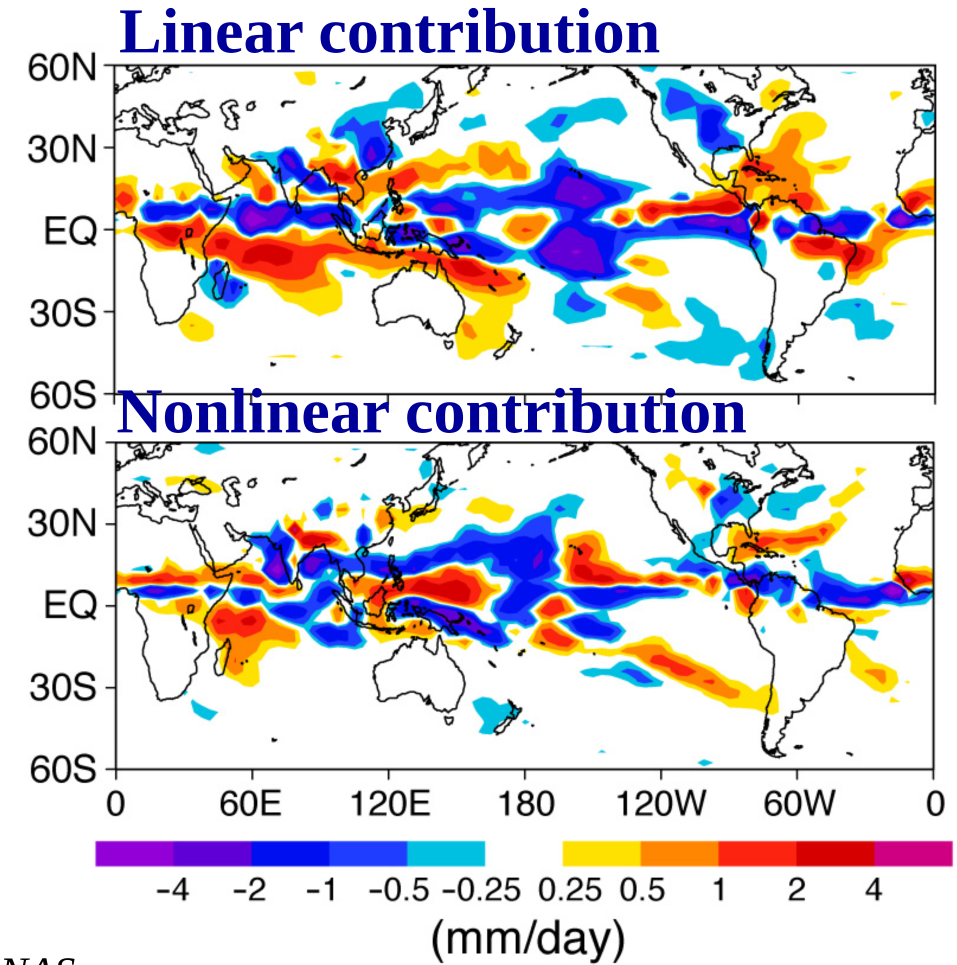
# Global warming precipitation change parameter sensitivity

ICTP AGCM coupled to mixed-layer ocean: $2xCO_2$ minus pre-industrial. JJA precip (as a departure from the annual mean) for Conv. rel. hum. param

