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GLOBAL CHANGES IN PRECIPITATION MINUS EVAPORATION

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National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

PLOS WATER

Water remains a blind spot in climate change policies

Hervé Douville[1]*, Richard P. Allan[2], Paola A. Arias[3], Richard A. Betts[4,5], Martina Angela Caretta[6], Annalisa Cherchi[7], Aditi Mukherji[8], Krishnan Raghavan[9], James Renwick[10]

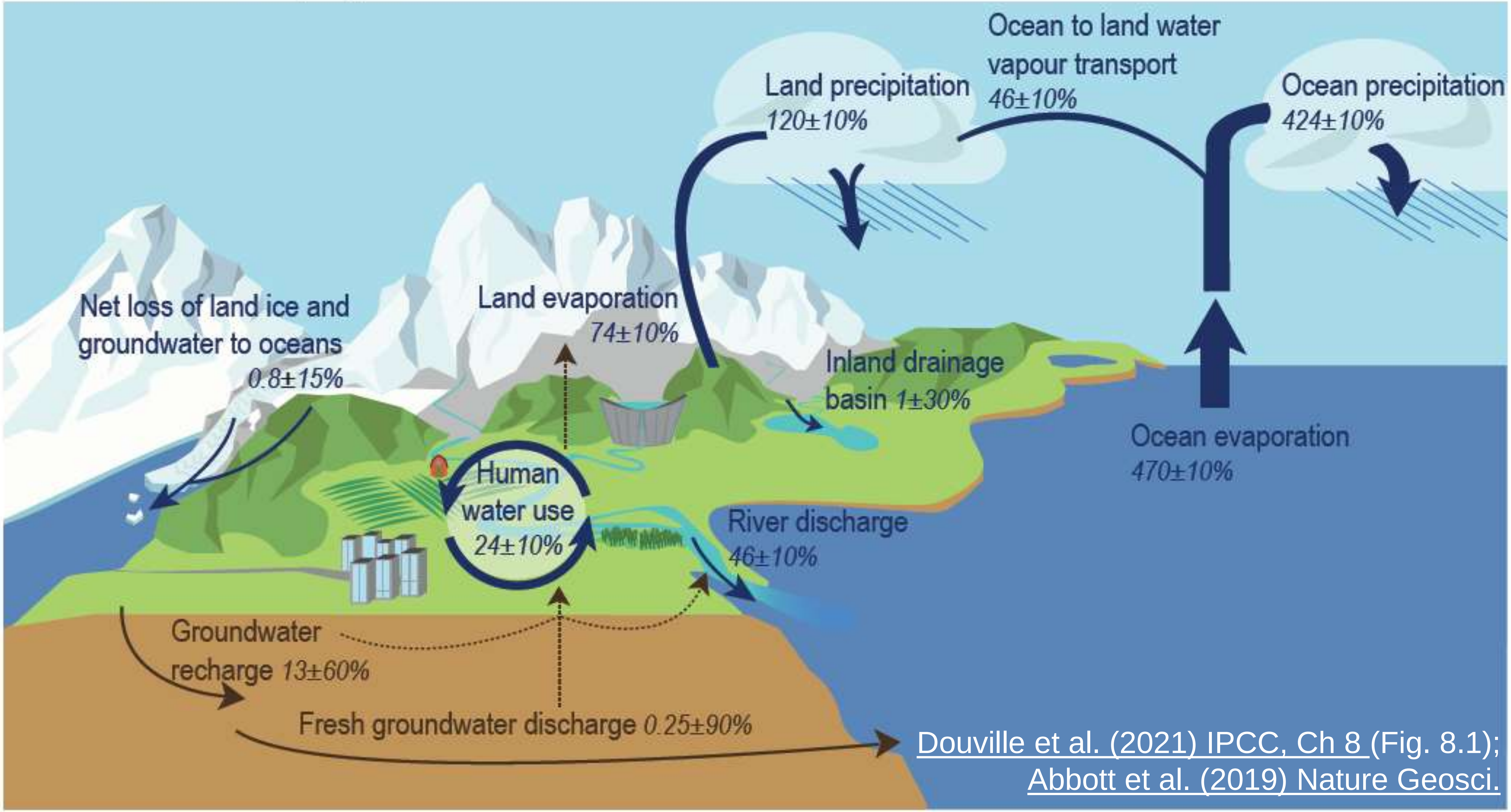
Water & policy

Water yet to received the full attention it deserves from policymakers

- Beyond temperature and daily weather extremes
- Longer duration events and variability important
- Mitigation as well as Adaptation strategies

The Global Water Cycle

(b) Water fluxes
Units in thousands of km^3 per year



Douville et al. (2021) IPCC, Ch 8 (Fig. 8.1); Abbott et al. (2019) Nature Geosci.

