Future Changes in the Asian Monsoon Rainfall under a Warmer Climate

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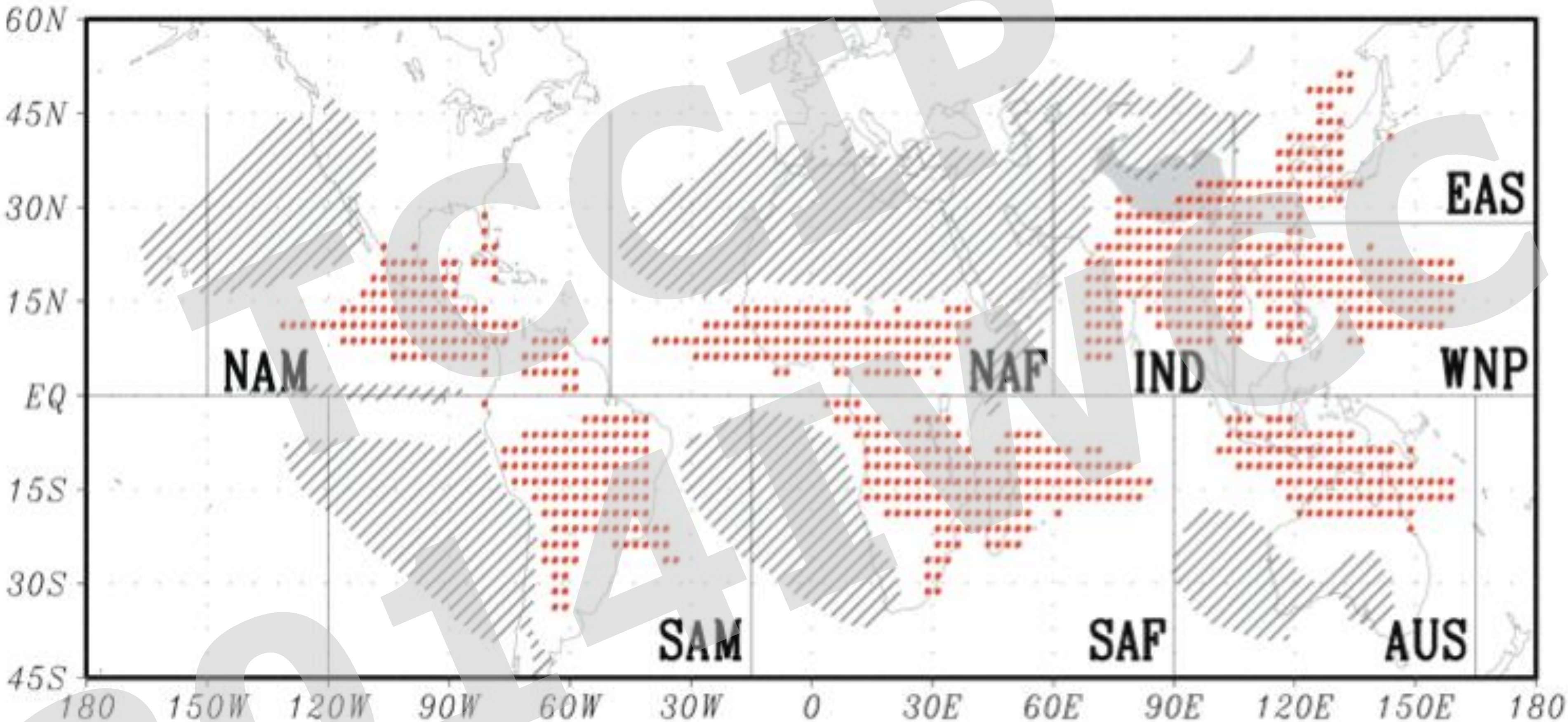
Introduction

Monsoons are responsible for the majority of summer rainfall within the tropics, where billions of people depend on the monsoon rainfall. Thus, reliable future projection for monsoon rainfall, especially on a regional-scale, has been strongly demanded.

- Provides a latest view of **global** and **regional monsoonal rainfall** changes as projected by **CMIP5 multi-models**.
- Investigates not only **mean precipitation** but also some **precipitation extreme indices.**
- Attributes future changes by **thermodynamic** effect versus **dynamic** effect.

Global monsoon precipitation domain



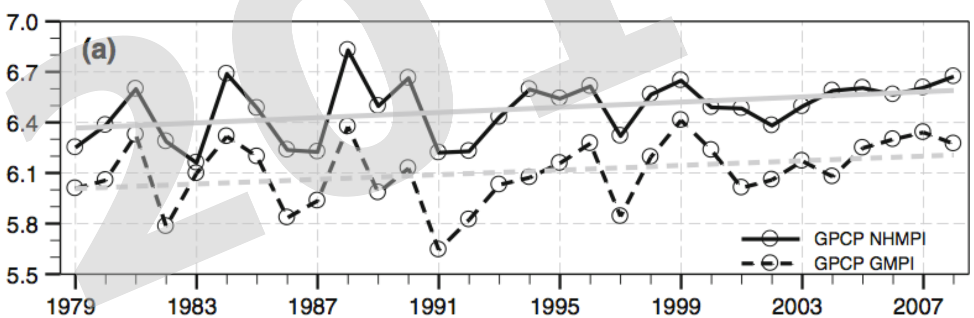
The approximate global monsoon precipitation domain is here defined where the local summer-minus-winter precipitation rate exceeds 2.5 mm/day and the local summer precipitation exceeds 55 % of the annual total (in red). Summer denotes May through September for the NH and November through March for the SH. The dry regions, where the local summer precipitation is less than 1 mm/day are hatched, and the 3000m height contour surrounding Tibetan Plateau is shaded. The merged Global Precipitation Climatology Project/Climate Prediction Center Merged Analysis of Precipitation precipitation data were used. [from **WCRP Monsoon Fact Sheet** prepared by CLIVAR AAMP]

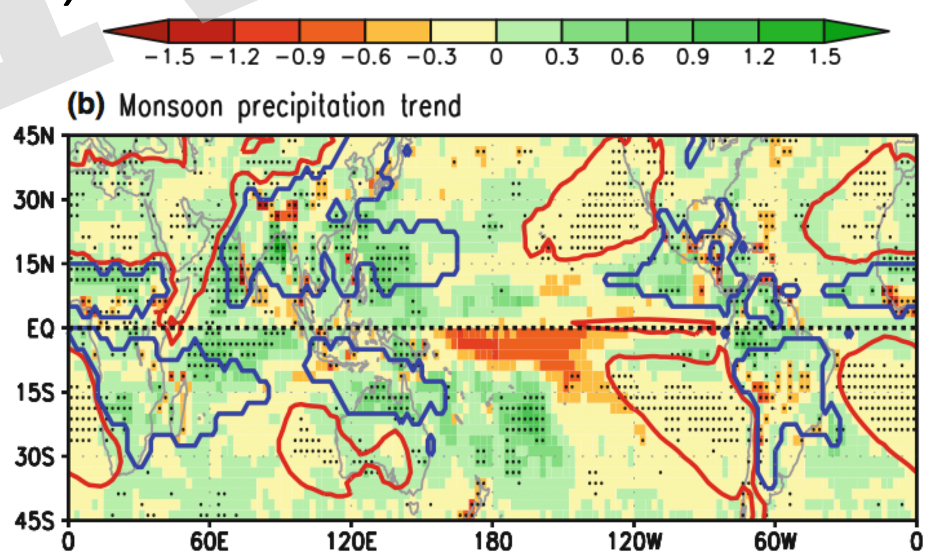
Past changes of the global monsoon

- Historical records
  - **Decreasing** trend in the global land monsoon precipitation over **the last half of the 20th century**.