RMS difference from refc case



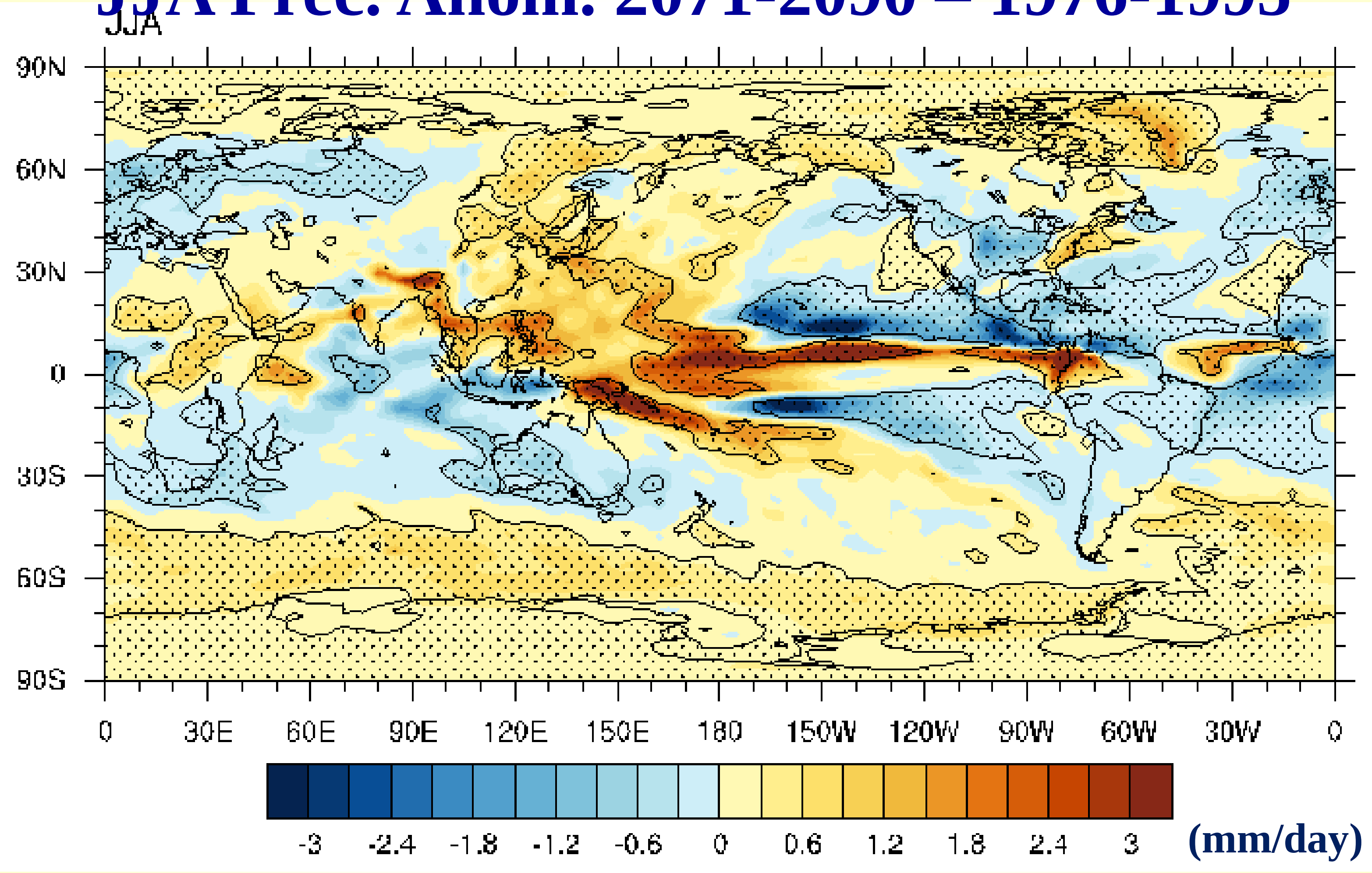

Quadratic metamodel linear and nonlinear contributions (dimensionalized for high rel to mid param values)