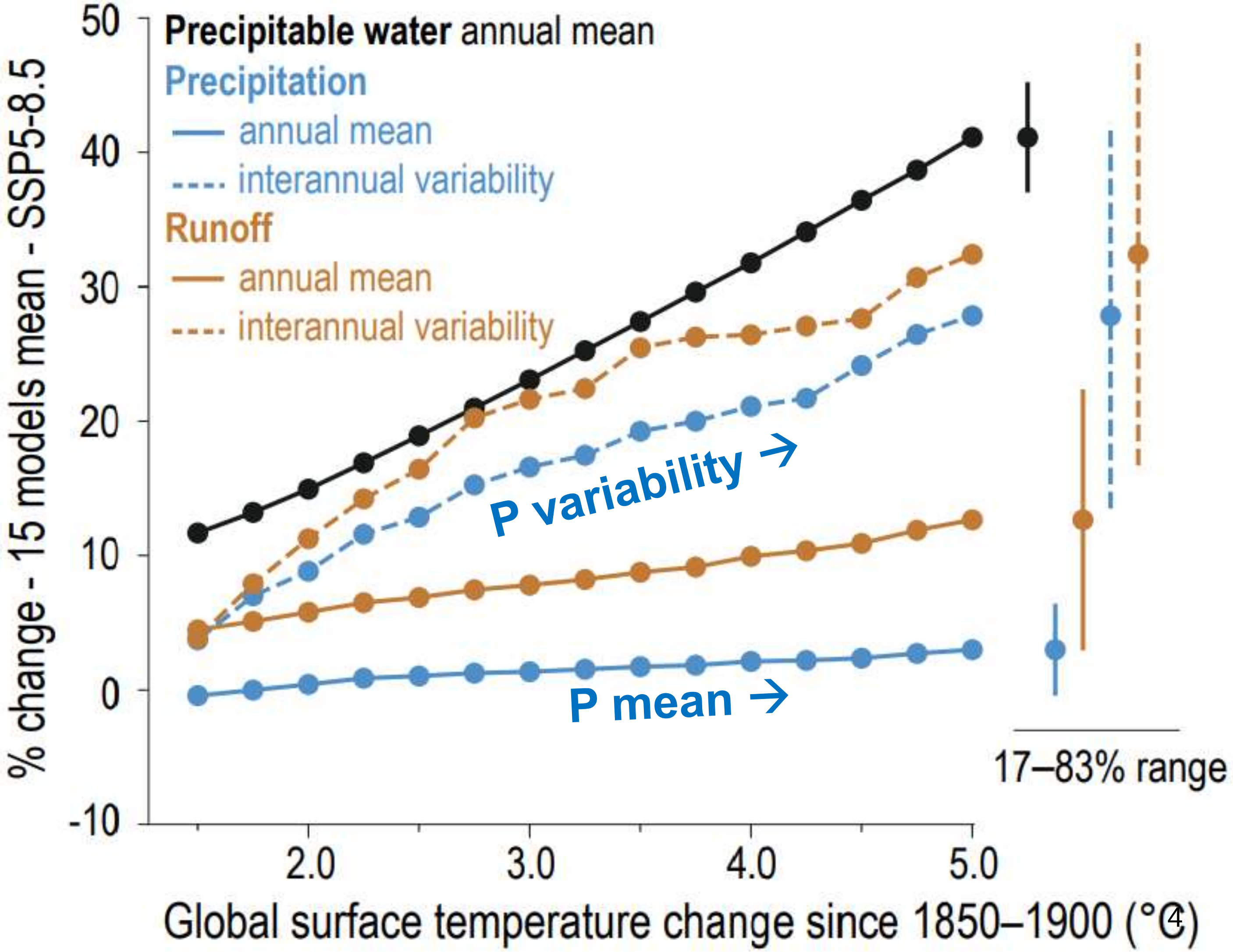
Increased water cycle variability

"Continued global warming is projected to further intensify the global water cycle, including its variability… and the severity of wet and dry events."
[IPCC, 2021 SPM]

see Pendergrass et al. (2017) Nature Clim.