    Wand and Ding (2006); Zhou et al. (2008)
  - **Increasing** trend in the combined (oceanic and land) monsoon precipitation for **recent decades** (1979-2008)

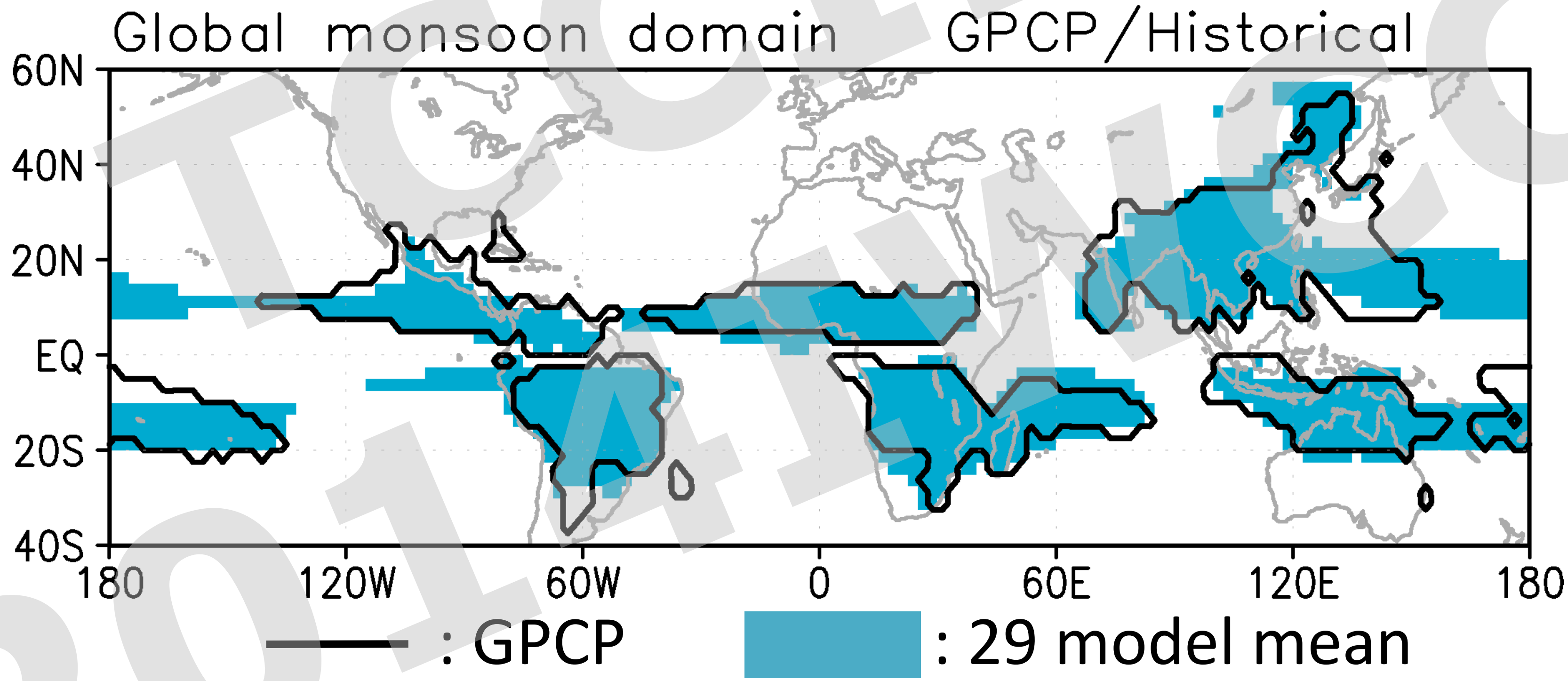
    Wang et al. (2012)





Global monsoon domain: CMIP5 present

- Model mean generally reproduces the observed domain
- Biases over eastern Asia and the tropical Pacific

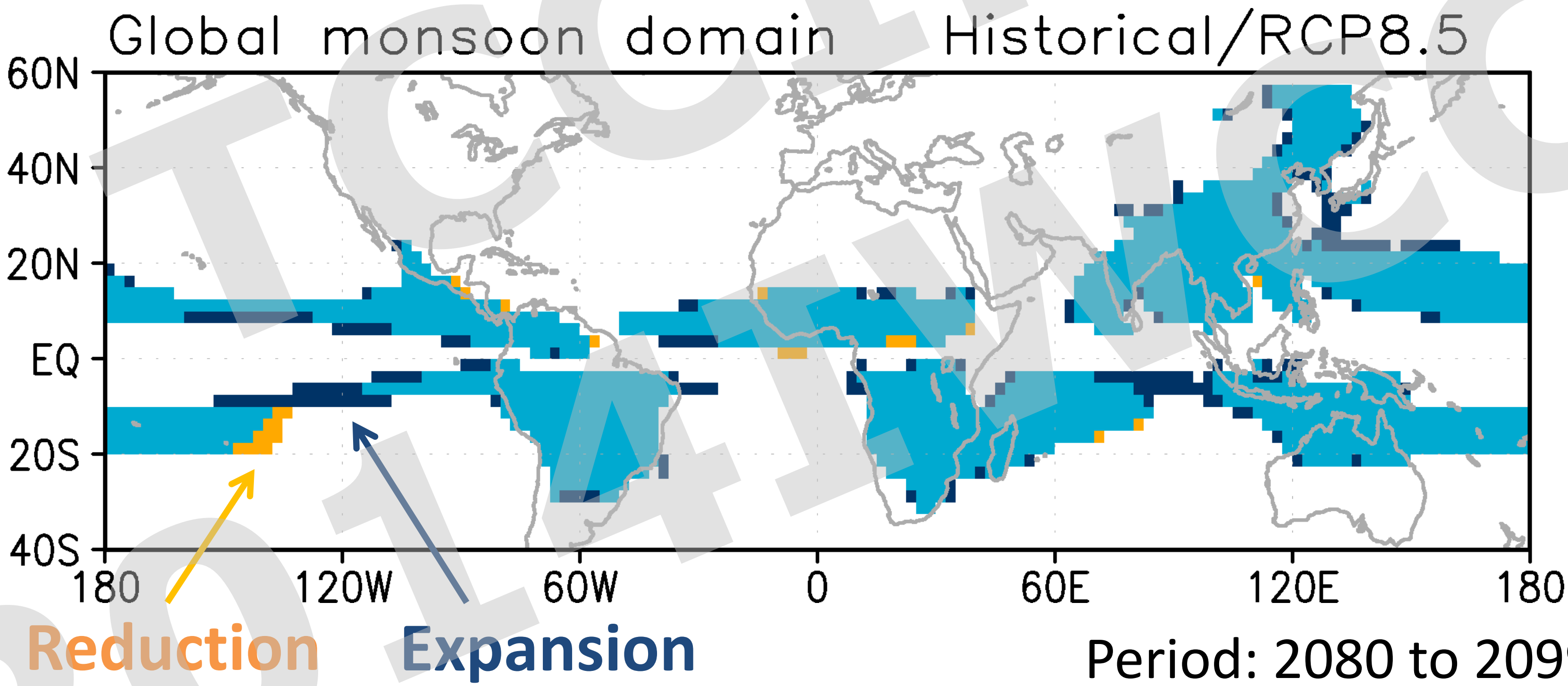


Monsoon domain: Annual range >= 2.5 mm day^{-1}

Annual range: Difference between MJJAS and NDJFM

Global monsoon domain: CMIP5 future

- Expansion over the central to eastern tropical Pacific, the southern Indian Ocean, and eastern Asia.



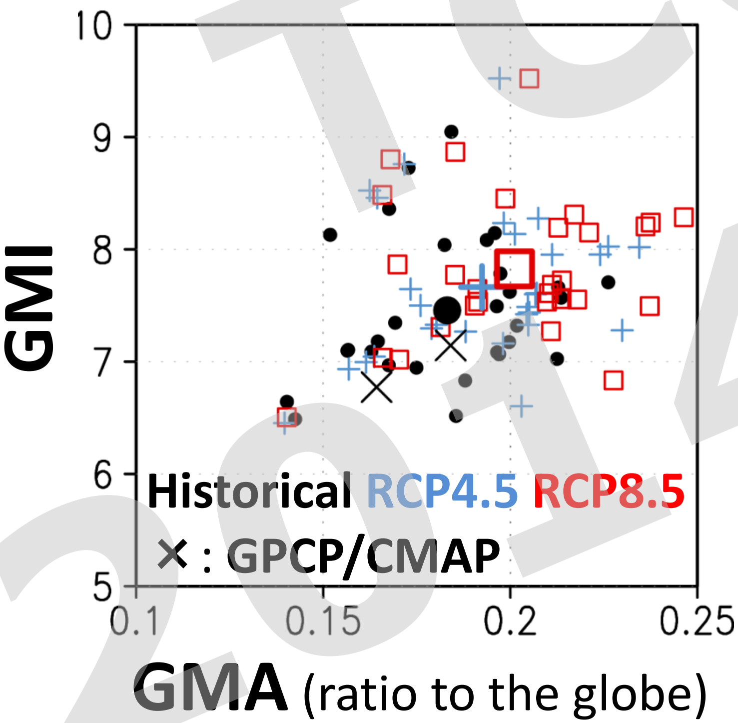
Period: 2080 to 2099

Monsoon domain: Annual range >= 2.5 mm day^{-1}

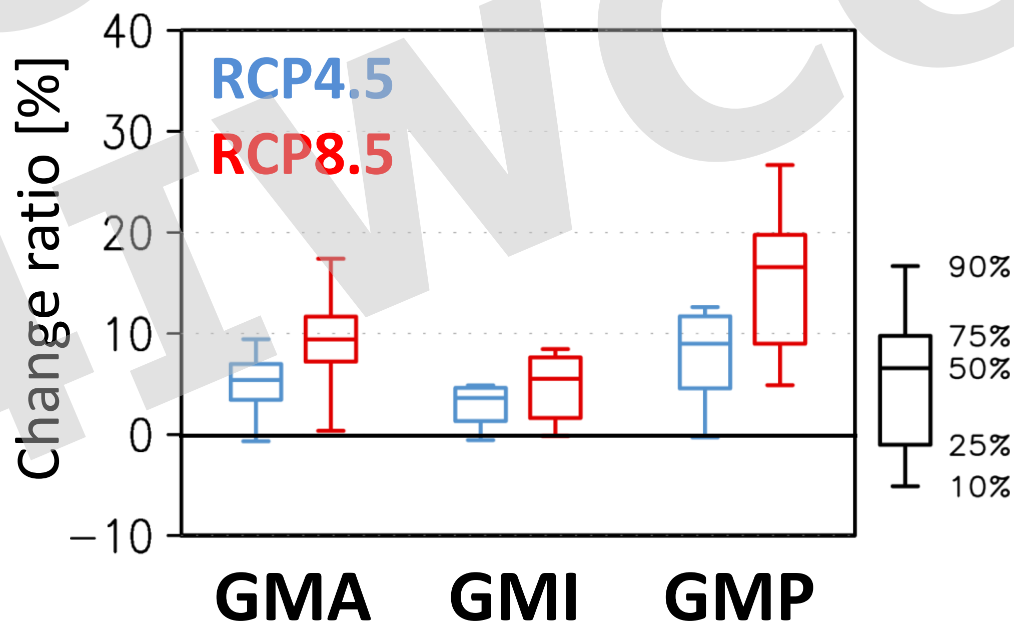
Annual range: Difference between MJJAS and NDJFM

