MOIST CLIMATE ACROSS THE AFRICAN AND ASIAN MONSOON REGIONS IN MID-PLIOCENE MODELS AND PROXIES

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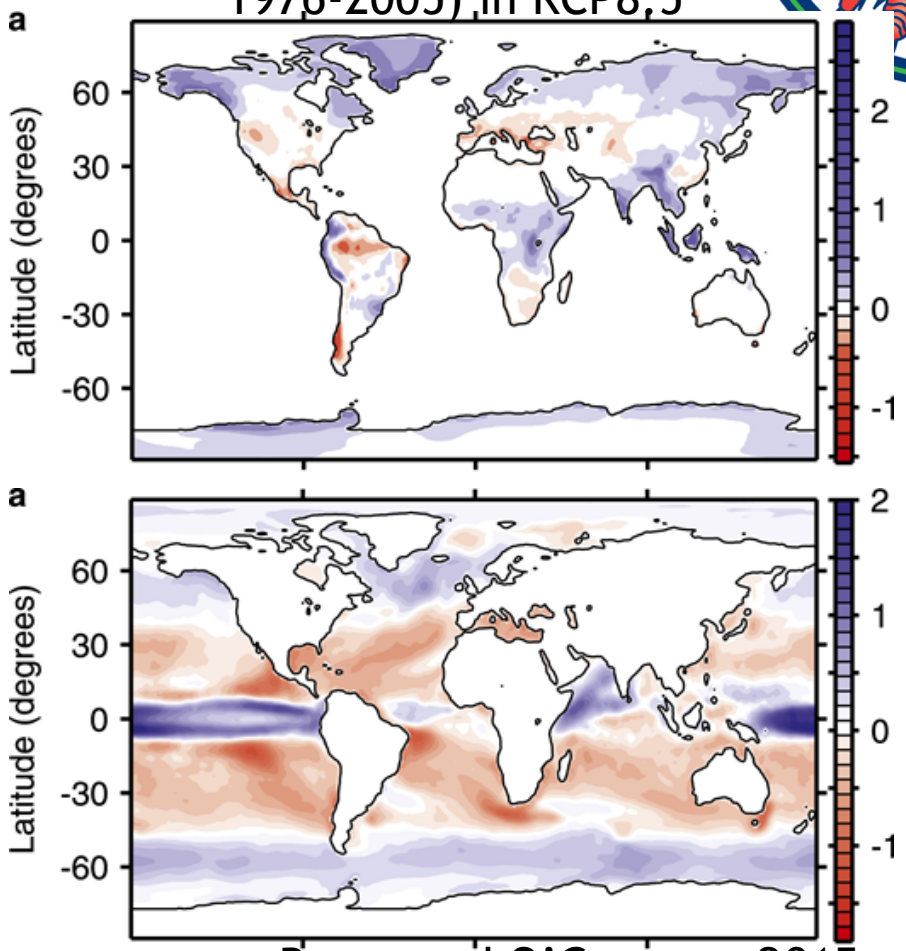
FUTURE CHANGES IN HYDROCLIMATE

