Monsoon dynamics in past and future climates: the Holocene is not an analogue of future projections

Roberta D'Agostino[1],

Jürgen Bader [1,2], Josephine Brown [3], Simona Bordoni [4,5], David Ferreira [6] , Aurel Moise [7,8], Hanh Nguyen [8], Pedro Silva-Dias [9], and Johann Jungclaus [1]

[1] Max-Planck-Institut für Meteorologie, Hamburg, Germany

[2] Uni Climate, Uni Research and the Bjerknes Centre for Climate Research, Bergen, Norway

[3] University of Melbourne, Melbourne, Victoria, Australia

[4] California Institute of Technology, Pasadena, California, United States of America

[5] University of Trento, Trento, Italy

[6] University of Reading, Reading, United Kingdom

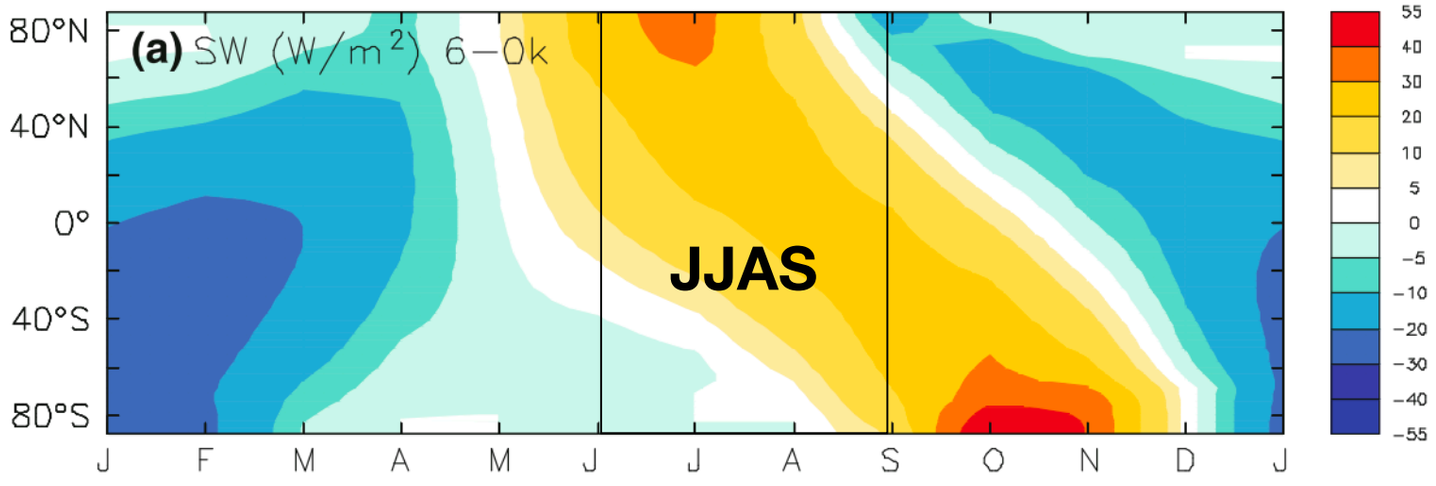
[7] Centre for Climate Research Singapore, Singapore

[8] Australian Bureau of Meteorology, Melbourne, Victoria, Australia

[9] University of Saō Paulo, Saō Paulo, Brazil

mid-Holocene ~ 6K Before Present

Insolation (W/m²) mid-Holocene -piControl



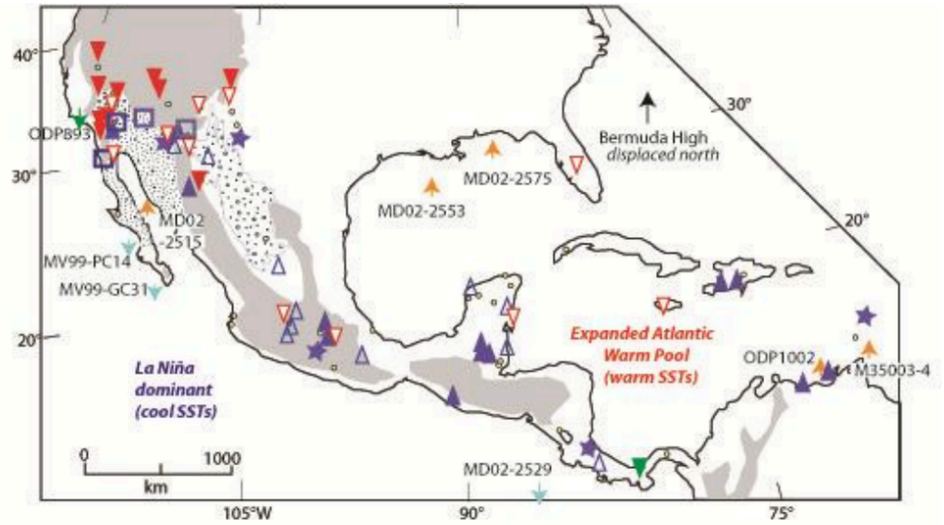
Warming of the NH

Enhanced inter-hemispheric thermal contrast

Documented increased rainfall in Northern Hemisphere monsoon (boreal summer)

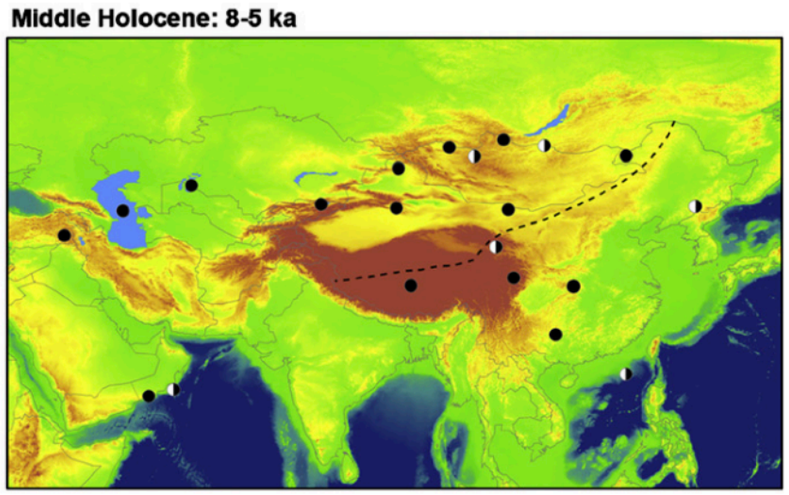
Wettening tendency in every Northern Hemisphere monsoons