tropical land

IPCC (2021) TS Box 8.2; Figure TS.12



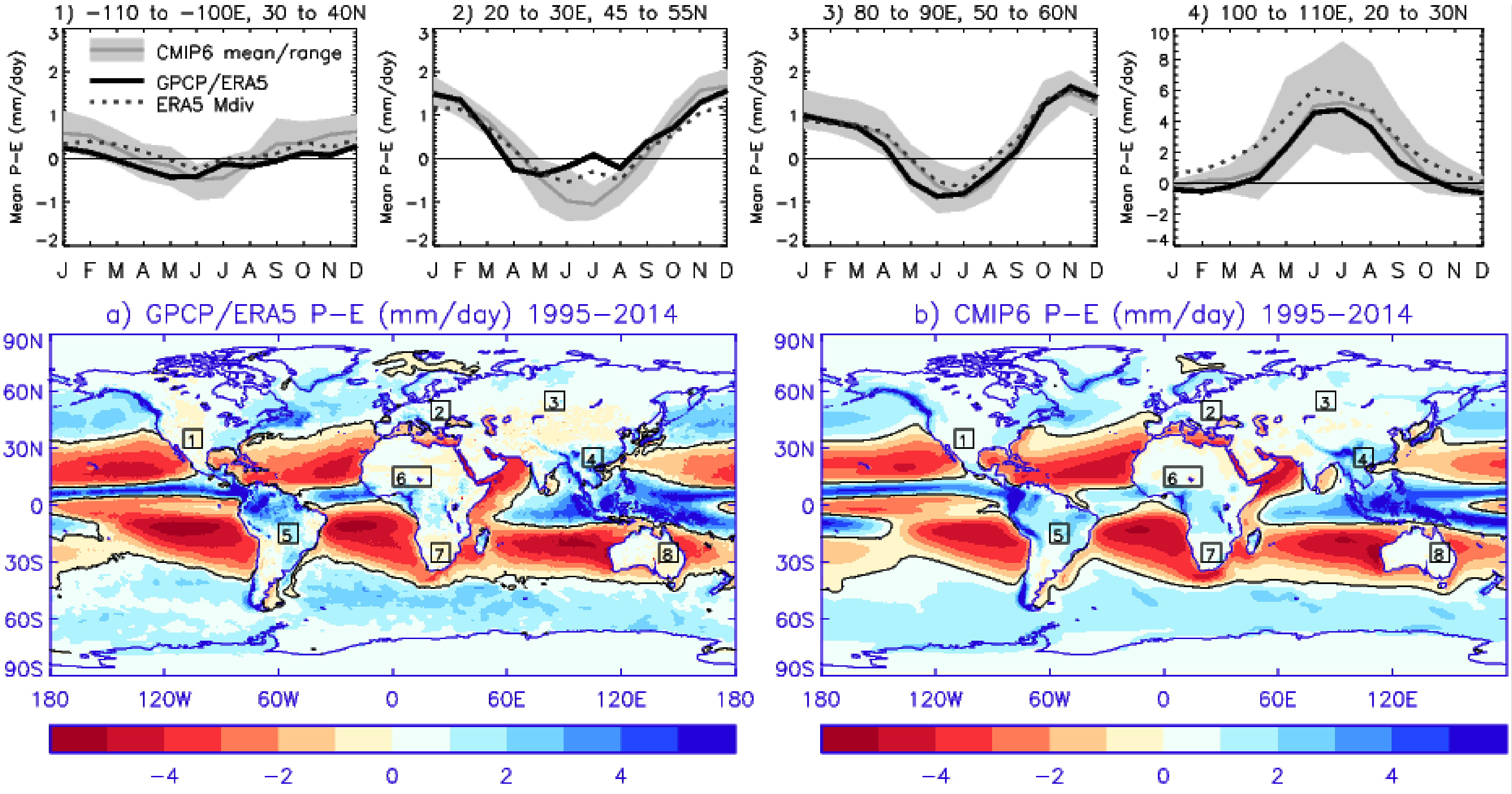
Precipitation minus Evaporation (P-E)

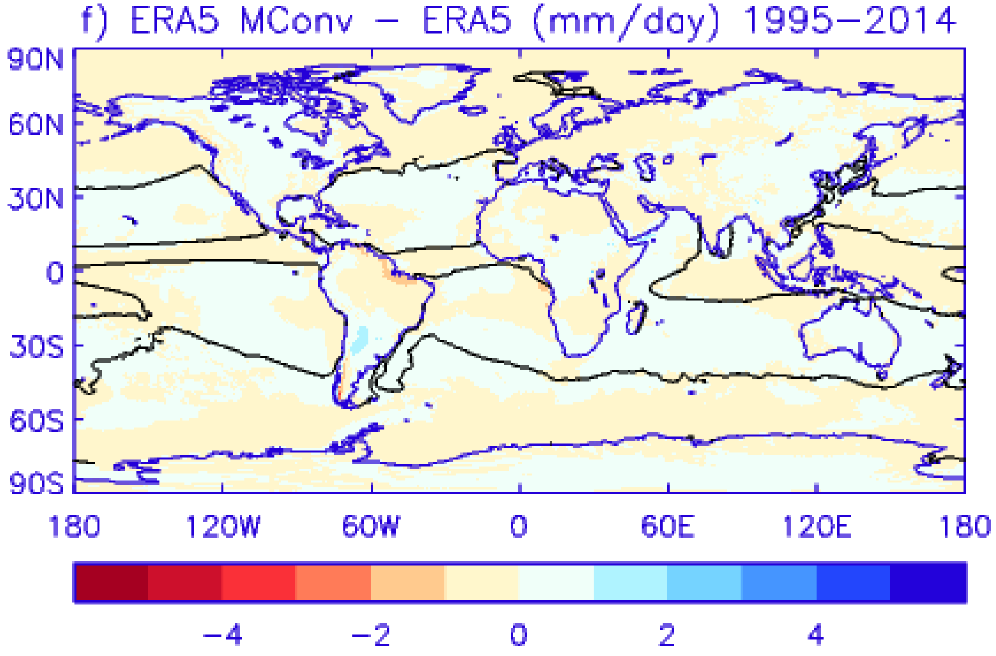
  - Net supply of Freshwater (land)
  - Surface salinity and circulation (ocean)
- Balanced by moisture transport (atmosphere) & runoff (surface)
- P-E maximum: wet season/months, precipitation driven
- P-E minimum: lack of precip, high evaporation, drying ground
  - diagnostic of dry period onset intensity
  - relevance to flash droughts e.g. Emily Black's talk