Global monsoon precipitation

- Multi-model ensemble matches the observations
- Monsoon-related precipitation will remarkably increase



Large marks: Mean of all models



GMA: Global monsoon (GM) area

GMP: GM summer total precipitation

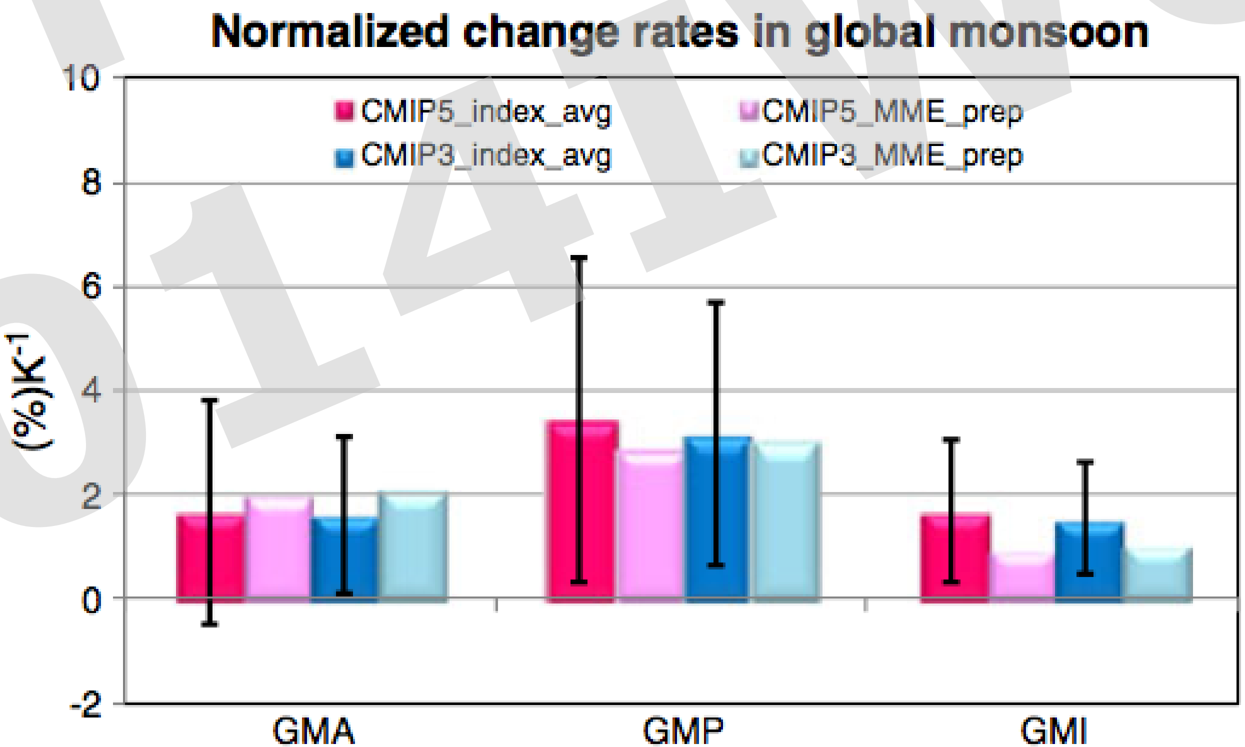
GMI: GM intensity (= GMP/GMA)

Global monsoon precipitation: CMIP3/5

- Future projections
  - **Increase** of global monsoon area and precipitation intensity.

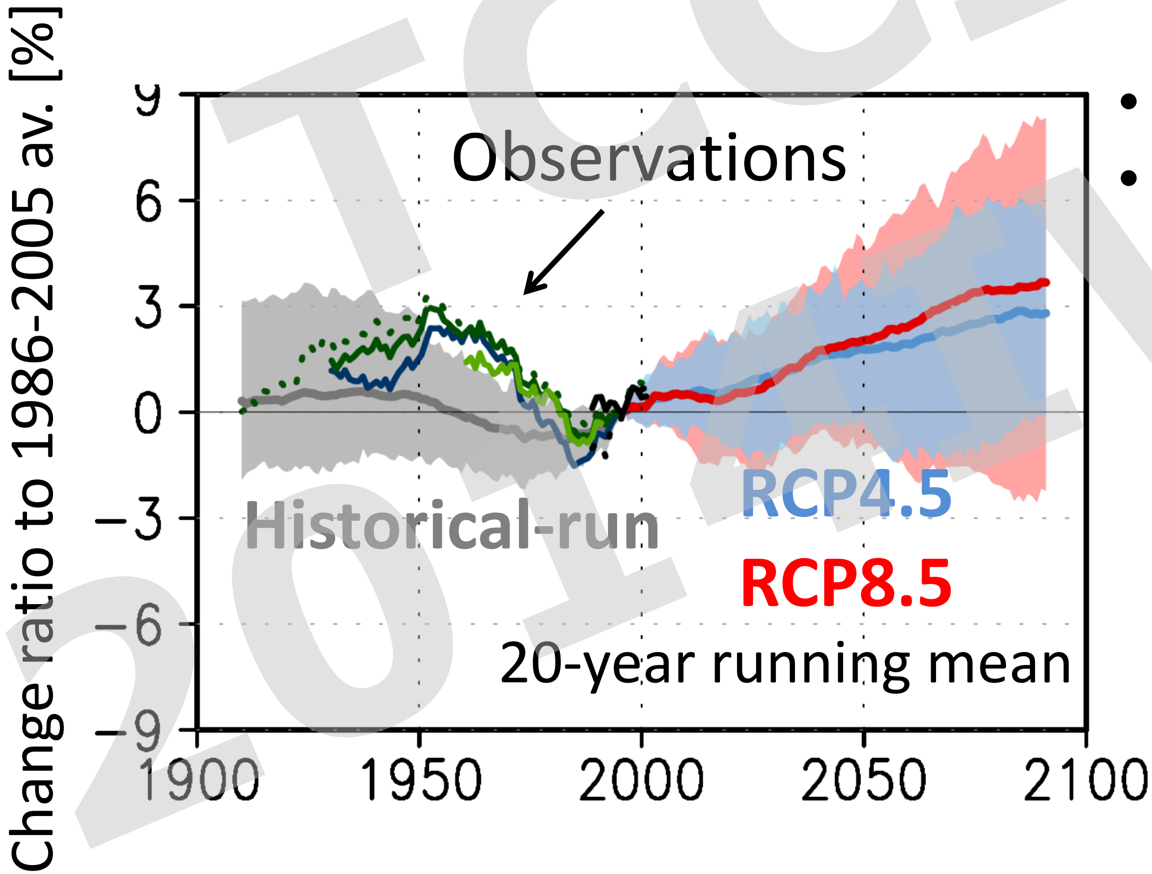
CMIP3: *Hsu et al. (2012)*

CMIP5: *Lee and Wang (2012), Hsu et al. (2013), Kitoh et al. (2013)*



Time series of global land monsoon

- Decrease from 1950s to 1980s, and increase in the 21st C
- The simulated trend is consistent with the observations, although magnitude is underestimated