Terrestrial proxies (caves, lakes, midden)



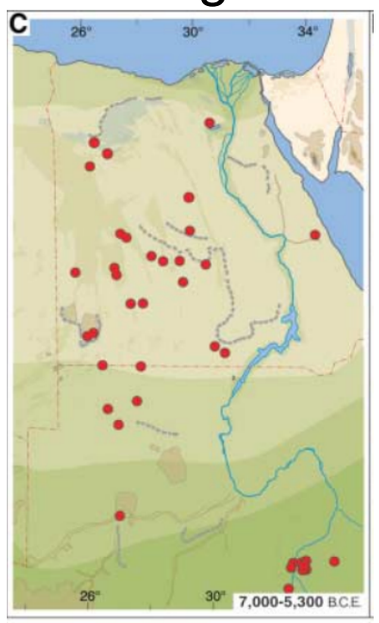
Metcalfe et al. 2015

Speleothems



Chen et al. 2008

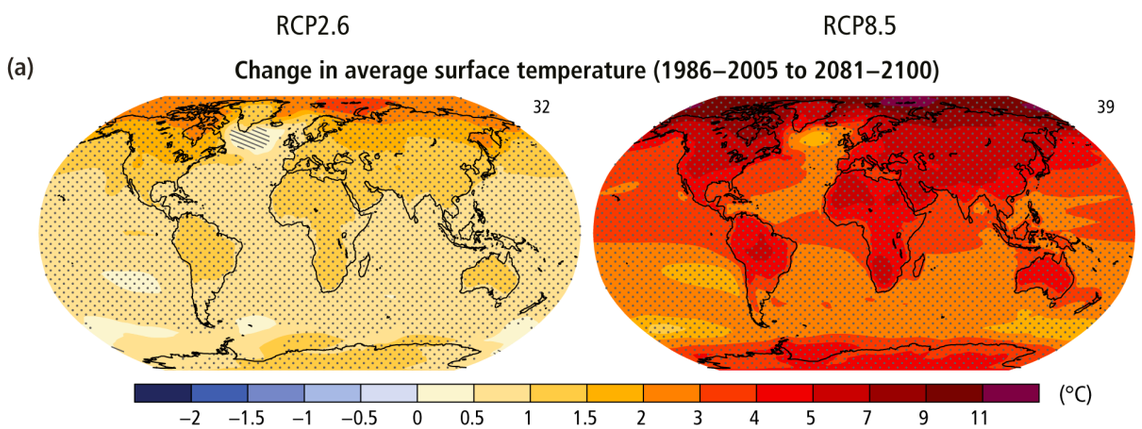
Archaeological sites



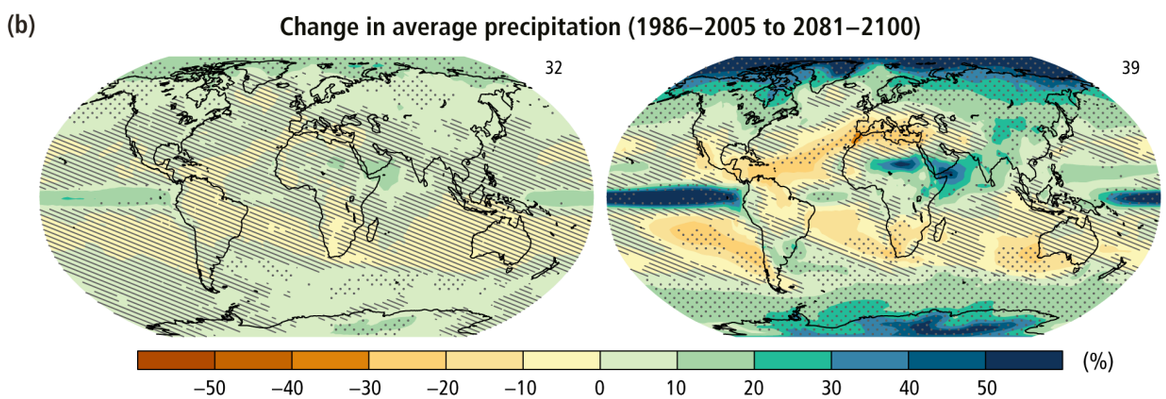
Kuper and Kröpelin 2006

rcp8.5 … end of the 21st century

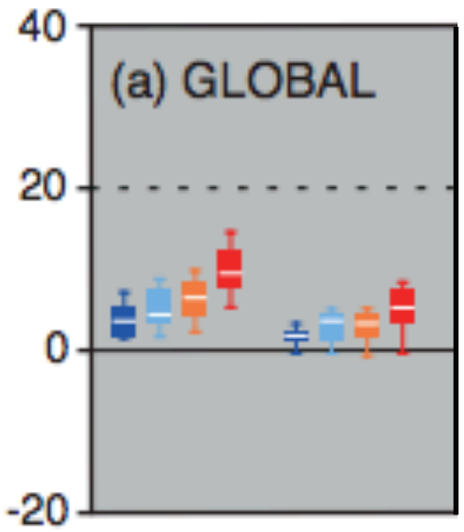
Warming of the NH, enhanced inter-hemispheric and land sea thermal contrast



Increased rainfall in global monsoon

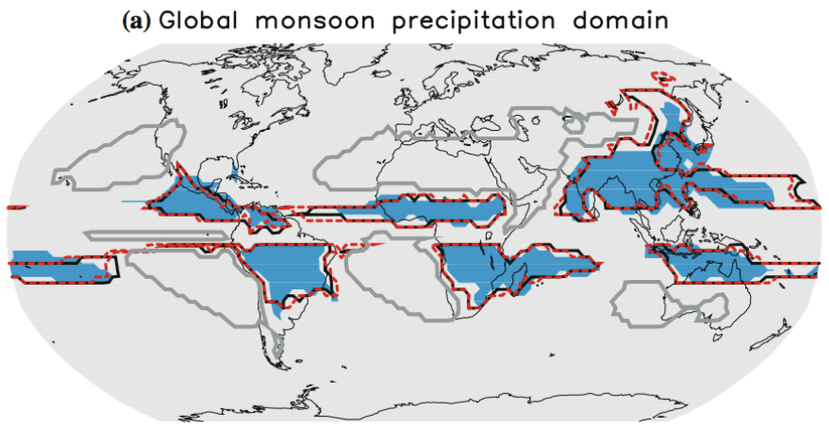


Strengthening and widening of the Northern Hemisphere monsoons with respect to the pre-industrial condition (piControl) and present-day (1980 - 2005).