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

# CESM1 Precip change under RCP8.5 global warming scenario (standard param values)

## JJA Prec. Anom. 2071-2090 – 1976-1995



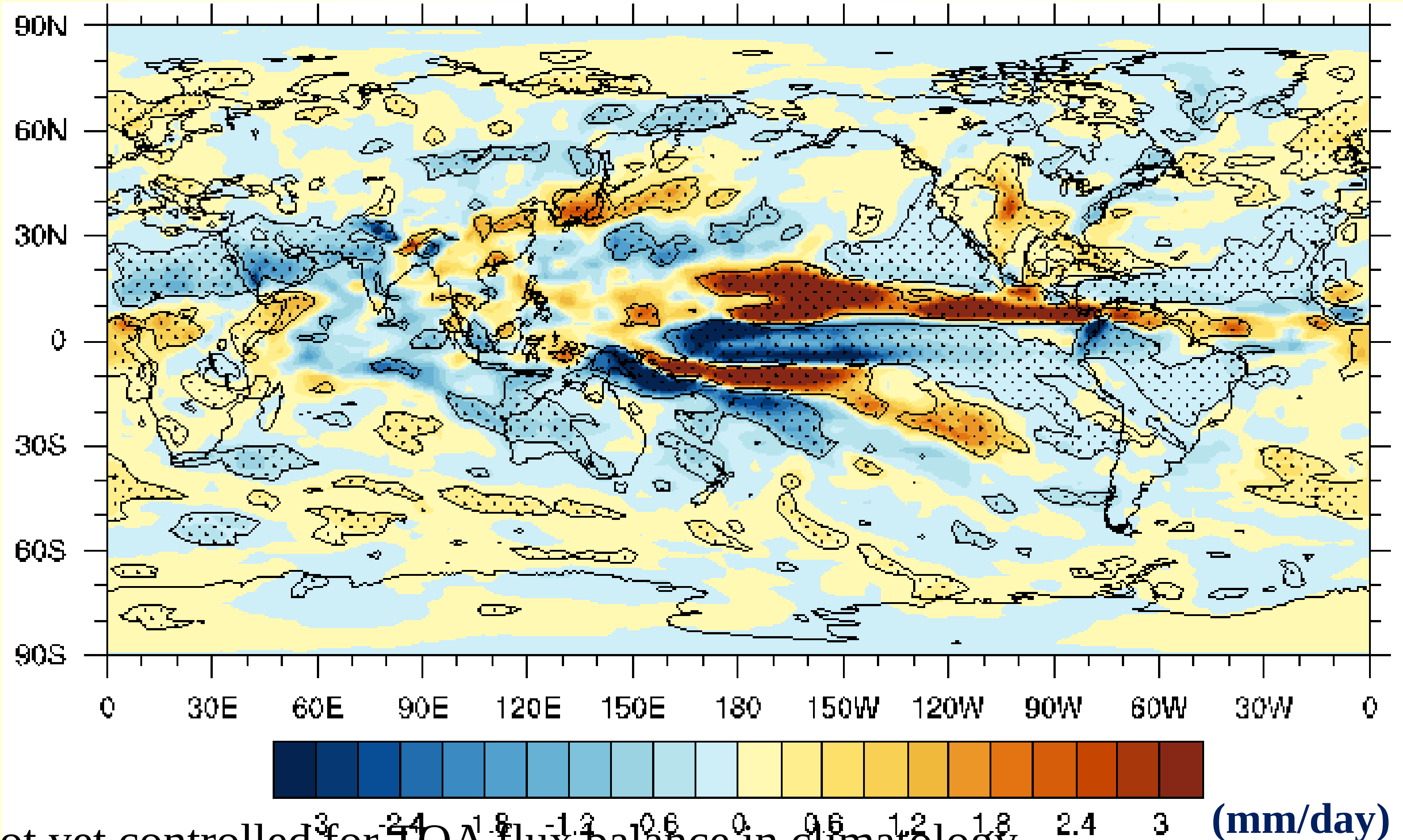

Runs & analysis: D. Bernstein

Stippled for T-test at 5% level

# CESM1 param. sensitivity of RCP8.5 prec. change

## JJA Prec. Anom. 2071-2090 – 1976-1995

## <u>downdraft fraction</u> across case 0.75 minus case 0




Note: not yet controlled for TOA flux balance in climatology
(eg., Shiogama et al. 2012, Clim. Dyn.)@@
but glob. av. temp. diffc small