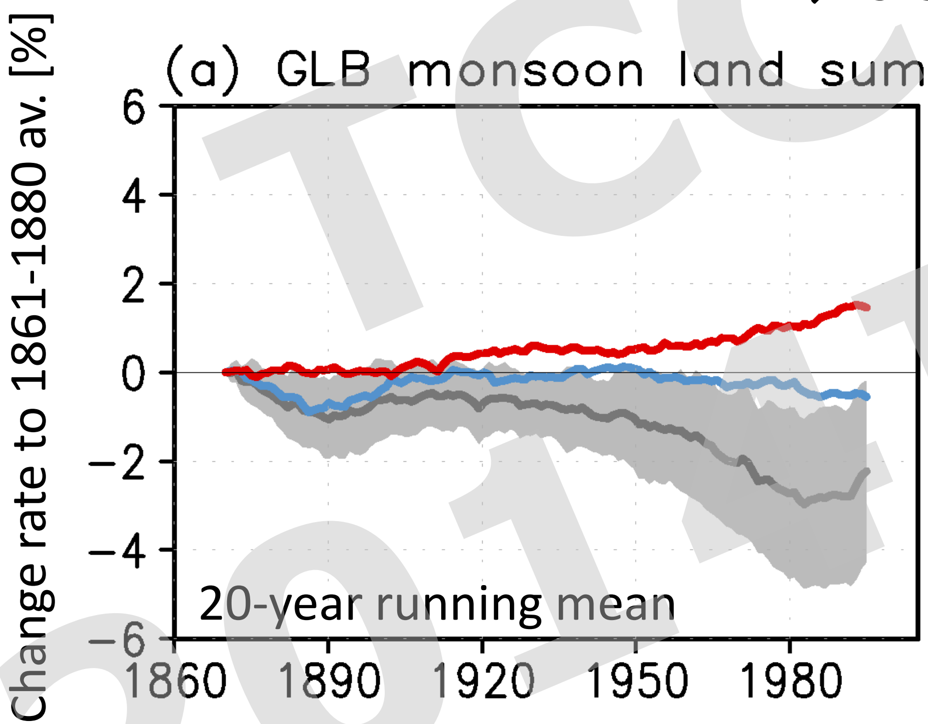
- Thick line : 29 model mean
- Shading : 29 model spread (10th-90th percentile)

➢ **Observational data**
- CRU-TS3.1
- GPCC-v6
- GPCC-VASClimO
- CMAP
- GPCP

Attribution of the decrease in the 20th C

Neither experiments with **GHG forcing** nor **natural forcing** reproduce the decreased trend simulated by the **all forcing**

→ **aerosol effect is essential**



- Thick line: 14 model mean
- Shading: Inter-model spread (S.D.)

HistoricalGHG: GHG forcing only

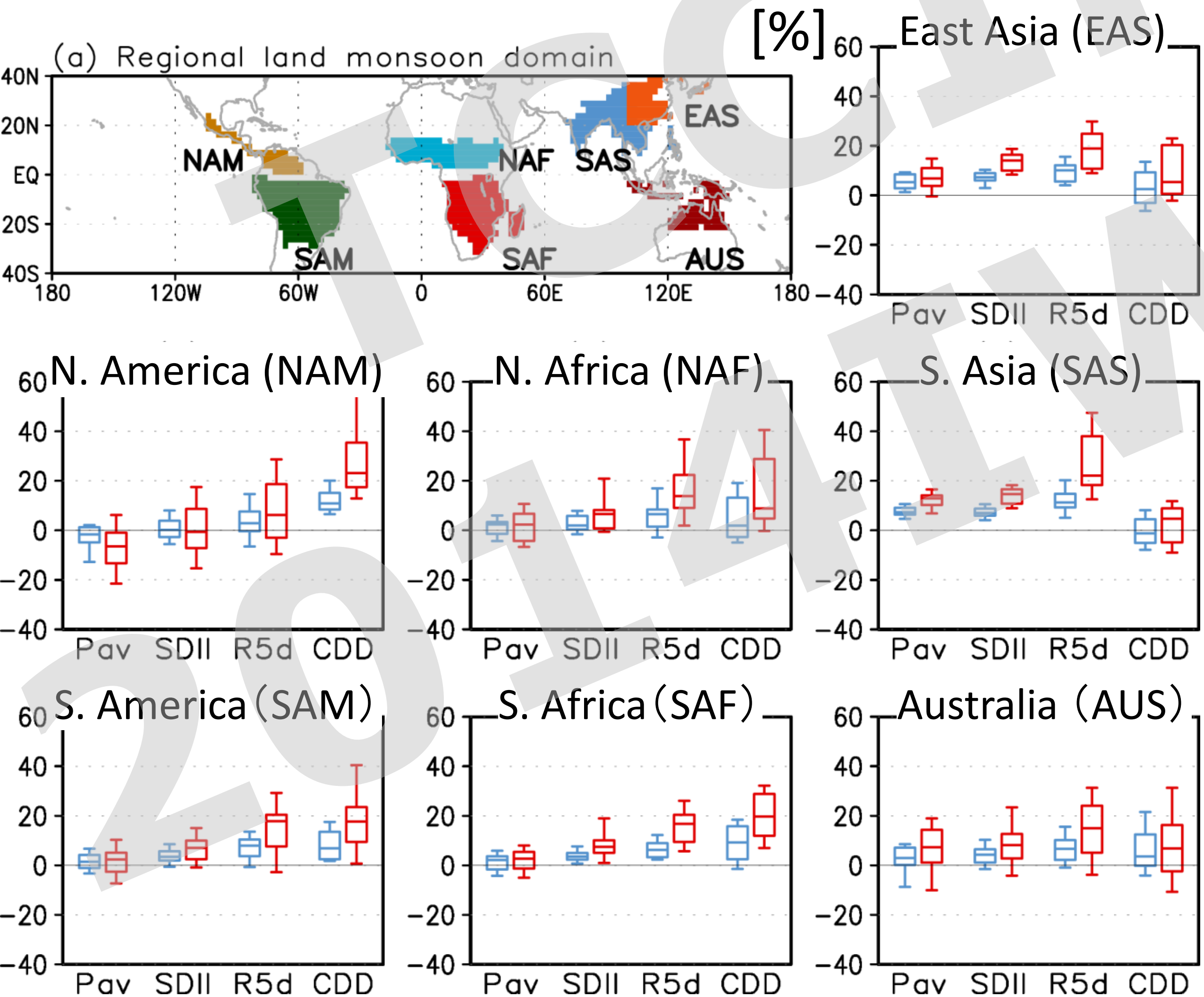
HistoricalNat: Natural forcing only

Historical: All forcing

14model = "CNRM-CM5 CSIRO-Mk3-6-0 CanESM2 GFDL-CM3 GFDL-ESM2M GISS-E2-H GISS-E2-R HadGEM2-ES IPSL-CM5A-LR MIROC-ESM-CHEM MIROC-ESM MRI-CGCM3 NorESM1-M bcc-csm1-1"

Future change of the precipitation indices

- Largest increases over the Asian monsoon domains
- Large increases in extremes over America and Africa