RCP2.6
RCP4.5
RCP6.0
RCP8.5

IPCC, WG1, 2013



Lee and Wang (2013)

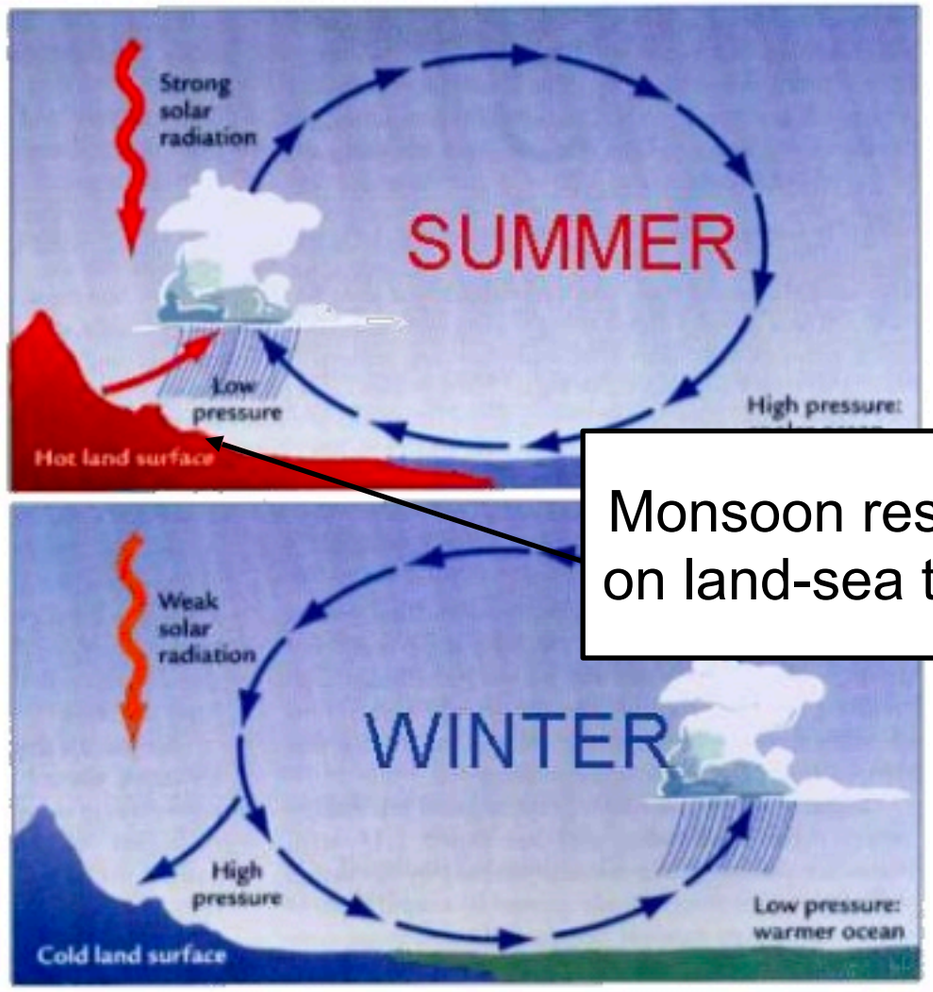
Monsoon dynamics

Traditional view of monsoons = large scale breezes

Differential heating

Summer: Intense heating of land mass. Oceans take longer to warm. This generates pressure differences leading to SW winds (Em and Tm air masses).

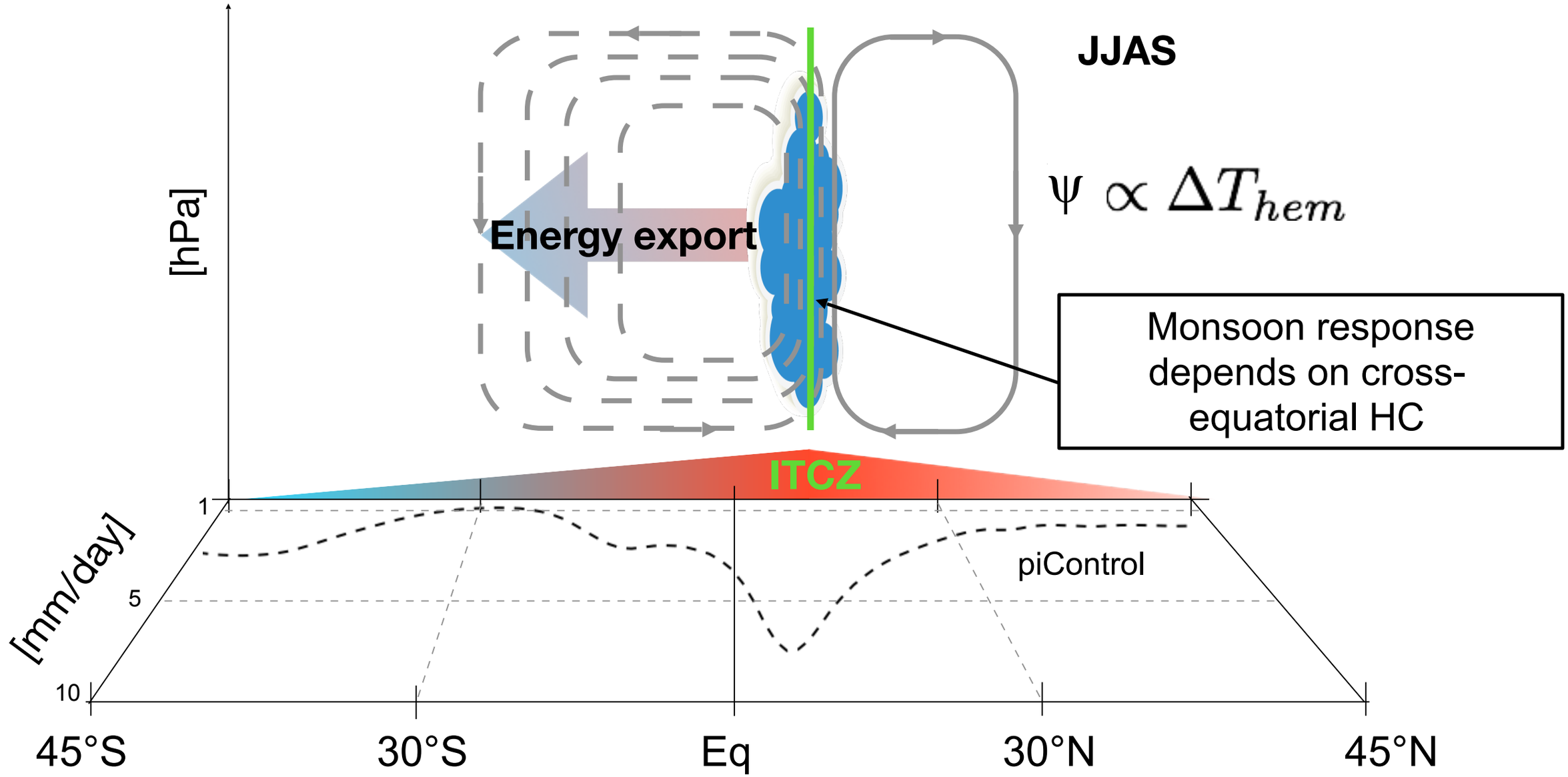
Winter: Land cools rapidly. Ocean retains warmth. Pressure change is reversed and winds move from NE (Tc and Pc from desert).