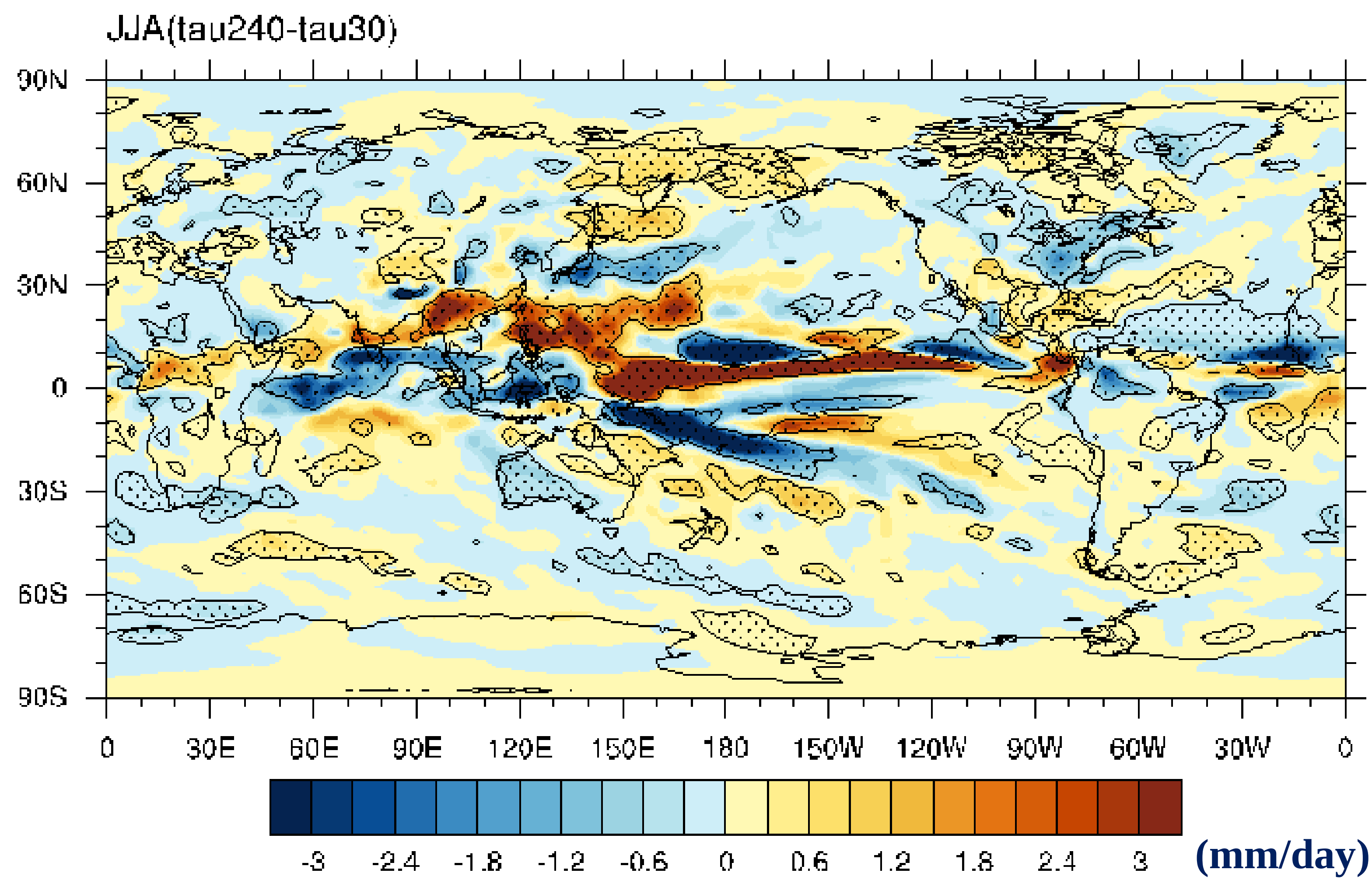
Runs & analysis: D. Bernstein
Stippled for T-test at 5% level