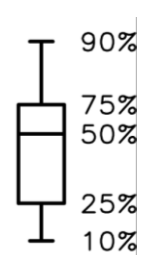
RCP4.5 **RCP8.5**

Pav: Average precipitation

SDII: Precipitation intensity

R5d: Seasonal maximum of 5-day precipitation

CDD: Seasonal maximum of consecutive dry days



Future change of the precipitation indices

Change rate of indices in the 50th percentile

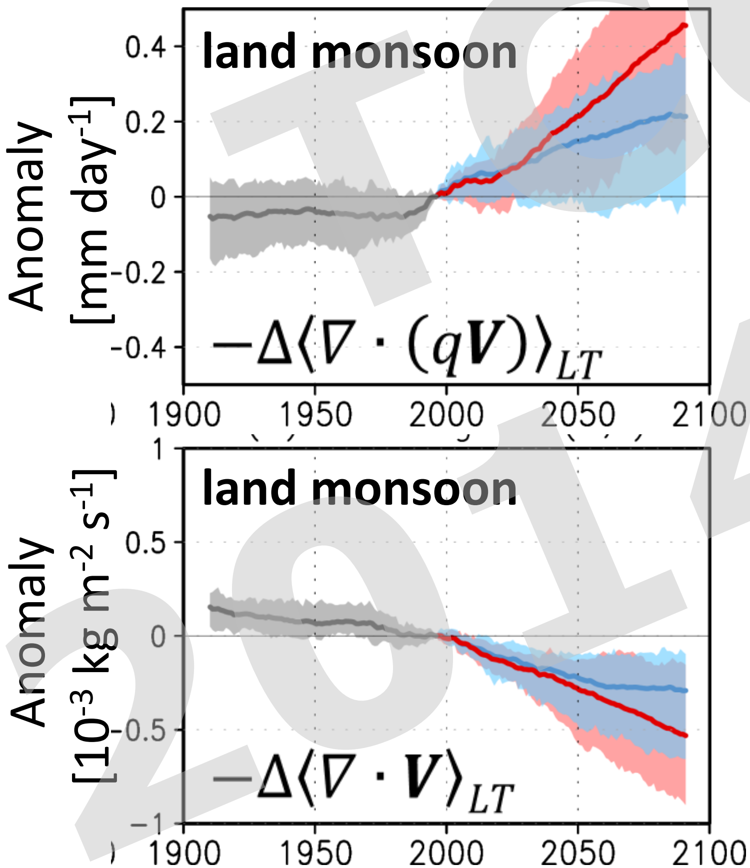
c) Future percentage change

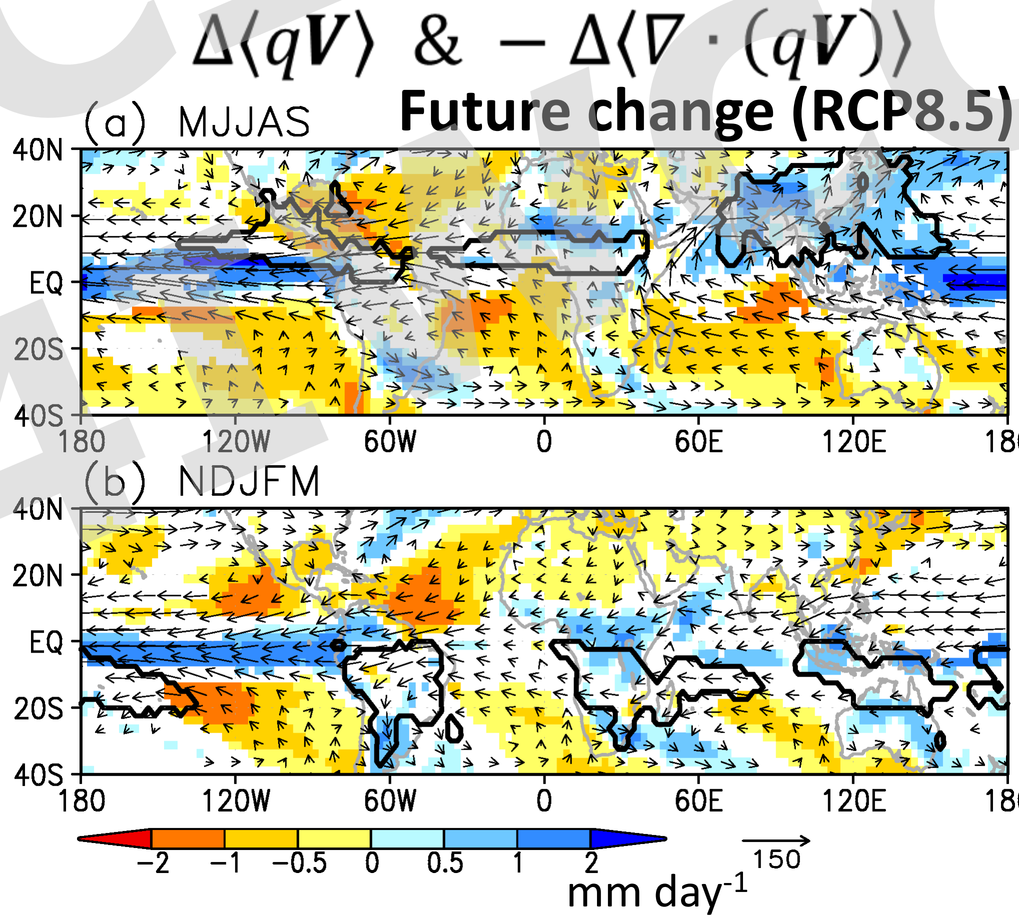
	Pav		SDII		R5d		CDD	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
NAM	-1.6	-6.5	0.2	-0.7	2.9	6.2	10.9	23.1
SAM	1.5	2.4	3.4	7.1	7.9	17.8	6.9	17.7
NAF	2.4	2.4	1.9	6.6	6.6	13.8	1.9	8.8
SAF	2.1	2.7	3.5	7.5	6.2	16.8	9.2	19.7
EAS	5.3	6.8	7.3	14.1	10.1	18.9	2.5	5.4
SAS	7.3	12.9	7.0	14.7	11.2	22.1	-1.2	4.7
AUS	2.9	7.3	4.3	8.2	6.7	15.0	3.6	6.8

Large change ratios in EAS and SAS

Attributions of changes in monsoon rainfall

- Enhanced moisture flux conv. due to increased moisture
  ⇒ increased monsoon rainfall
- However, large differences among the monsoon regions