Monsoon response depends on land-sea thermal contrast

Monsoon dynamics

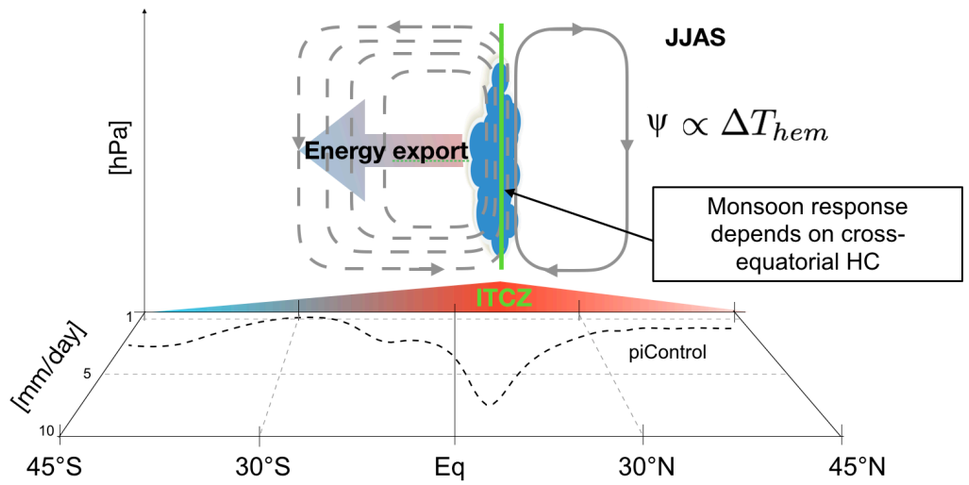
Recent view = Monsoons coupled to Hadley Cells

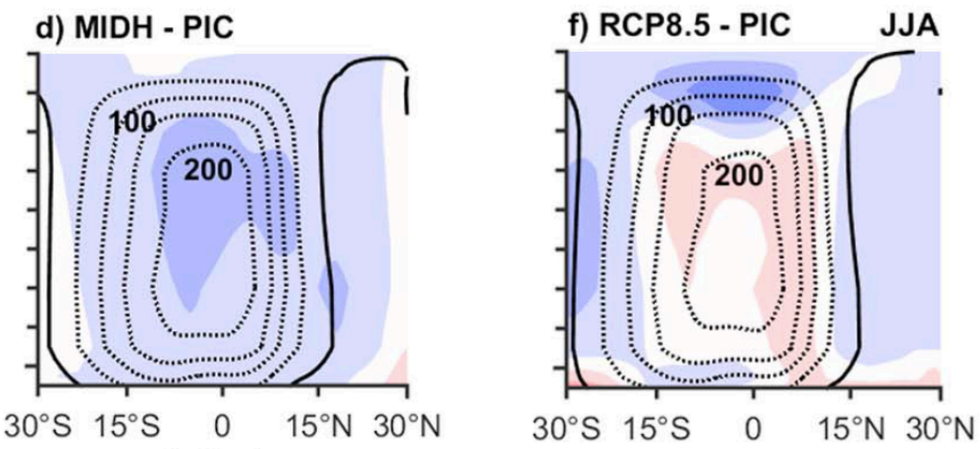


Monsoon response?

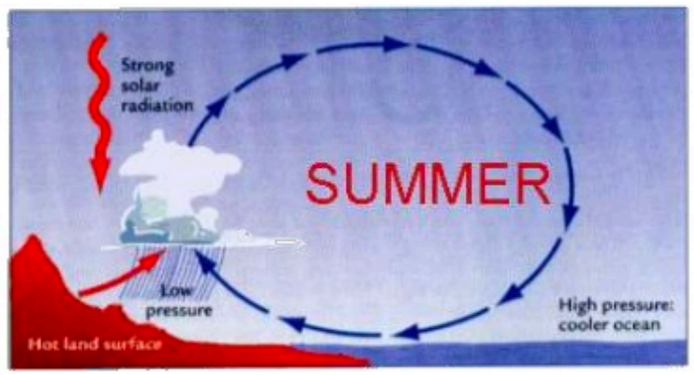
mid-Holocene
Stronger cross-equatorial Hadley cell than pre-industrial