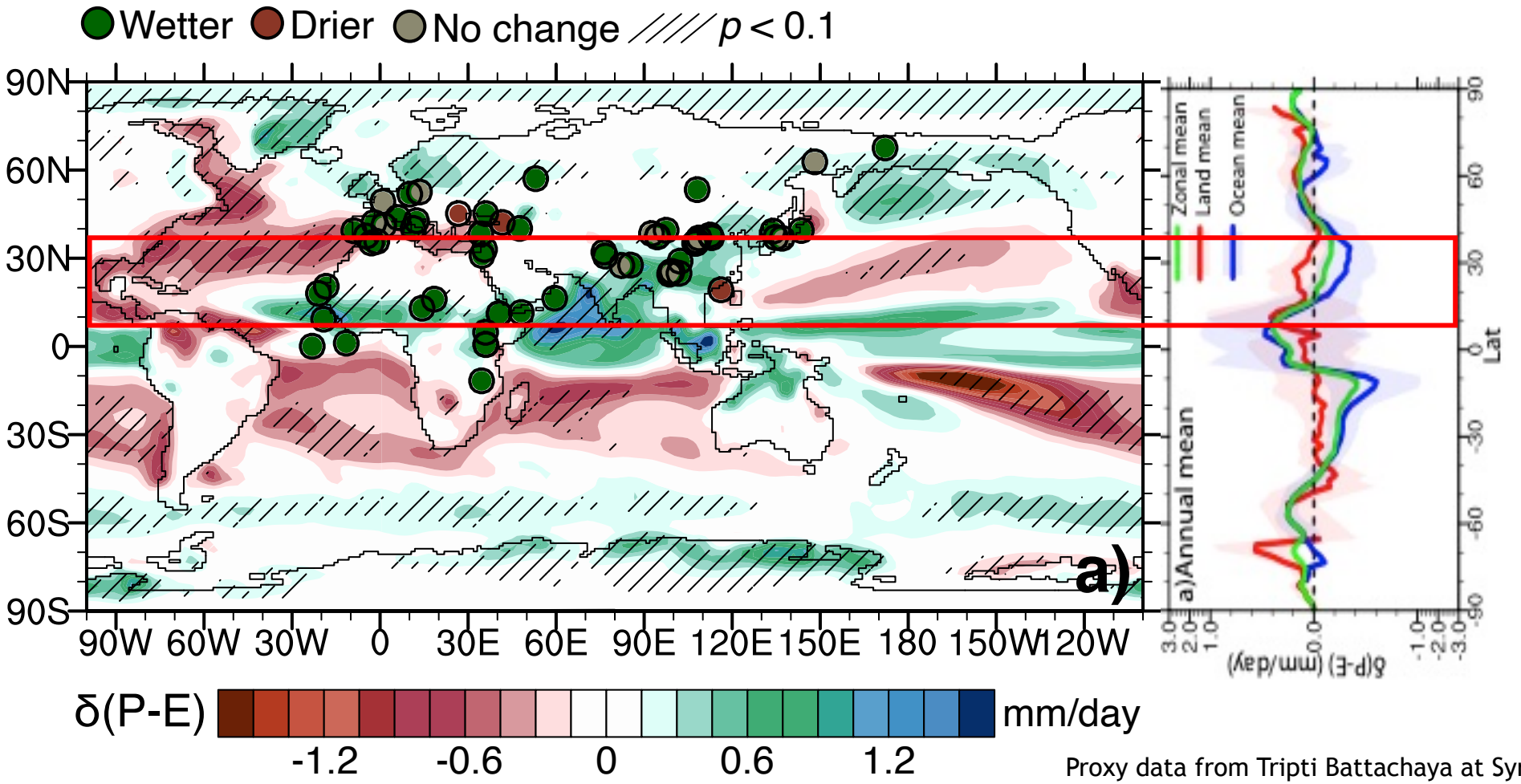
- P-E measures the net water flux to the surface
- On land:
  - Changes of P-E ($\delta(P-E)$) is positive especially in high latitudes, tropical Africa and southern Asia
- Across the ocean
  - The typical wet-gets-wetter, dry-gets-drier paradigm