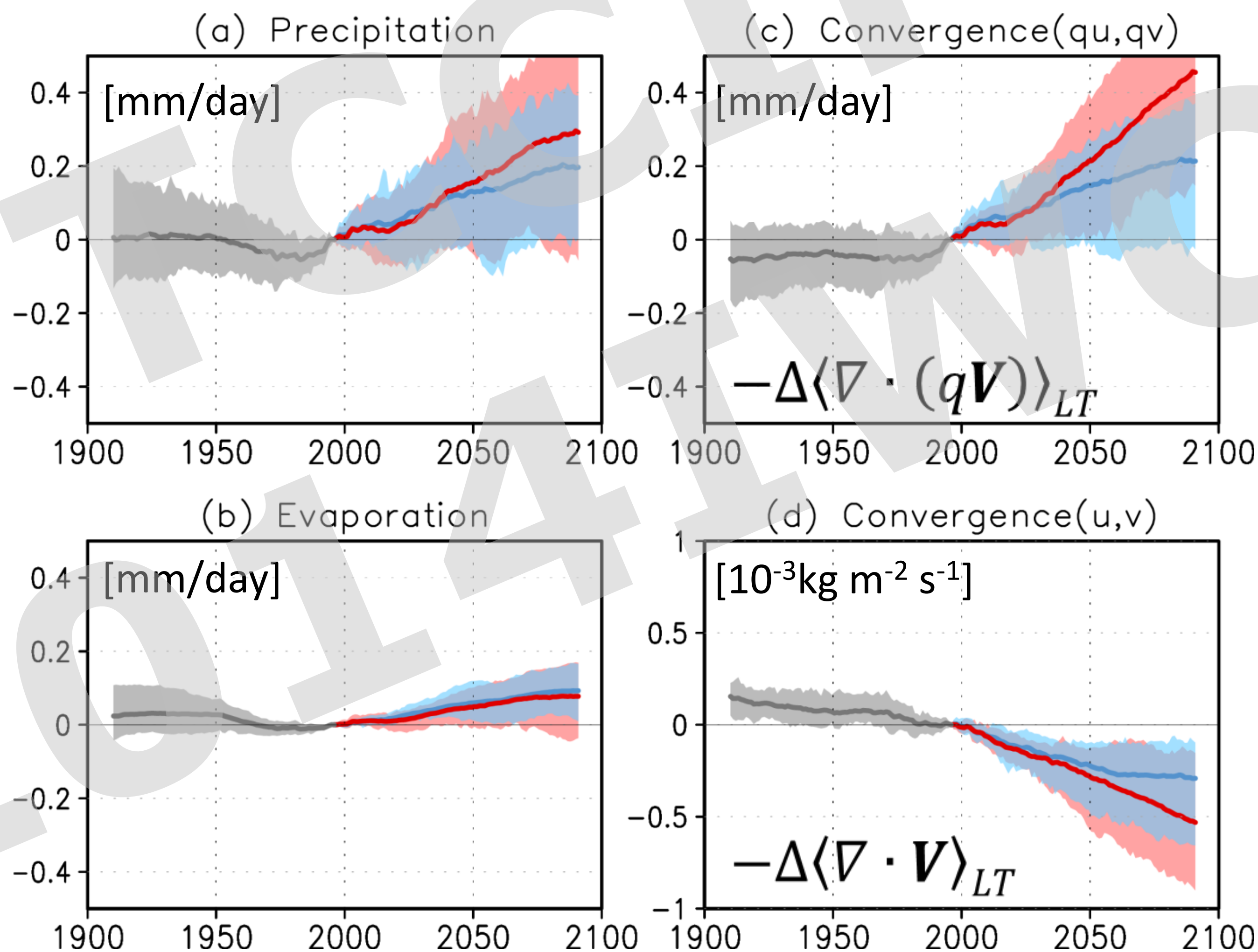


< > $_{LT}$: Integration in 1000-500hPa

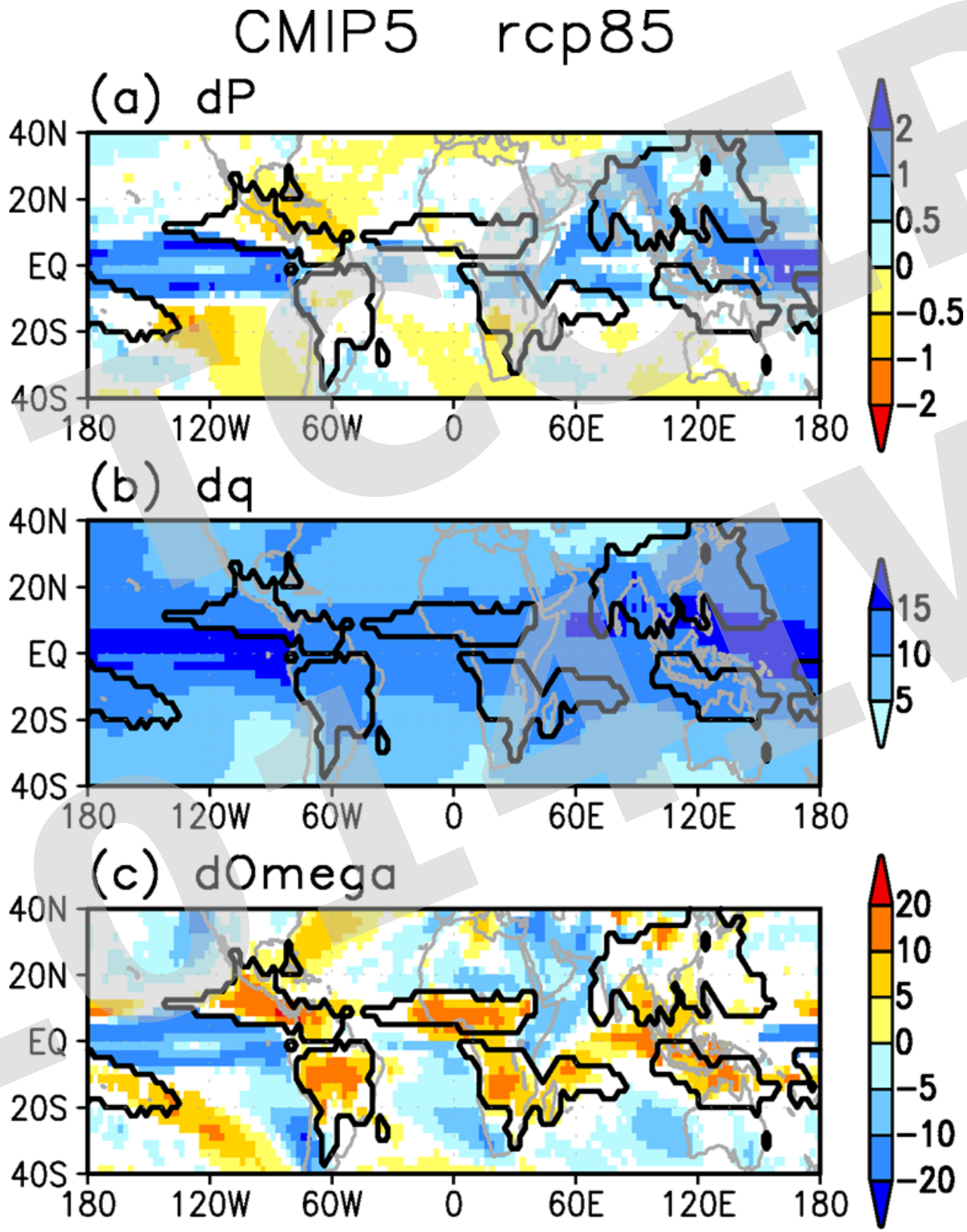
Changes with consensus of more than 75% of models

Attribution of changes in monsoon rainfall

$$\Delta P = -\Delta\langle \nabla \cdot (q\boldsymbol{V})\rangle + \Delta E$$



Precipitation, water vapor and vertical velocity



MJJAS for NH
NDJFM for SH

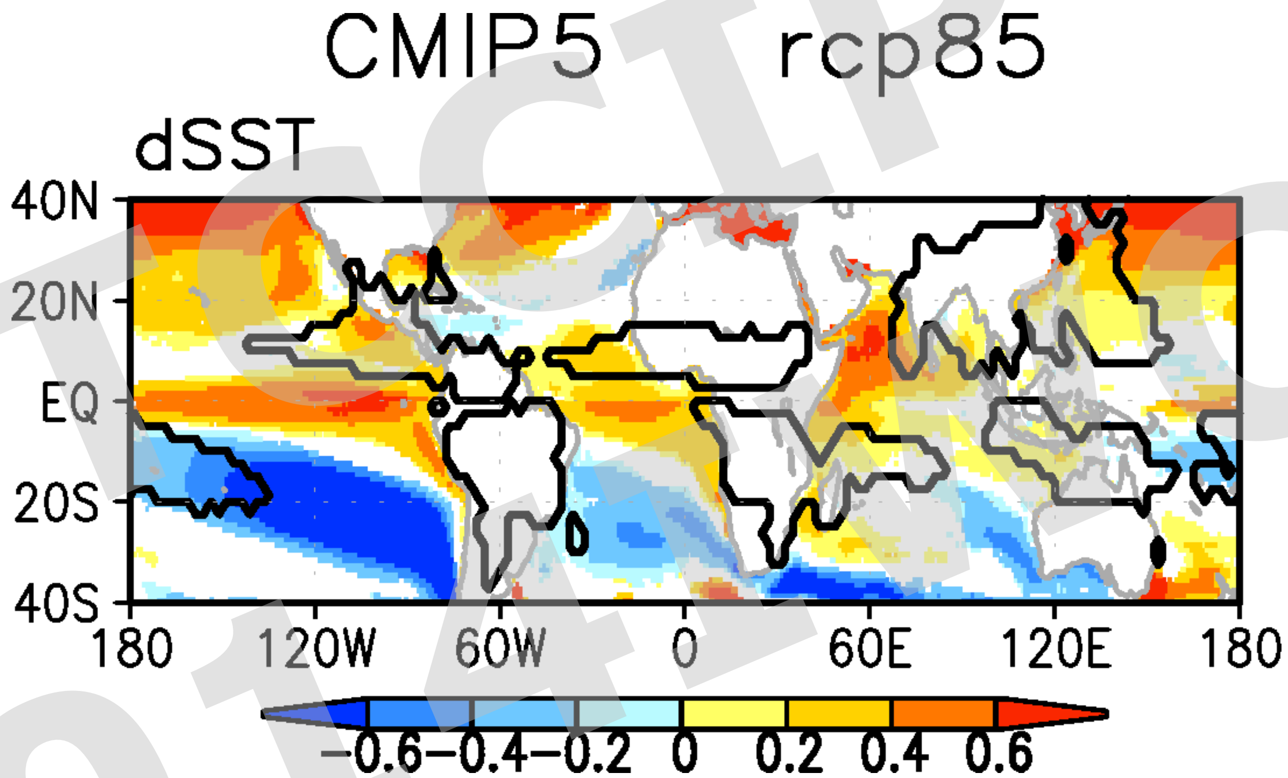
Precipitation increase is clear over Asia

Water vapor increases everywhere

Upward motion largely decreases over the monsoon regions except Asia where decrease is smaller

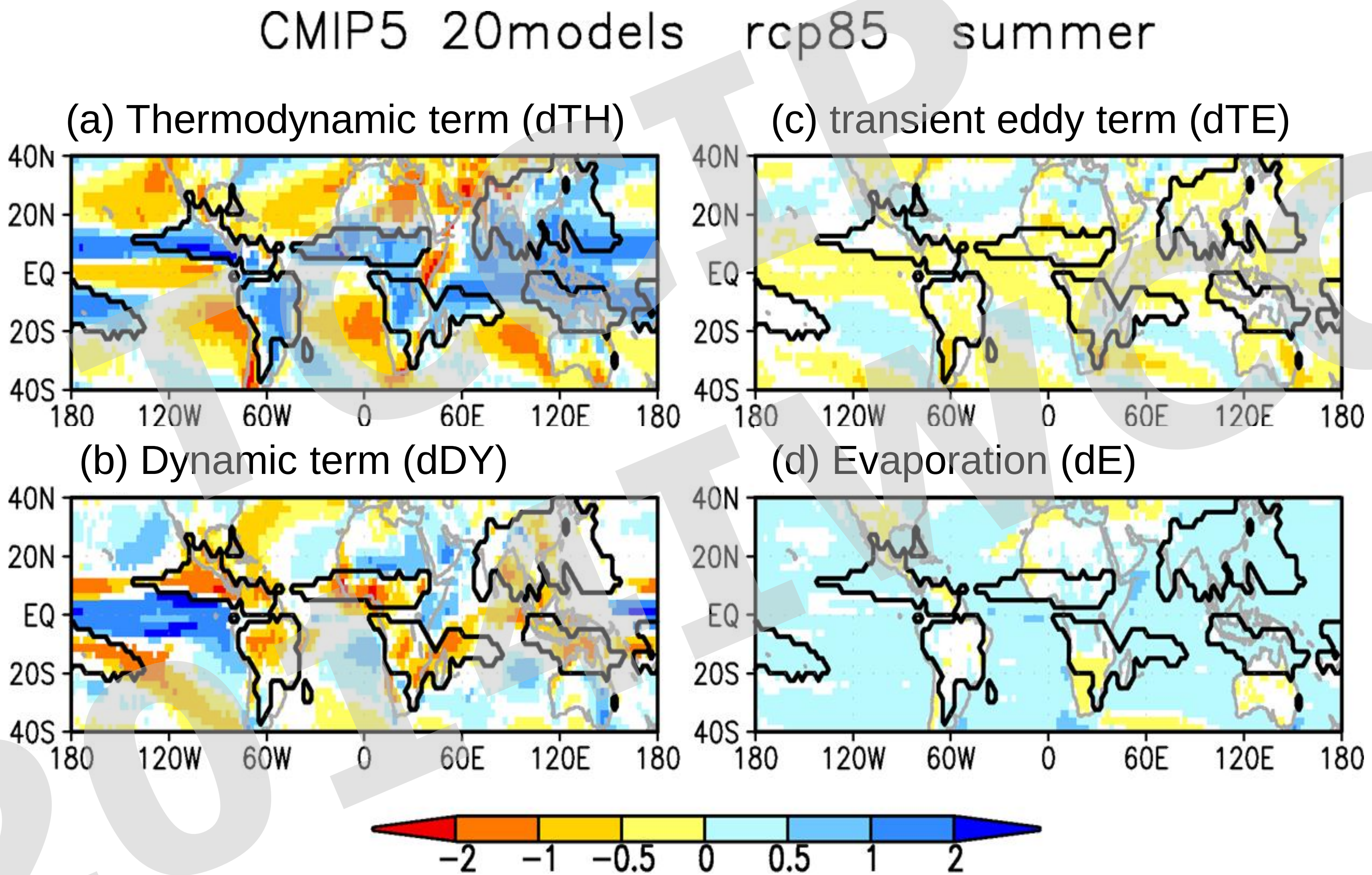
Consistent changes among models are colored