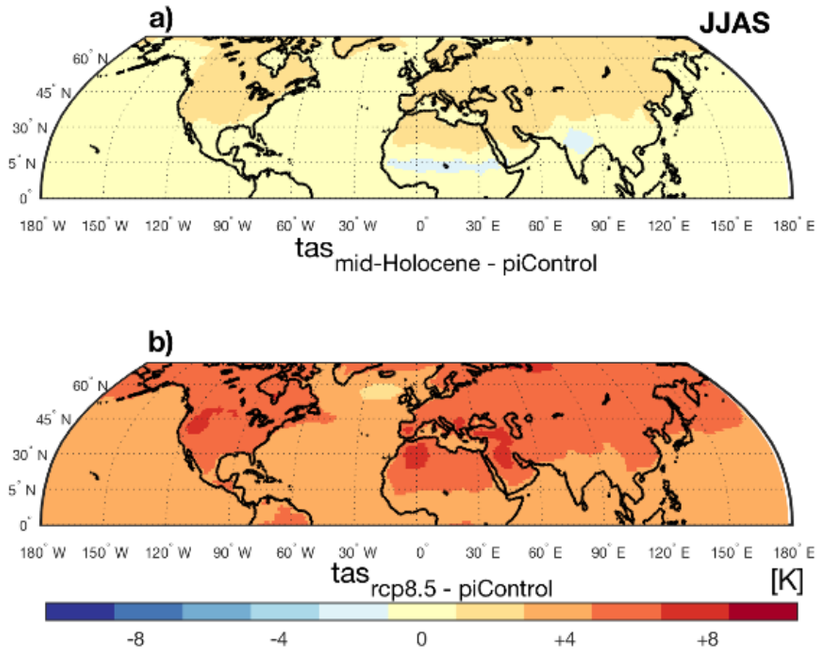
rcp8.5
Stronger land-sea thermal contrast and global warming than pre-industrial





D'Agostino et al., 2017





D'Agostino et al., 2019

CMIP5 Simulations

6000 yrs BP

mid-Holocene

Orbital parameter changed
GHG fixed to piControl

Before industrial revolution

piControl

2070 - 2100

rcp8.5

Orbital parameters fixed to
piControl
GHG increased

SW forcing

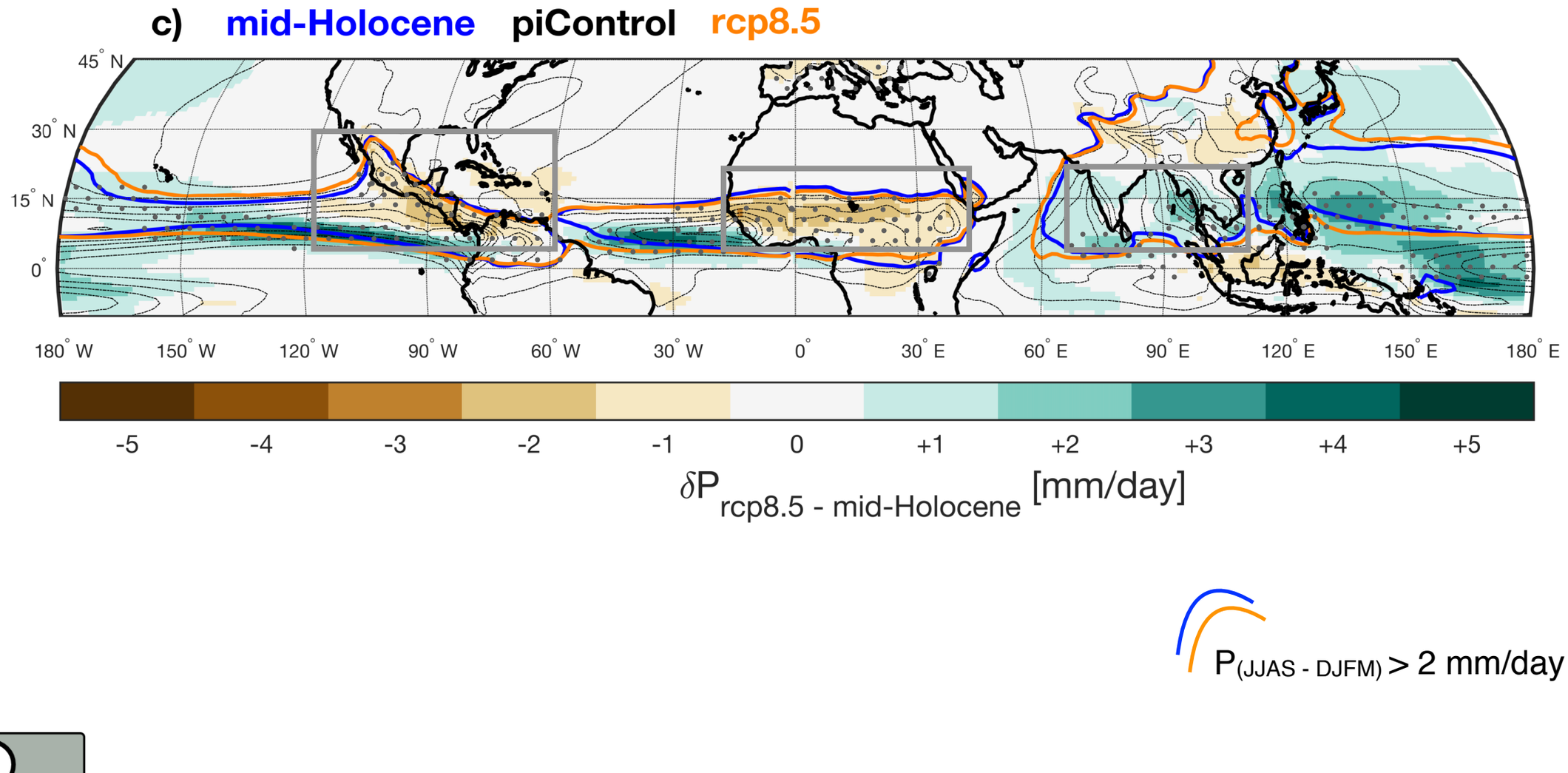
LW forcing

Model list:

r1i1p1 ensemble. Monthly data are interpolated on a common 1 x 1.25 grid and on 17 pressure levels.	bcc-csm-1-1 CCSM4 CNRM-CM5A CSIRO-Mk3-6-0 IPSL-CM5A-LR FGOALS-g2 HadGEM2-ES MIROC-ESM MRI-CGCM3

Precipitation difference

Multi-model ensemble mean precipitation difference (**rcp8.5** - **mid-Holocene**)



Monsoon Statistics

Despite:
- Larger global warming
- Larger inter-hemispheric contrast
- Larger land-sea contrast