Changes in P-E (2070 – 2099 – 1976-2005) in RCP8.5



Byrne and O'Gorman, 2015

MID-PLIOCENE CLIMATE SHOWS A SUBSTANTIAL INCREASE IN LAND $\delta(P-E)$ IN THE MONSOON REGIONS

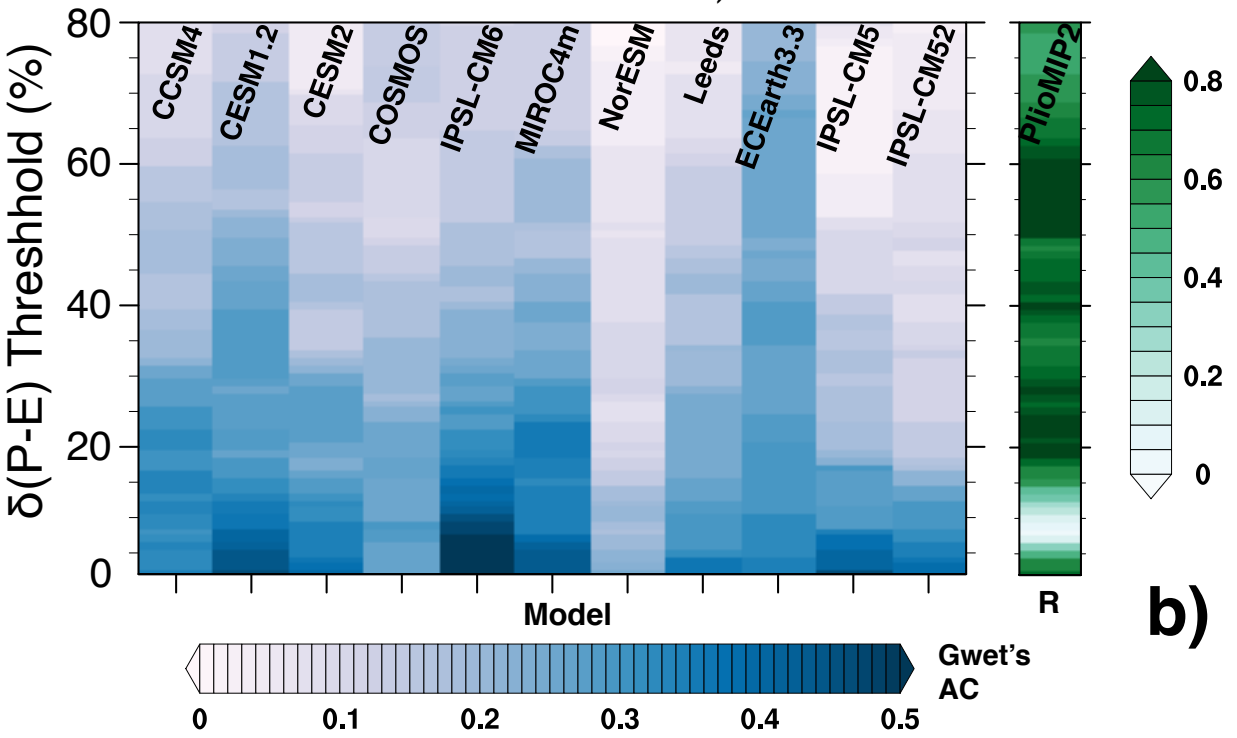


Proxy data from Tripti Battachaya at Syracuse University

PROXY DATA SUPPORT A WETTER SUBTROPICS

- **Definition of wetter and drier in the model**
  - **Wetter: $\delta(P-E)$>a% of (P-E) of preindustrial**
  - **Drier: $\delta(P-E)$<-a% of (P-E) of preindustrial**
  - **No change: -a%<$\delta(P-E)$<a%**
- **Most models and multi-model mean show good correlation with proxy hydroclimate indicators for a range of $\delta(P-E)$ threshold.**

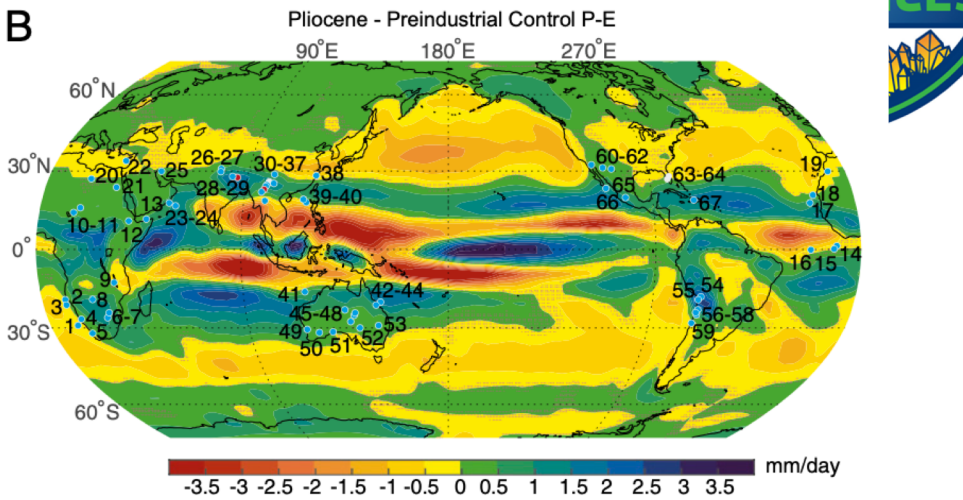
Gwet's AC (pattern correlation between proxy data and model)