SST change pattern



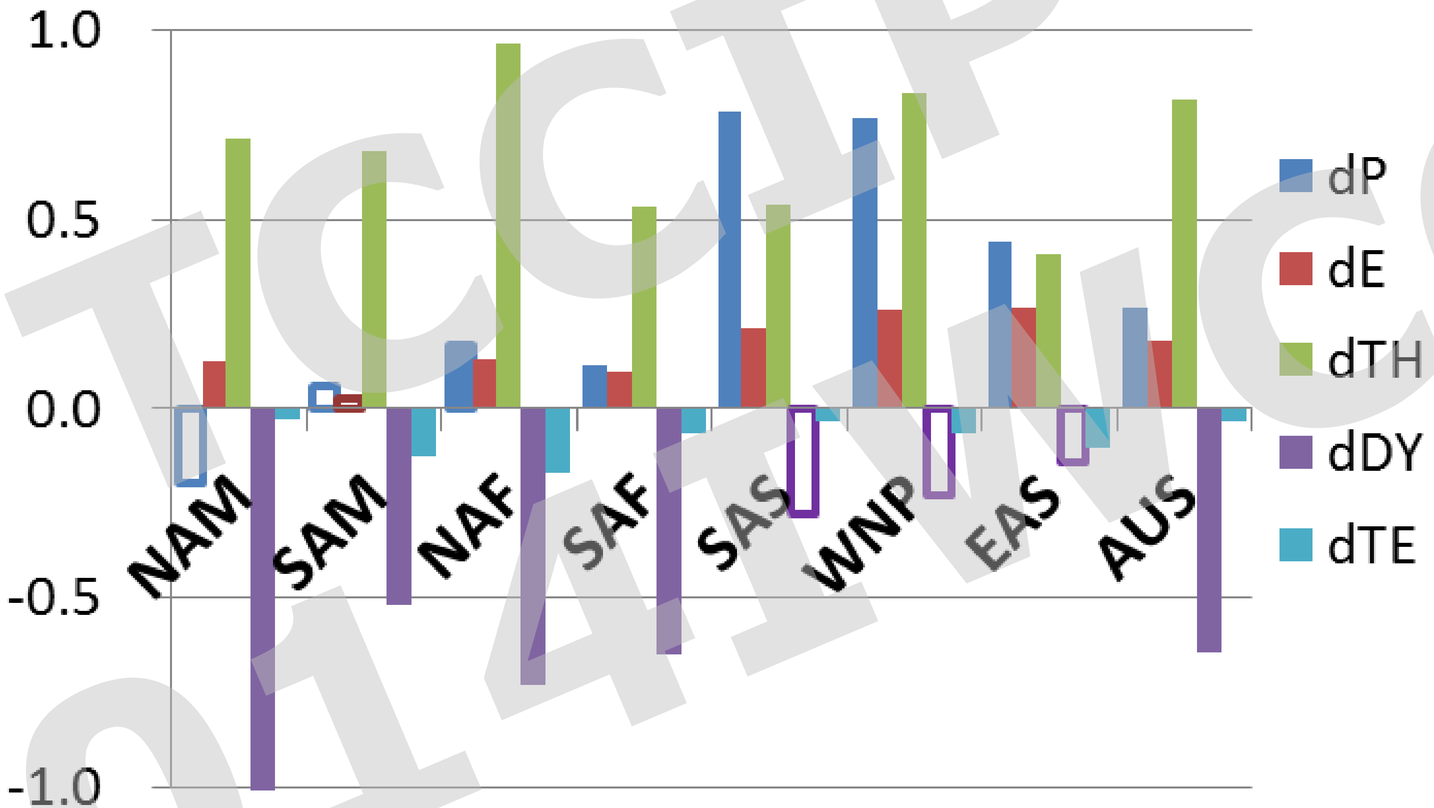
- ΔSST departure from tropical mean
- summer season
- Shadings denote model agreement > 2/3

Changes in moisture budget



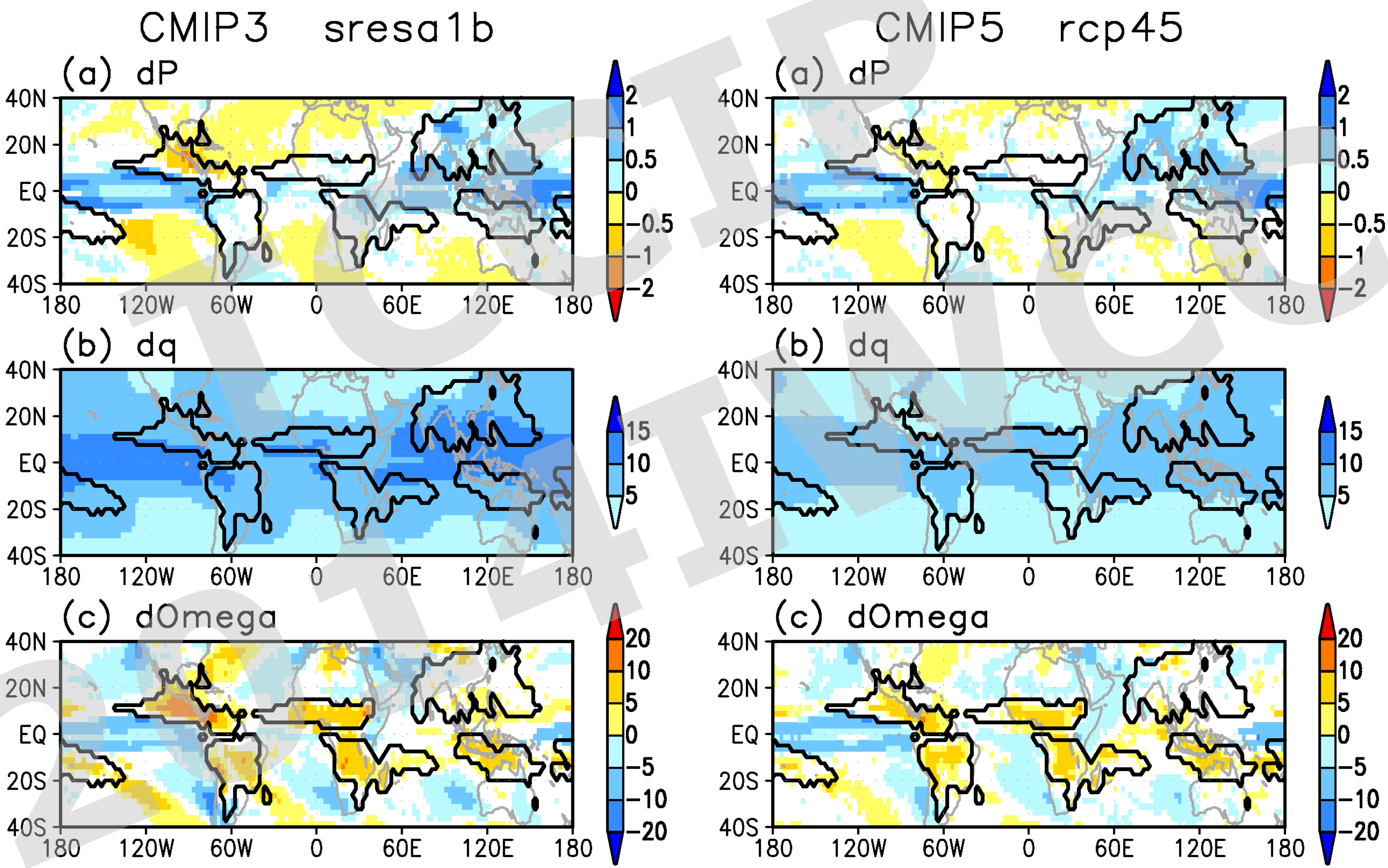
Thermodynamic effect is mostly compensated by dynamic effect, except for the Asian monsoon, where dynamic effect is small ⇒ large increase in monsoon rainfall

Contribution of each term



Over Asia, dynamic effect is smaller and local evaporation is larger than other regions

CMIP3 vs CMIP5



Common features in CMIP3 and CMIP5 models

Summary

- Global monsoon
  - **Decreased** monsoon rainfall from the 1950s to 1980s both in observations and simulations
  - **Remarkable increase** in monsoon precipitation in the 21st century
- Regional monsoon
  - Increase rate of **Asian monsoon rainfall** is much larger than other monsoons
  - Dynamical weakening of the Asian monsoon is less than other monsoons
  - These features are common in CMIP3 and CMIP5 model projections

[Kitoh et al., 2013, JGR; Endo and Kitoh, 2014, submitted]

Kitoh, A., H. Endo, K. Krishna Kumar, I.F.A. Cavalcanti, P. Goswami, T. Zhou, 2013: Monsoons in a changing world: a regional perspective in a global context. J. Geophys. Res. Atmos., 118, 3053-3065, doi:10.1002/jgrd.50258.