Land-monsoons	Extent (10^6 Km)			Strength (mm/day)		
	piControl	*mid-Holocene*	*rcp8.5*	*piControl*	*mid-Holocene*	*rcp8.5*
African	5.2 (±0.7)	+15.4%	+4.4%	5.3 (±11.0)	+20.3%	+1.2%
Indian	3.1 (±0.4)	+9.2%	+7.4%	8.5 (±1.3)	+1.6%	+4.8%
North American	2.8 (±0.5)	+3.7%	-4.3%	5.8 (±1.3)	+7.8%	-5.8%
NH	9.3 (±1.0)	+15.1%	+4.8%	7.0 (±0.5)	+1.1%	-1.8%

Future monsoons will be narrower and weaker than in the past

→ Use moisture budget analysis to elucidate mechanisms

Moisture budget decomposition

$$\rho_w g \delta(P-E) \;=\; -\int_0^{p_s} \nabla\cdot(\delta\overline{q}\;\overline{\mathbf{u}}_{\mathrm{piControl}})\,dp \;-\; \int_0^{p_s} \nabla\cdot(\overline{q}_{\mathrm{piControl}}\,\delta\overline{\mathbf{u}})\,dp \;-Res$$

THermodynamic

(Humidity change)

DYnamic

(Mean flow change)

Residual

Transient eddies and surface terms

Every δ describes the difference between each experiment (mid-Holocene or rcp8.5) and the reference climate (piControl):

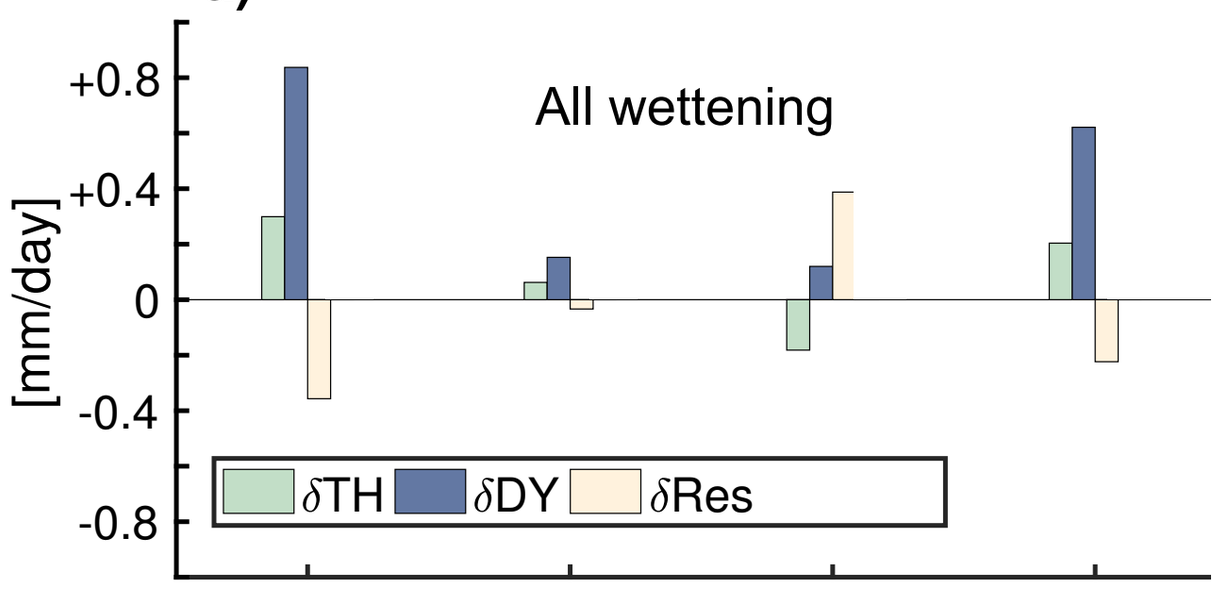
$$\delta(\cdot) \;=\; (\cdot)_{\mathrm{MIDH\ or\ RCP8.5}} \;-\; (\cdot)_{\mathrm{PIC}}$$

Trenberth & Guillemot, 1995, Seager et al., 2010

mid-Holocene vs rcp8.5

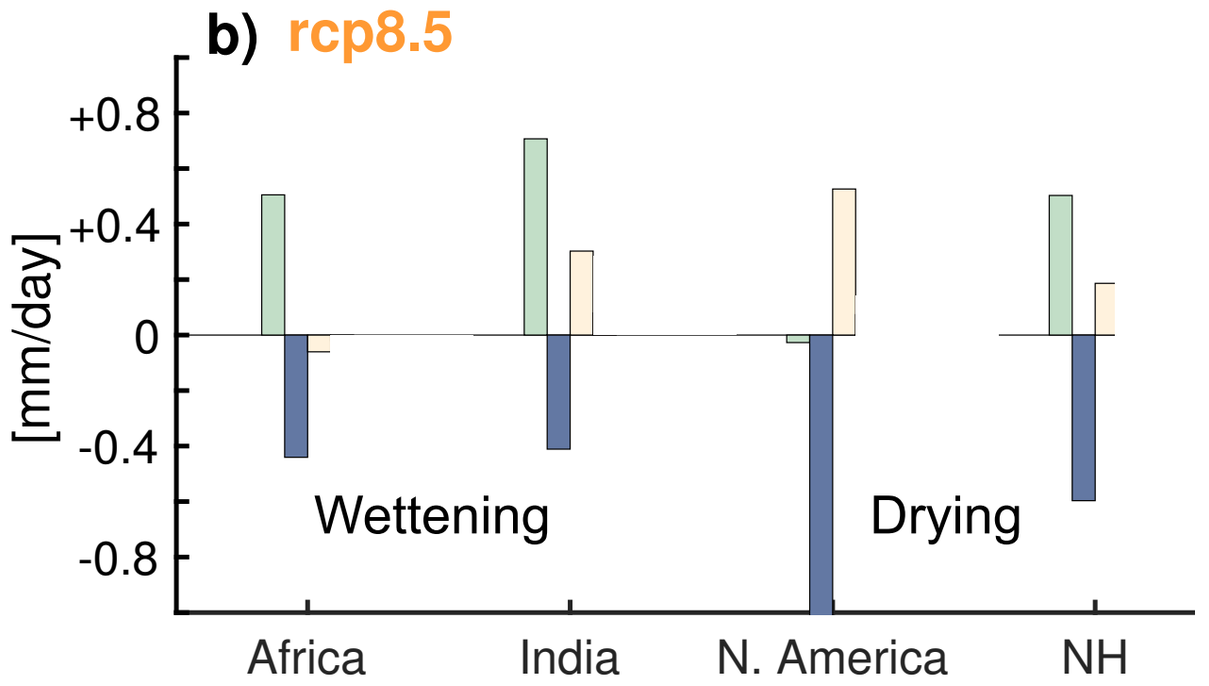
DY tendency (wettening) dominates and reinforces TH tendency