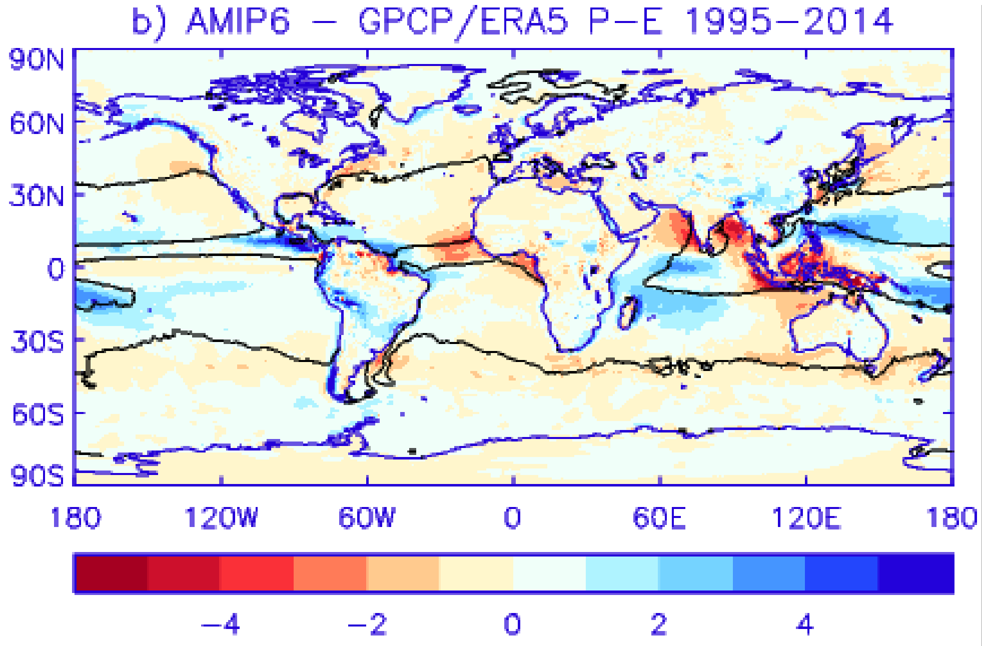
METHOD:

- annual grid-point mean P-E and 3-month or 1-month annual max & min
- GPCP/ERA5 (1983-2019); ERA5, ERA5 moisture divergence (1960-2020)
- 17 CMIP6 models historical/ssp2-4.5 (1950-2014-2100); amip (1979-2014)

Climatological P minus E

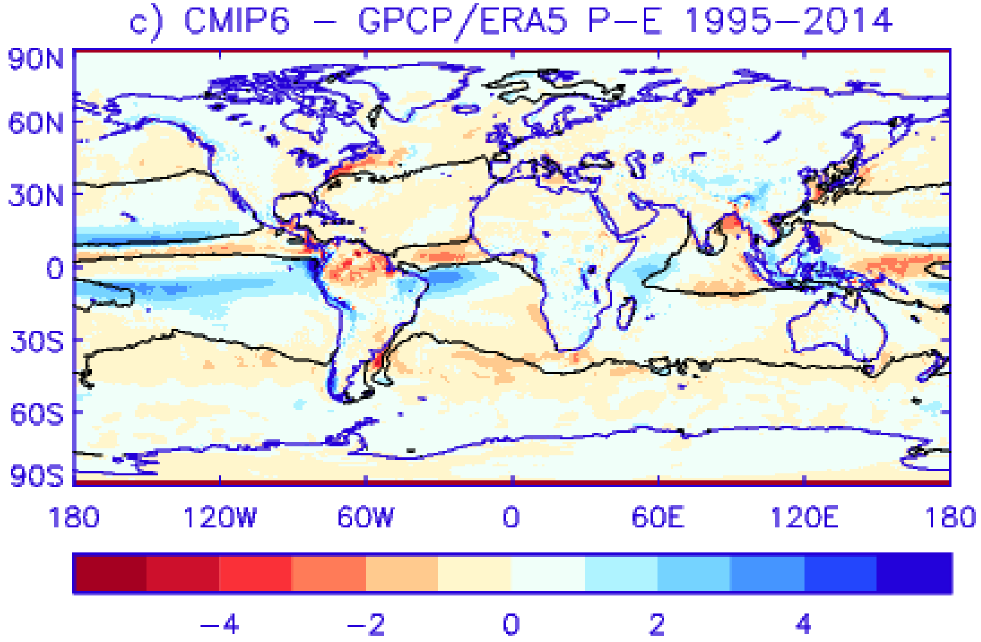


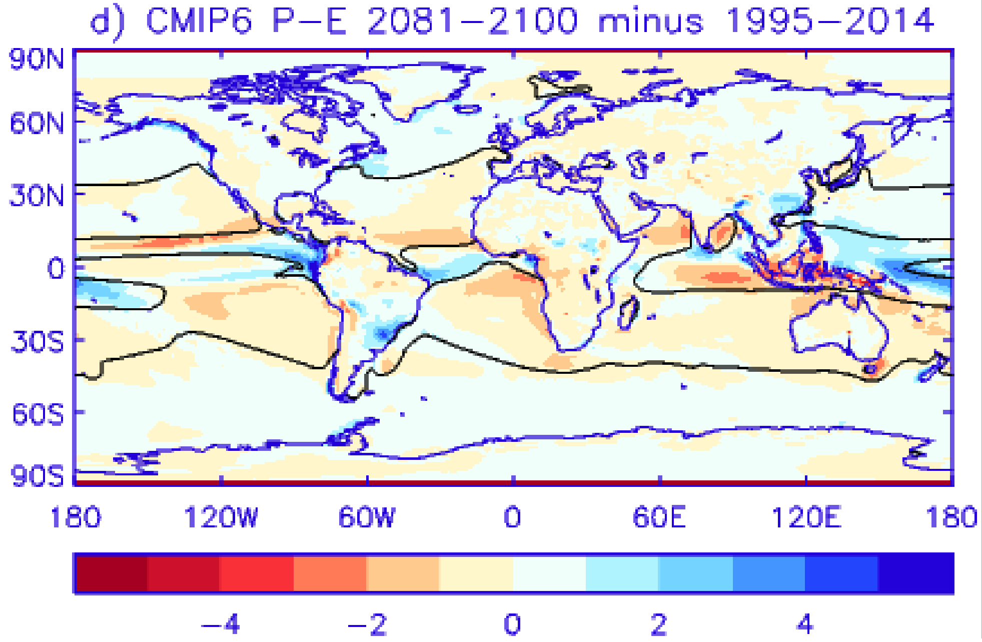




ERA5 Bias
CMIP Bias

AMIP Bias
CMIP6 Future Projection





Amplification of P-E patterns

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$$\mathbf{P - E = -\nabla.F - \Delta W}$$