**Downdraft fraction α**

# CESM1 param. sensitivity of RCP8.5 prec. change

## JJA Prec. Anom. 2071-2090 – 1976-1995

**deep convective adjustment time across case 240 min minus case 30 min**




Runs & analysis: D. Bernstein

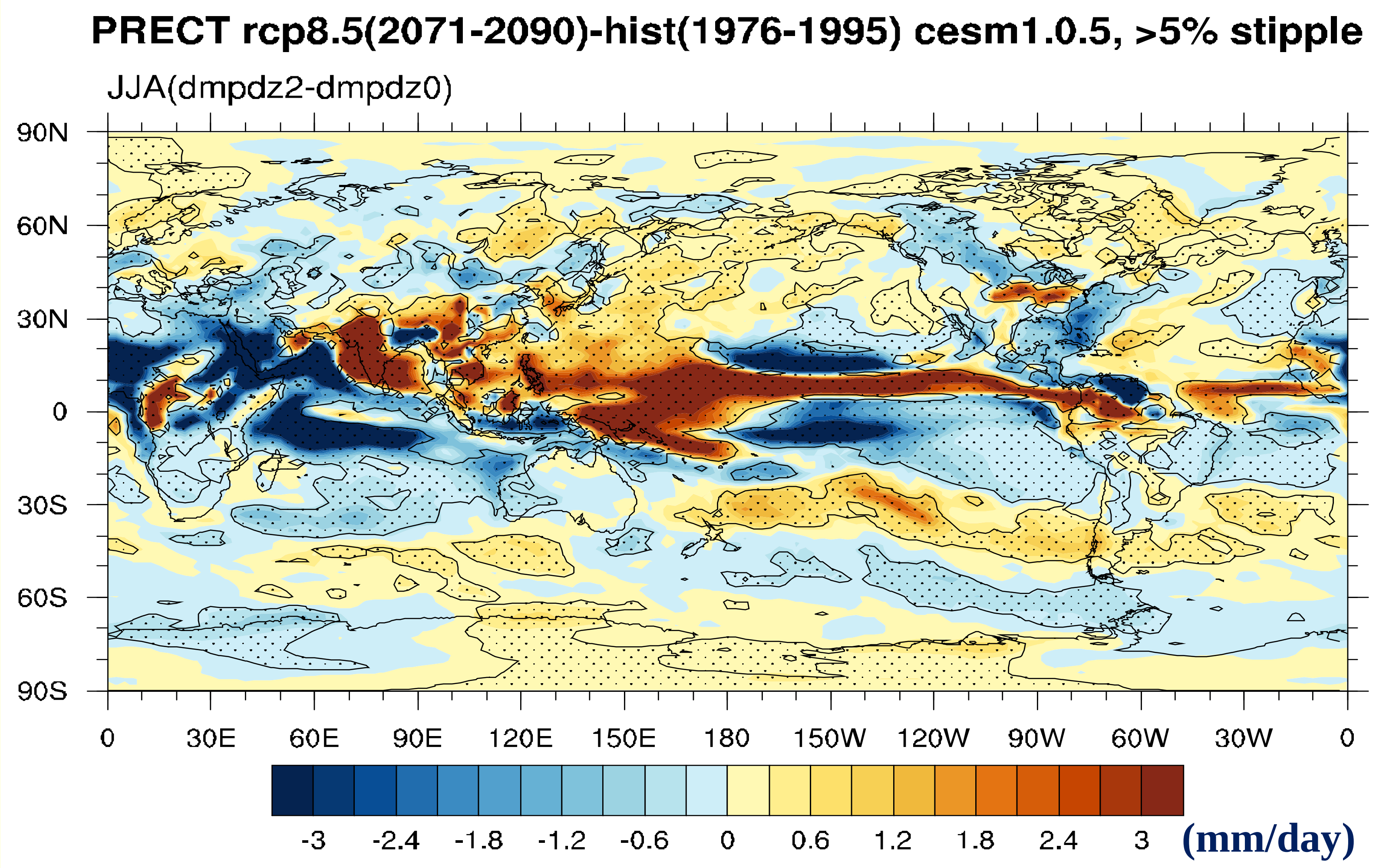
Stippled for T-test at 5% level

**Deep convection adjustment time τ**

# CESM1 param. sensitivity of RCP8.5 prec. change

## JJA Prec. Anom. 2071-2090 – 1976-1995

**entrainment across case at 2km -1 minus case 0**



(mm/day)