DY strengthening = Wettening



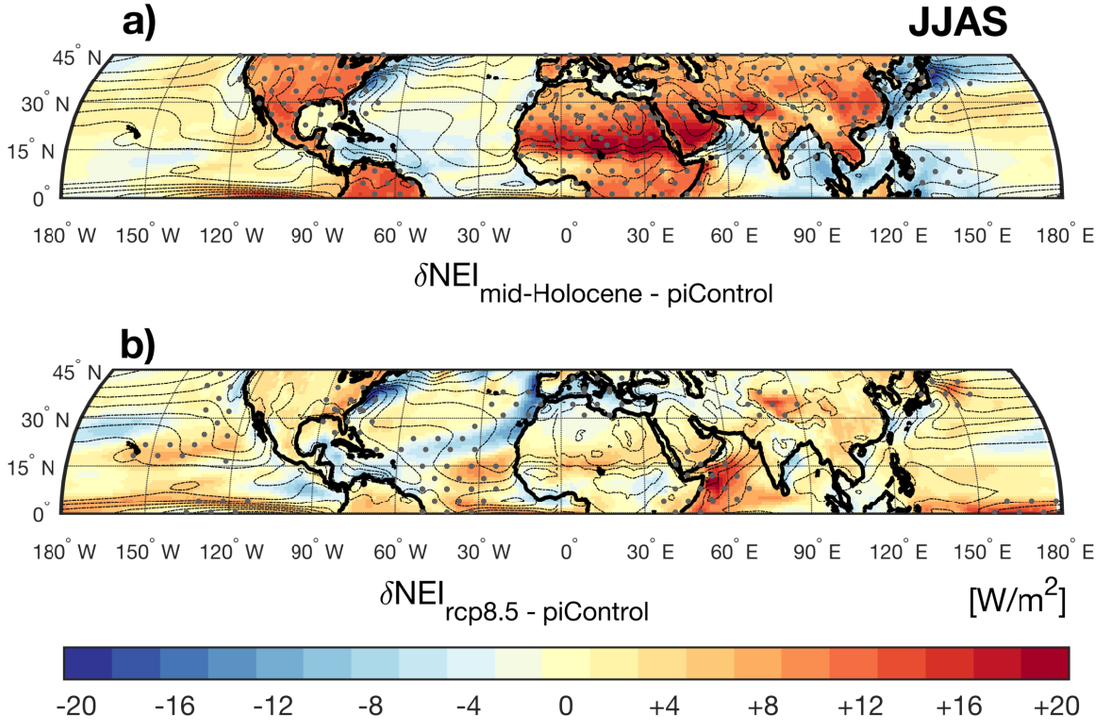
DY tendency (drying) counteracts TH tendency (wettening)

DY weakening = Drying

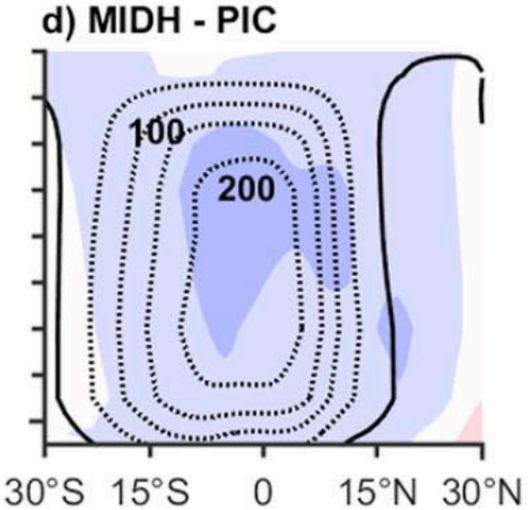


Atmospheric Net Energy Input

Atmospheric net energy input = Top-of-atmosphere - surface fluxes

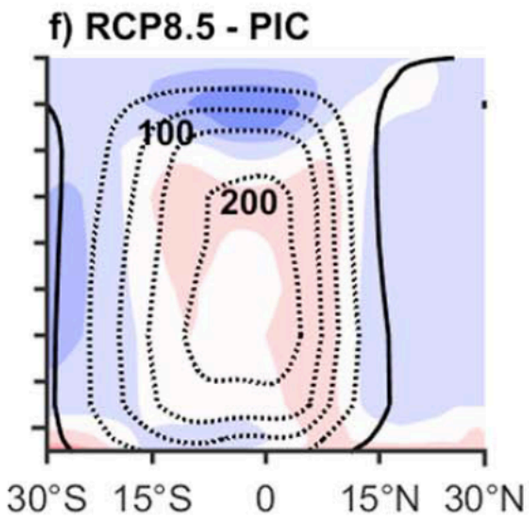


D'Agostino et al., 2019



The strengthening of the DY is due to stronger tropical circulation in mid-Holocene because the Hadley cell needs to export more energy from areas with high NEI to region with low NEI.