$$\Delta W = \Delta \frac{1}{g}\int_{p_s}^{0} q\,dp \text{ is small; } \quad F = -\frac{1}{g}\int_{p_s}^{0} q\,u\,dp$$

$$\Delta F \sim \alpha \Delta T . F$$

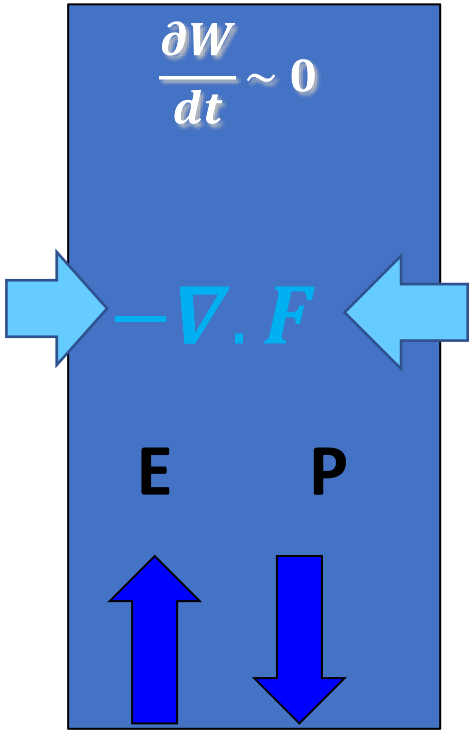
$\alpha \sim dF/F \sim dq/q \sim de_s/e_s \sim 7\%/^oC$, assuming changes in mean & eddy flow small so determined by increases in saturation vapour pressure by Clausius Clapeyron equation, assuming constant RH

$$\Delta(P - E) \sim -\nabla.\Delta F \sim \alpha\Delta T(-\nabla.F)$$

assuming temperature gradients and relative humidity changes & gradients can be removed from derivative, …more of a stretch

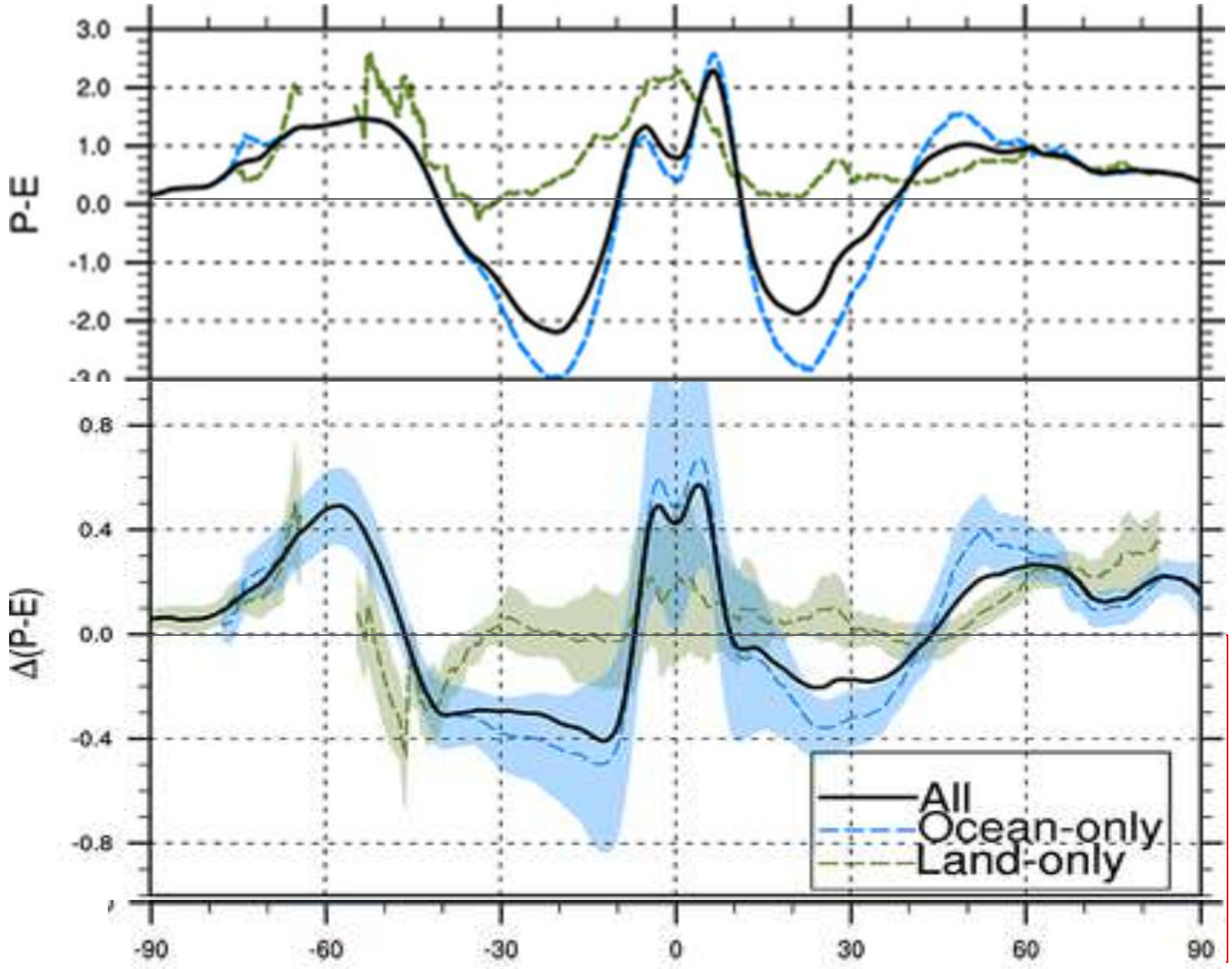
$$\Delta(P - E) \sim \alpha \Delta T(P - E)$$