Endo, H. and A. Kitoh: Thermodynamic and dynamic effects on regional monsoon rainfall changes in a warmer climate. submitted to Geophys. Res. Lett.

Thermodynamic or Dynamic

$$\rho_w g(P-E) = -\int_0^{p_s} (\overline{\mathbf{u}}\cdot\nabla\overline{q} + \overline{q}\nabla\cdot\overline{\mathbf{u}})\,dp - \int_0^{p_s} \nabla\cdot(\overline{\mathbf{u}'q'})\,dp - q_s\mathbf{u}_s\cdot\nabla p_s. \quad (1)$$

$$\delta(\cdot) = (\cdot)_{21} - (\cdot)_{20}, \quad (2)$$

$$\rho_w g\delta(P-E) \approx -\int_0^{p_s} (\delta\overline{\mathbf{u}}\cdot\nabla\overline{q}_{20} + \overline{\mathbf{u}}_{20}\cdot\nabla\delta\overline{q} + \delta\overline{q}\nabla\cdot\overline{\mathbf{u}}_{20} + \overline{q}_{20}\nabla\cdot\delta\overline{\mathbf{u}})\,dp - \int_0^{p_s}\nabla\cdot\delta(\overline{\mathbf{u}'q'})\,dp - \delta S. \quad (3)$$

$$\rho_w g\delta(P-E) \approx \delta\mathrm{TH} + \delta\mathrm{MCD} + \delta\mathrm{TE} - \delta S, \quad (4)$$

$$\delta\mathrm{TH} = -\int_0^{p_s}\nabla\cdot(\overline{\mathbf{u}}_{20}[\delta\overline{q}])\,dp, \quad (5)$$

$$\delta\mathrm{MCD} = -\int_0^{p_s}\nabla\cdot([\delta\overline{\mathbf{u}}]\overline{q}_{20})\,dp, \quad \text{and} \quad (6)$$

$$\delta\mathrm{TE} = -\int_0^{p_s}\nabla\cdot\delta(\overline{\mathbf{u}'q'})\,dp. \quad (7)$$

TH: thermodynamic
MCD: mean circulation dynamics

$$\delta\mathrm{TH} = \delta\mathrm{TH}_A + \delta\mathrm{TH}_D, \quad (8)$$

$$\delta\mathrm{TH}_A = -\int_0^{p_s}(\overline{\mathbf{u}}_{20}\cdot\nabla\delta\overline{q})\,dp, \quad \text{and} \quad (9)$$

$$\delta\mathrm{TH}_D = -\int_0^{p_s}(\delta\overline{q}\nabla\cdot\overline{\mathbf{u}}_{20})\,dp; \quad (10)$$

$$\delta\mathrm{MCD} = \delta\mathrm{MCD}_A + \delta\mathrm{MCD}_D, \quad (11)$$

$$\delta\mathrm{MCD}_A = -\int_0^{p_s}(\delta\overline{\mathbf{u}}\cdot\nabla\overline{q}_{20})\,dp, \quad \text{and} \quad (12)$$

$$\delta\mathrm{MCD}_D = -\int_0^{p_s}(\overline{q}_{20}\nabla\cdot\delta\overline{\mathbf{u}})\,dp. \quad (13)$$

A: advection
D: divergence

Seager et al. (2010, JCLI)

Future change (RCP8.5)

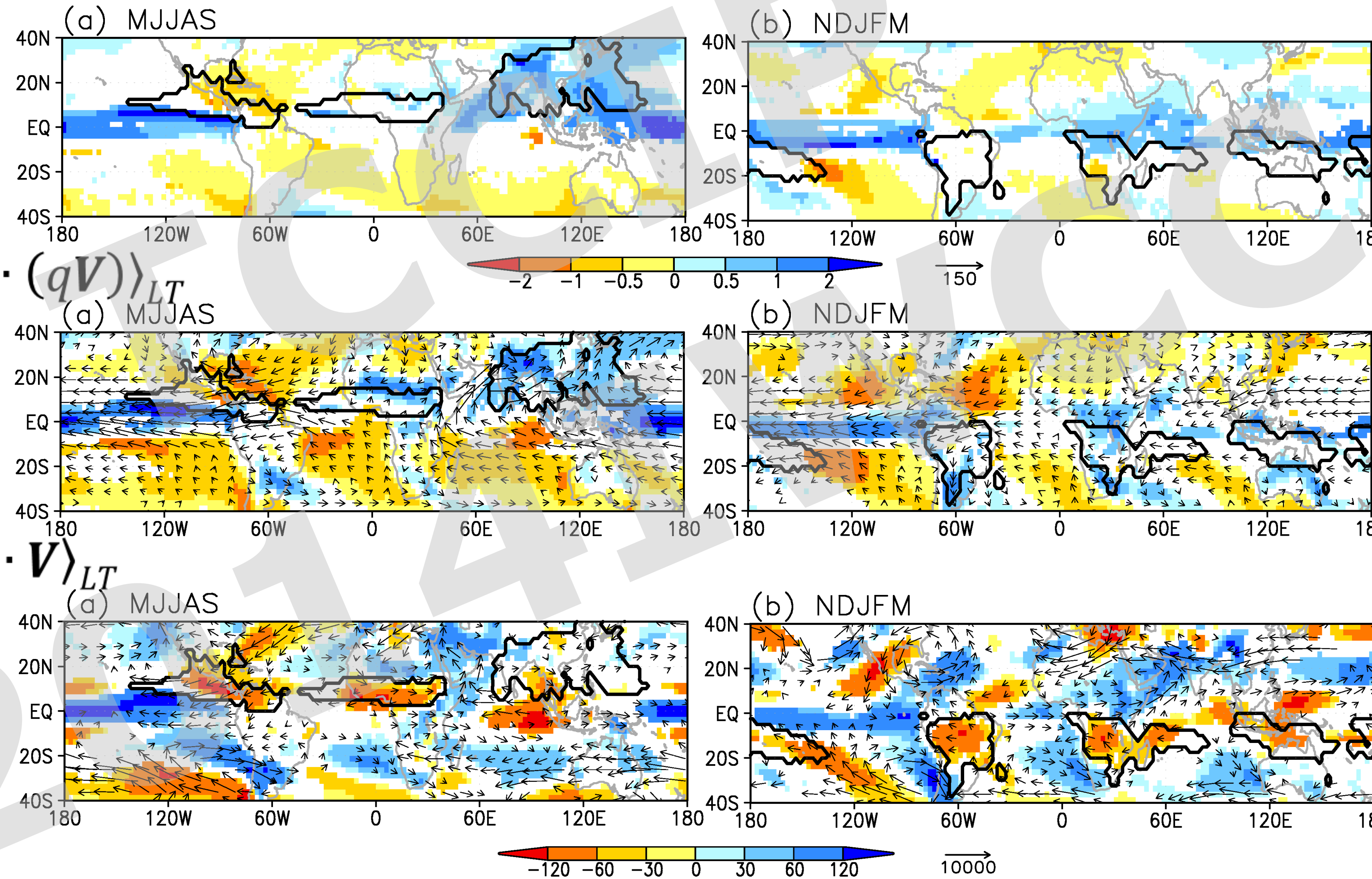
$$\Delta P = -\Delta\langle \nabla \cdot (q\boldsymbol{V}) \rangle + \Delta E$$

MJJAS NDJFM

ΔP

$-\Delta\langle \nabla \cdot (q\boldsymbol{V}) \rangle_{LT}$

$-\Delta\langle \nabla \cdot \boldsymbol{V} \rangle_{LT}$



- < > $_{LT}$: Vertical integration in the lower troposphere (1000hPa-500hPa)
- Only changes with consensus of more than 75% of models are shown