D'Agostino et al., 2017

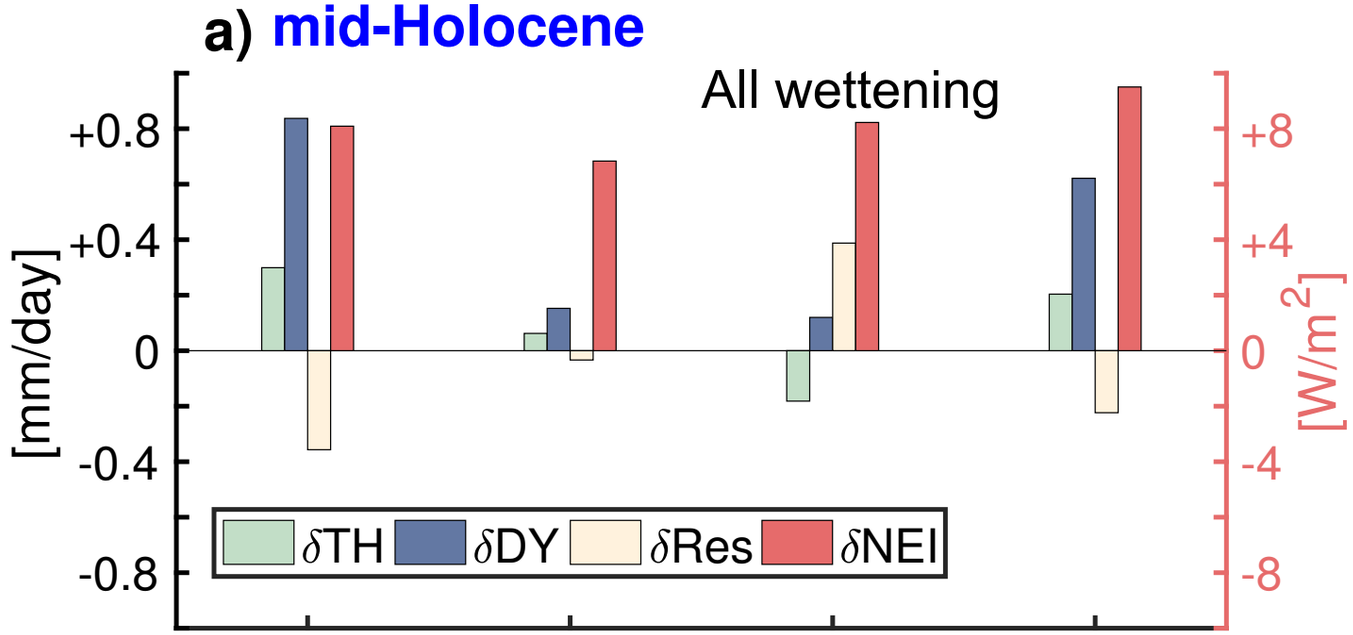


The weakening of the DY is due to weaker tropical circulation in future because the Hadley cell exports less energy given the low NEI difference among tropical domain.

mid-Holocene vs rcp8.5

DY tendency (wettening) dominates and reinforces TH tendency

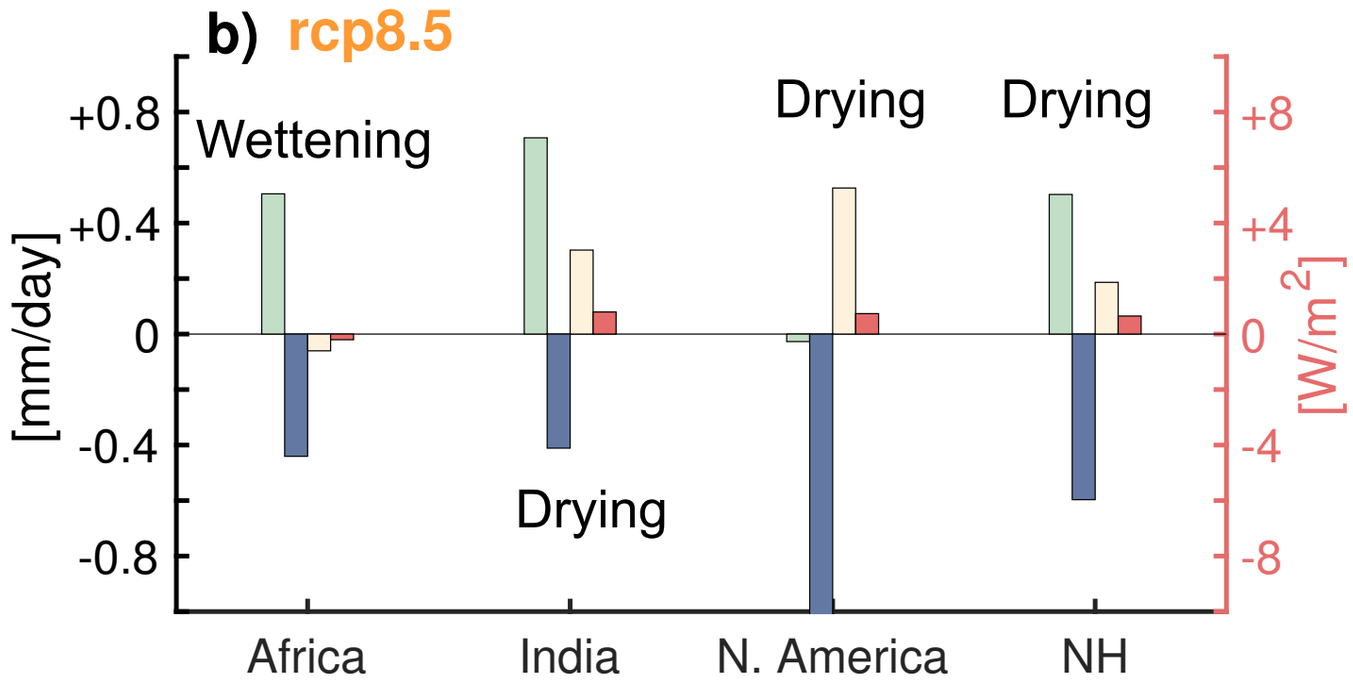
DY strengthening = Wettening



Monsoon precipitation is related to local Net Energy Input

DY tendency (drying) counteracts TH tendency (wettening)

DY weakening = Drying



Conclusions

1) In the future, land monsoons will be narrow and weaker than in the mid-Holocene.

2) The tropical circulation weakening will limit the further monsoonal rainfall increase due to atmospheric warming.

3) The weakening of the tropical circulation (e.g. Walker and Hadley cells) represents a constraint for future land monsoon response.

Emergent Constraint ?

4) The mid-Holocene is not an analogue of the future, <u>because past and future involved mechanisms are different.</u>

D'Agostino, R., Bader, J., Bordoni, S., Ferreira, D., & Jungclaus, J. (2019). Northern Hemisphere Monsoon Response to Mid−Holocene Orbital Forcing and Greenhouse Gas−Induced Global Warming. *Geophysical Research Letters*, *46*(3), 1591-1601.

Thanks for your attention!

roberta.dagostino@mpimet.mpg.de