P-E changes roughly scale with P-E: amplification of P-E patterns



$$P - E \sim -\nabla.F$$

Held & Soden (2006) J. Clim;
Byrne & O'Gorman (2015) J. Clim;
Zaitchik et al. (2023) Nature Water



Wet wetter, dry drier?

- P-E zonal mean
- P-E zonal mean projected change

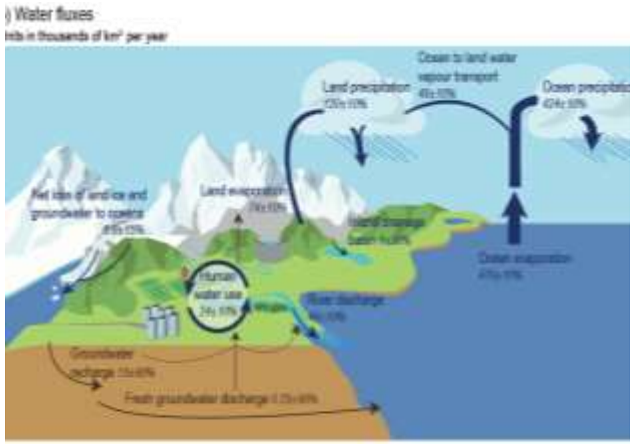
Greve & Seneviratne (2015) GRL

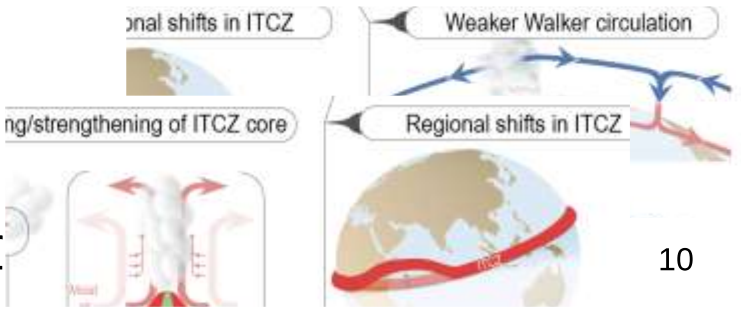
See Douville et al. (2021) IPCC, Ch 8 (Section 2.2); Allan et al. (2020) NYAS; Zaitchik et al. (2023) Nature Water