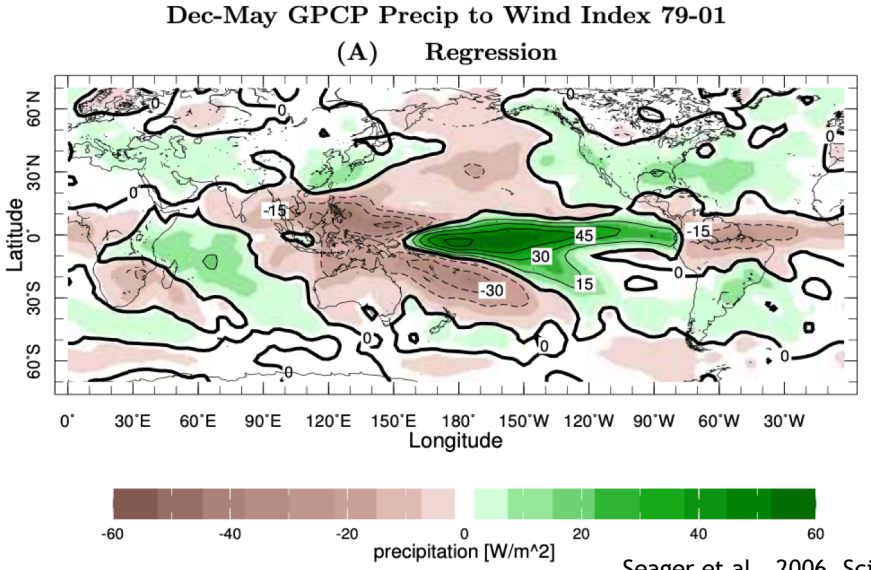
Calculation and figure from Tripti Battachaya at Syracuse University

POTENTIAL DRIVERS FOR LAND $\delta(P-E)$

- **Changes in Hadley Circulation**
  - **Weakened Hadley Circulation - weaker subsidence and moisture divergence from the subtropics (e.g., Rind, 1998; Brierley et al., 2009; Feng et al., 2016; Burl and Fedorov, 2017)**
  - **Poleward expansion of the Hadley circulation subsidence (Lu et al., 2007)**
- **El Nino-Teleconnection?**
  - **Strengthening of the subtropical jet**
  - **Southward shift of storm rack (in winter) (e.g. Seager et al., 2006; Goldner et al., 2014)**
- **Changes in the land warming pattern, and land-sea warm contrast**
  - **Driving continental hydroclimate responses (Byrne and O'Gorman, 2015; He et al., 2017)**



Burls and Fedorov, 2017, PNAS.



Seager et al., 2006, Science.

MOISTURE BUDGET ANALYSIS – IDENTIFY KEY DRIVERS

Following Seager and Henderson (2013), q: specific humidity, u: horizonal wind speed:

- $P - E = -\frac{1}{g\rho_w}\frac{\partial}{\partial t}\int_0^{Ps} qdp - \frac{1}{g\rho_w}\nabla \cdot \int_0^{Ps} uqdp$
- **P-E = -(temporal variability of column integrated moisture + divergence of integrated moisture transport)**

1. Consider a pair of experiments and apply the small perturbation method:

- $q_2 = q_1 + \delta q, u_2 = u_1 + \delta u, (P-E)_2 = (P-E)_1 + \delta(P-E), p_{s2} = p_{s1} + \delta p_s$

MOISTURE BUDGET ANALYSIS

2. Apply Reynolds decomposition to partition terms into climatology and transient:

- $\delta q = \delta\bar{q} + \delta q', \delta u = \delta\bar{u} + \delta u', \delta(P-E) = \overline{\delta(P-E)} + \delta(P-E)', u_1 = \bar{u}_1 + u_1', q_1 = \bar{q}_1 + q_1'$

partition climatologies into zonal mean and spatial variability:

- $\delta\bar{q} = \delta[\bar{q}] + \delta q_a, \delta\bar{u} = \delta[\bar{u}] + \delta u_a$

MOISTURE BUDGET ANALYSIS

- $\overline{\delta(P-E)} =$

$$-\frac{1}{g\rho_w}\frac{\partial}{\partial t}\int_0^{\overline{P_{s2}}}\overline{\delta q}\,dp - \frac{1}{g\rho_w}\nabla\cdot\int_0^{\overline{P_{s2}}}(\bar{u}_1(\delta[\bar{q}]+\delta q_a)+\bar{q}_1(\delta[\bar{u}]+\delta u_a)+\delta\bar{u}\delta\bar{q})dp$$
$$+resi\ 1+resi\ 2$$

From left to right:

- **Changes in seasonal cycle - almost none (not shown)**
- **Changes in zonal mean moisture content**
- **Changes in zonal variability of moisture**
- **Changes zonal mean circulation**
- **Changes in stationary waves kinetics**
- **Covarying changes in moisture content and horizontal wind – nonlinear term**
- **Changes in surface pressure(resi 1) + changes in eddy kinetics and eddy moisture transport (resi 2) – not enough available data for (less important)**

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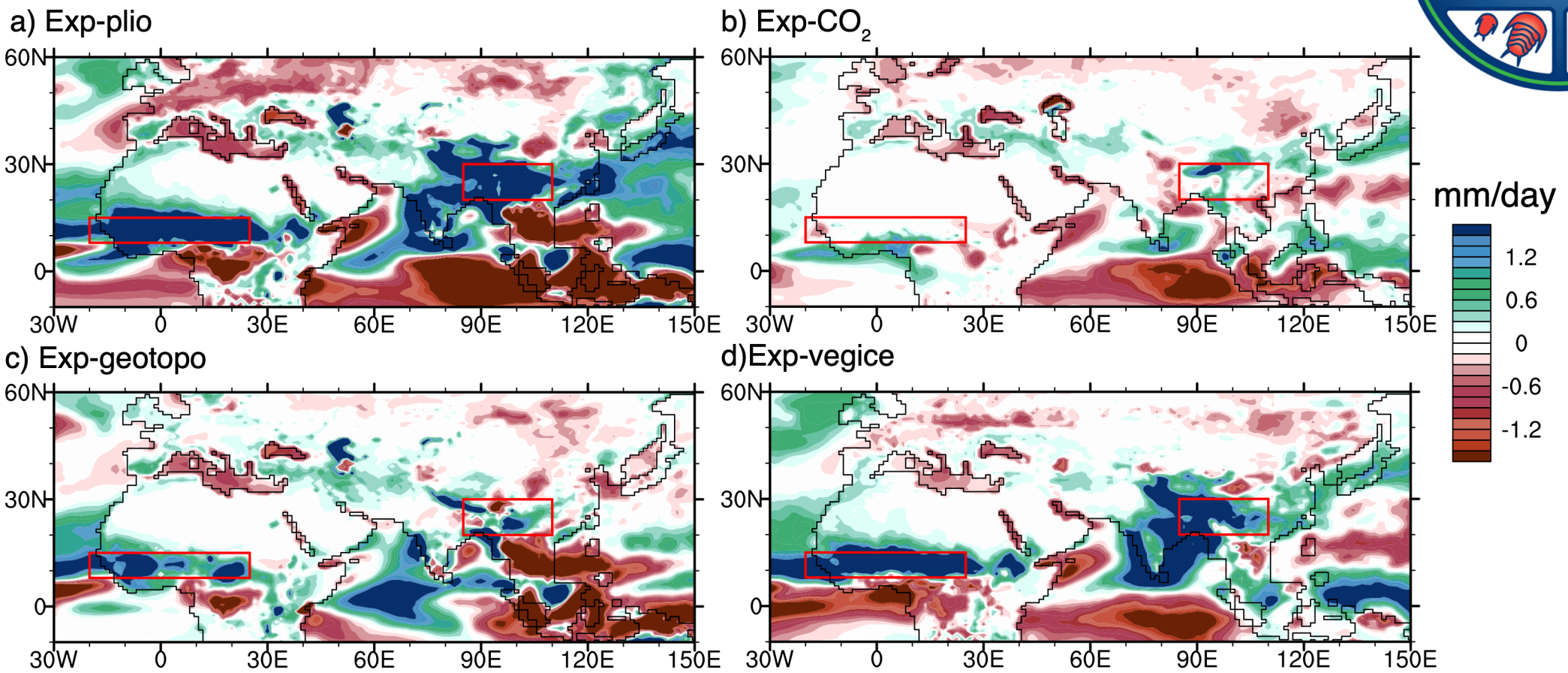
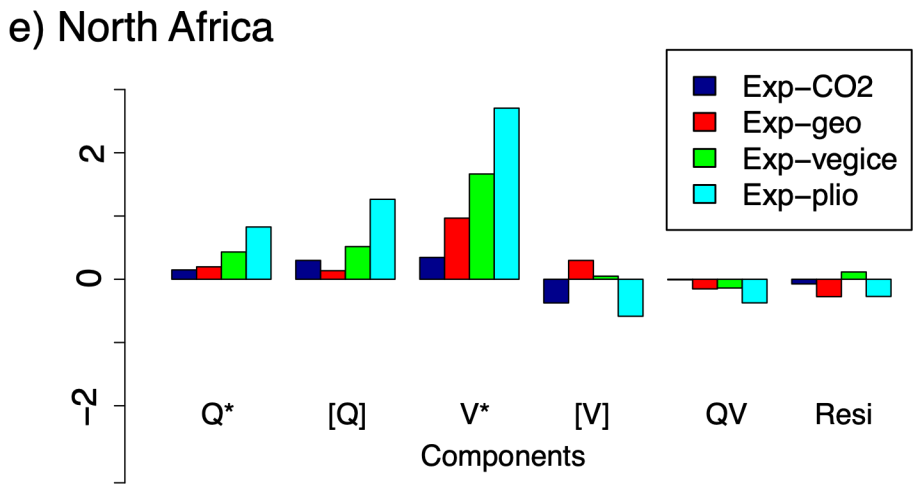
CESM2 EXPERIMENTS TO UNDERSTAND DRIVERS OF INCREASING (P-E) IN MONSOON REGIONS OF MID-PLIOCENE