Runs & analysis: D. Bernstein

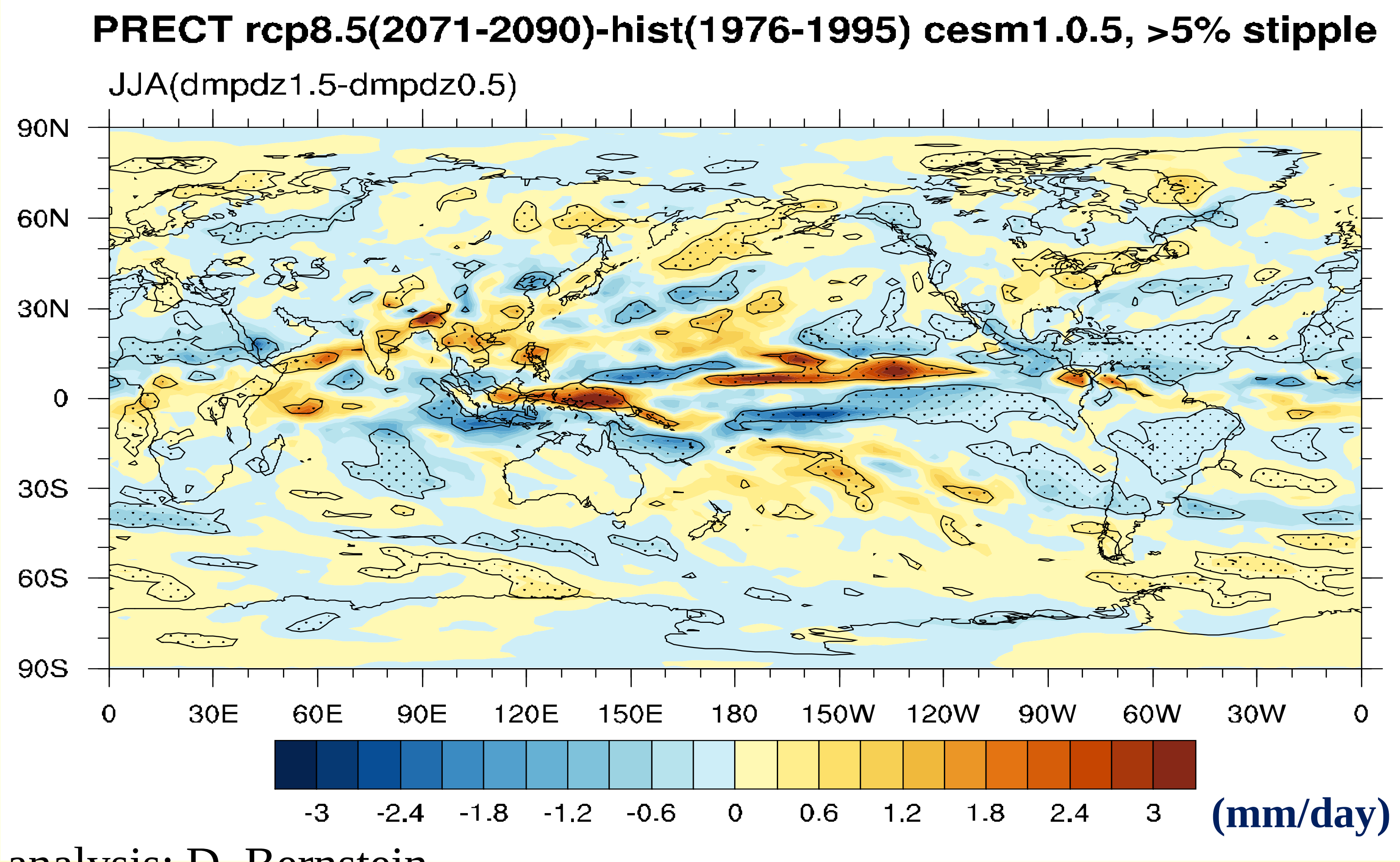
Stippled for T-test at 5% level

**Entrainment parameter dmpdz**

# CESM1 param. sensitivity of RCP8.5 prec. change

## JJA Prec. Anom. 2071-2090 – 1976-1995

**entrainment for narrowed range: case at 1.5km$^{-1}$ minus case 0.5**




Runs & analysis: D. Bernstein

Stippled for T-test at 5% level

**Entrainment parameter dmpdz**

# Approaches to dealing with regional Precip uncertainty

- ✓ multi-model ensemble average; average statistics across regions of substantial size—OK but underestimates amplitude, and impacts depend on local changes; danger of misinterpretation, e.g. not all subtropics drier
- ✓ improve statements of variation from wet-get-wetter/warm-get- wetter/rich-get-richer
- ✓ include hydrological effects affected by surface temperature e.g. evapotranspiration, snowmelt
- ✓ regional modeling e.g. where topographic effects important–tendency to inherit errors from larger-scale
- ✓ statements of physical processes involved in uncertainty—at least gives decision-makers a coherent scenario
- ✓ wait for detection — high internal variability implies multi-decadal delay at regional scale

## Hydrological cycle sensitivity for regional projections

- Likely not a fundamental issue with rough parameter dependence. Despite high nonlinearity along trajectories internal variability acts as stochastic forcing ⇒ smooth enough for key climate stats
- but exceptions can occur ⇒ need to check
- strong sensitivity and commonly nonlinear for many observables; smoothness ⇒ tools to quantify, esp. if quadratic param. depc (as a fn of space) adequate

➢ Identify nonlinear & sensitive ranges coordinated between present and climate change projections

➢ seek indep. constraints from obs., esp. at timescale of parameterized physics; Fast-process diagnostics

➢ e.g., low entrainment range not consistent with obs. deep convective onset; elimination in CESM1 param. range ⇒ reduction in precip change uncertainty est.