P-E response over land complex

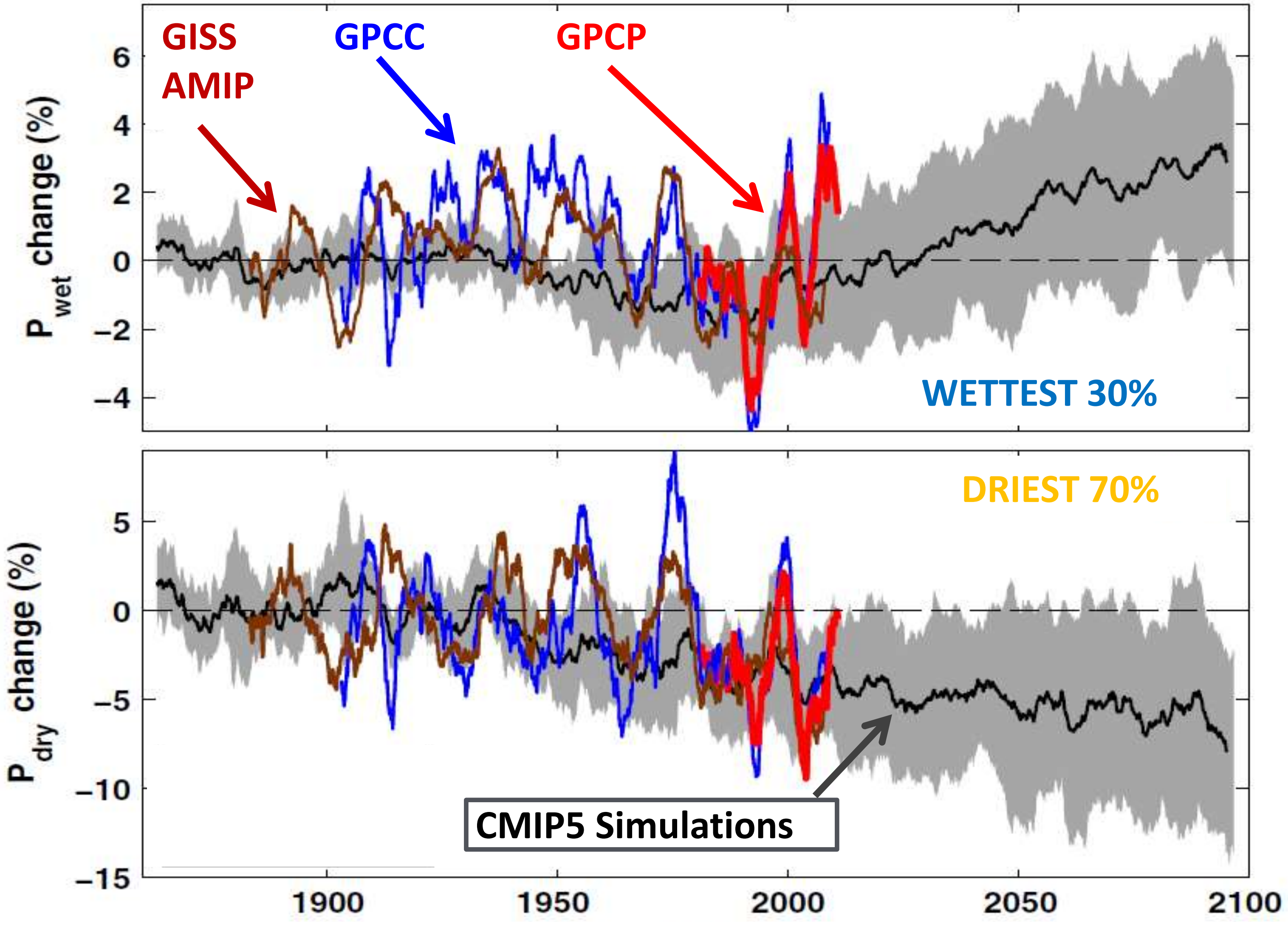
- Multi-annual P-E > 0 over land: implies increased P-E
  Held & Soden (2006) J. Clim.; Greve et al. 2014 Nature Geosci.
- Changes in T/RH gradients, land-ocean warming contrast, vegetation response & feedbacks important
  Byrne & O'Gorman 2015, 2016 J. Clim; Berg et al. 2013 Nature Geosci.
- But P-E < 0 in dry season over land: more intense dry *and* wet seasons?
  Liu & Allan 2013; Kumar et al. 2015 GRL; Wainwright et al. 2022 GRL
- Aridity or demand surplus/deficit more relevant
  Scheff & Frierson 2015 J. Clim.; Greve & Seneviratne 2015 GRL; Roderick et al. 2014 HESS ; Milly & Dunne 2016 Nature Clim.; Ficklin et al. 2022 Earth's Future; Xu et al. 2022 Nature Comms:
- …changes in circulation dominate locally
  Scheff & Frierson 2012; Chadwick et al. 2013; Muller & O'Gorman 2011; Allan 2014 Nature Geosci.; He & Soden (2016) Nature Clim.:

see reviews in Allan et al. (2020) NYAS & Zaitchik et al. (2023) Nature Water





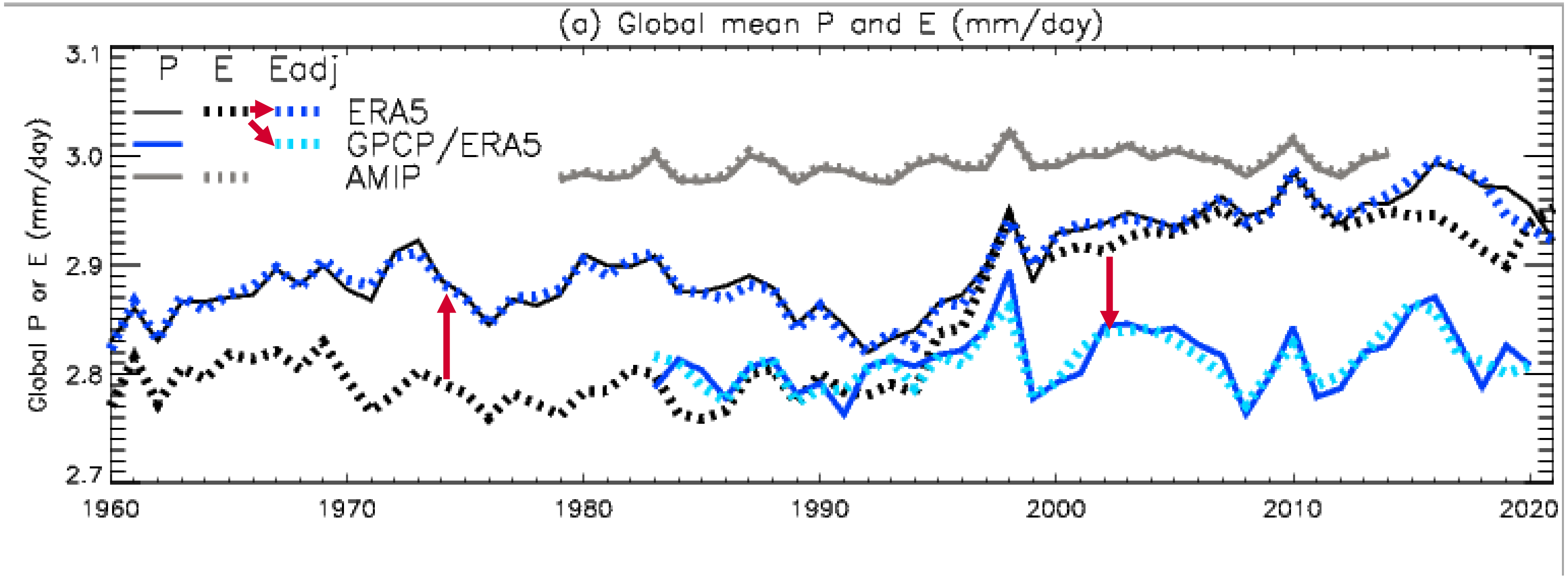
Larger seasonal & interannual contrasts in tropics