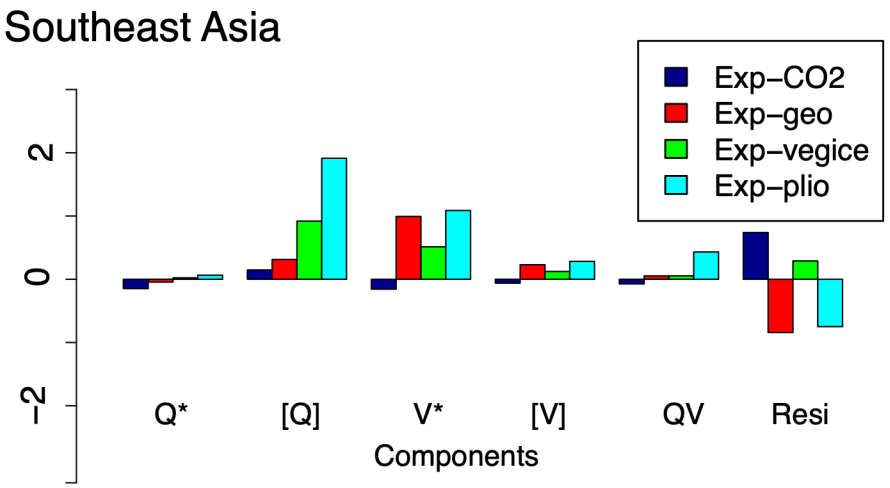
Experiment sets	Experiments	CO_2	Topography and Bathymetry	Vegetation and ice sheets
Exp-plio	Sensitivity-mid-Pliocene simulation	400 ppm	Mid-Pliocene	Mid-Pliocene
	Control (PI experiment)	284.7 ppm	PI	PI
Exp-CO_2	Sensitivity – new simulation	400 ppm	PI	PI
	Control (PI experiment)	284.7 ppm	PI	PI
Exp-geotop	Sensitivity – new simulation	284.7 ppm	Mid-Pliocene	PI
	Control (PI experiment)	284.7 ppm	PI	PI
Exp-vegice	Sensitivity (CESM2 PlioMIP2 experiment)	400 ppm	Mid-Pliocene	Mid-Pliocene
	Control (new simulation)	400 ppm	Mid-Pliocene	PI

RESULTS: $\delta(P - E)$ CHANGES



RESULTS: BUDGET ANALYSIS





Resi: small, consistent with reduction in 850 hPa Eddy kinetic energy and weakened subtropical jet

[V]: small, despite weakening of the northern Hadley circulation, little contribution from zonal mean circulation

[Q]: substantial, thermodynamic component (wet-gets-wetter, dry-gets-drier)

V*: substantial, stationary wave kinetics

CONCLUSION

- Moistening of monsoon regions in the North Africa and Southeast Asia in mid-Pliocene simulations is consistent with proxy data
- Changes in (P-E) is primarily driven by continental greening and loss of ice sheet through enhancing the moisture content of troposphere and altering stationary wave kinetics
- Little or negative effect from changes in zonal mean circulation or transient eddy – suggesting unimportant role of Hadley Circulation and El Nino-like SSTs (not necessary to reproduce wet continental climate in the subtropics…)

Thank you!

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