- Dynamically track wettest 30%, driest 70% regions each month
- Tropical land precipitation increases in wet regime, decreases in dry regime
- Observed decadal variability explained by internal variability

See also **Schurer et al. (2020) ERL**; **Kumar et al. (2015) GRL**

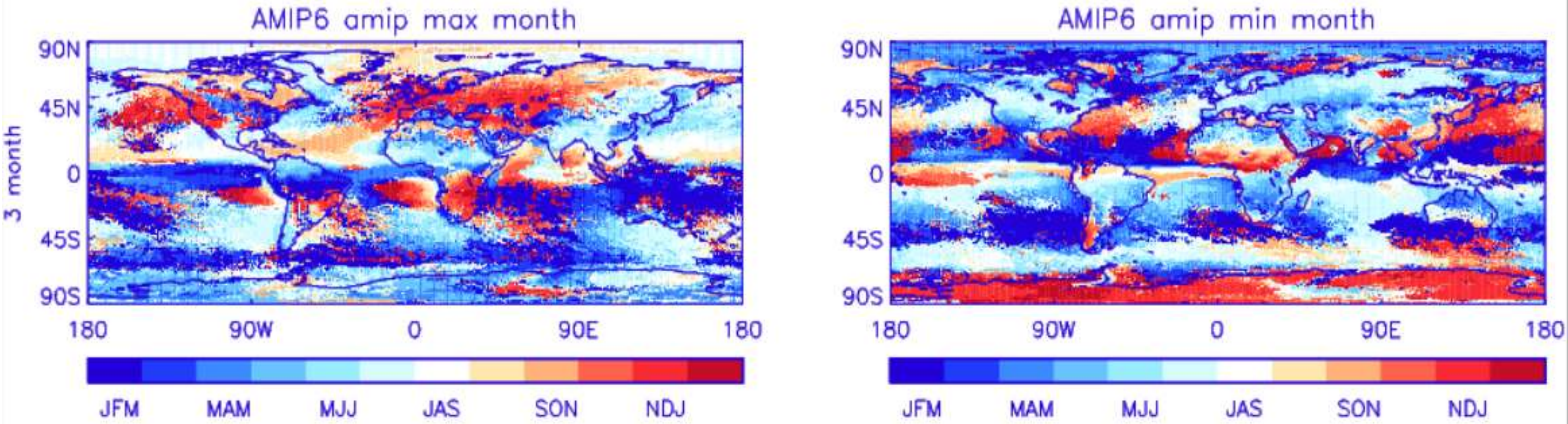
Liu & Allan (2013) ERL update in *Tropical Extremes: Natural Variability & Trends*



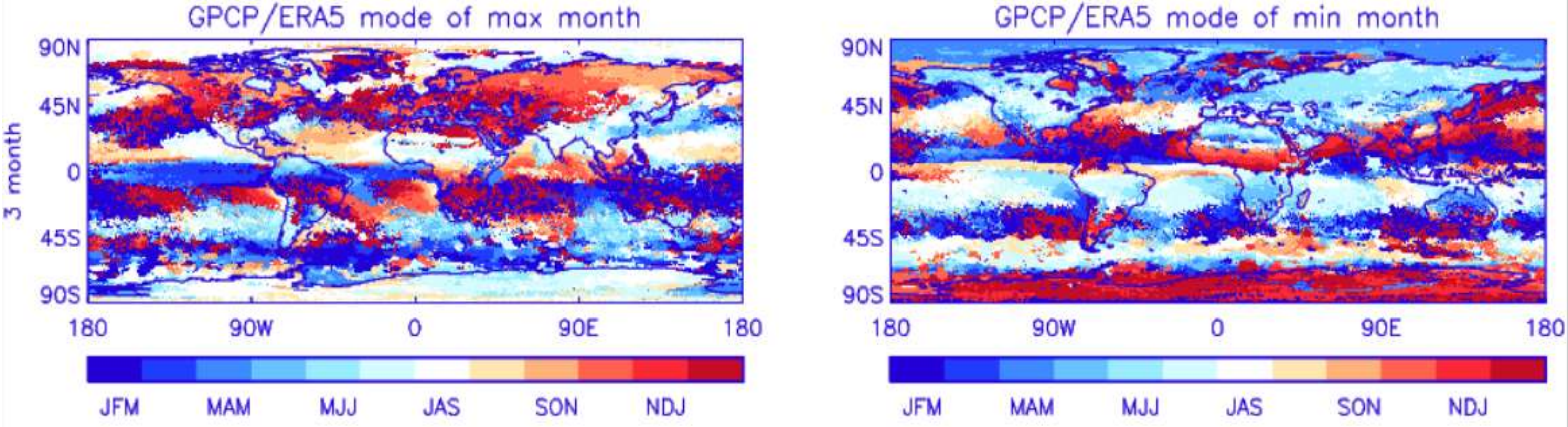
Constrain to Global mean ∫(P – E) = 0

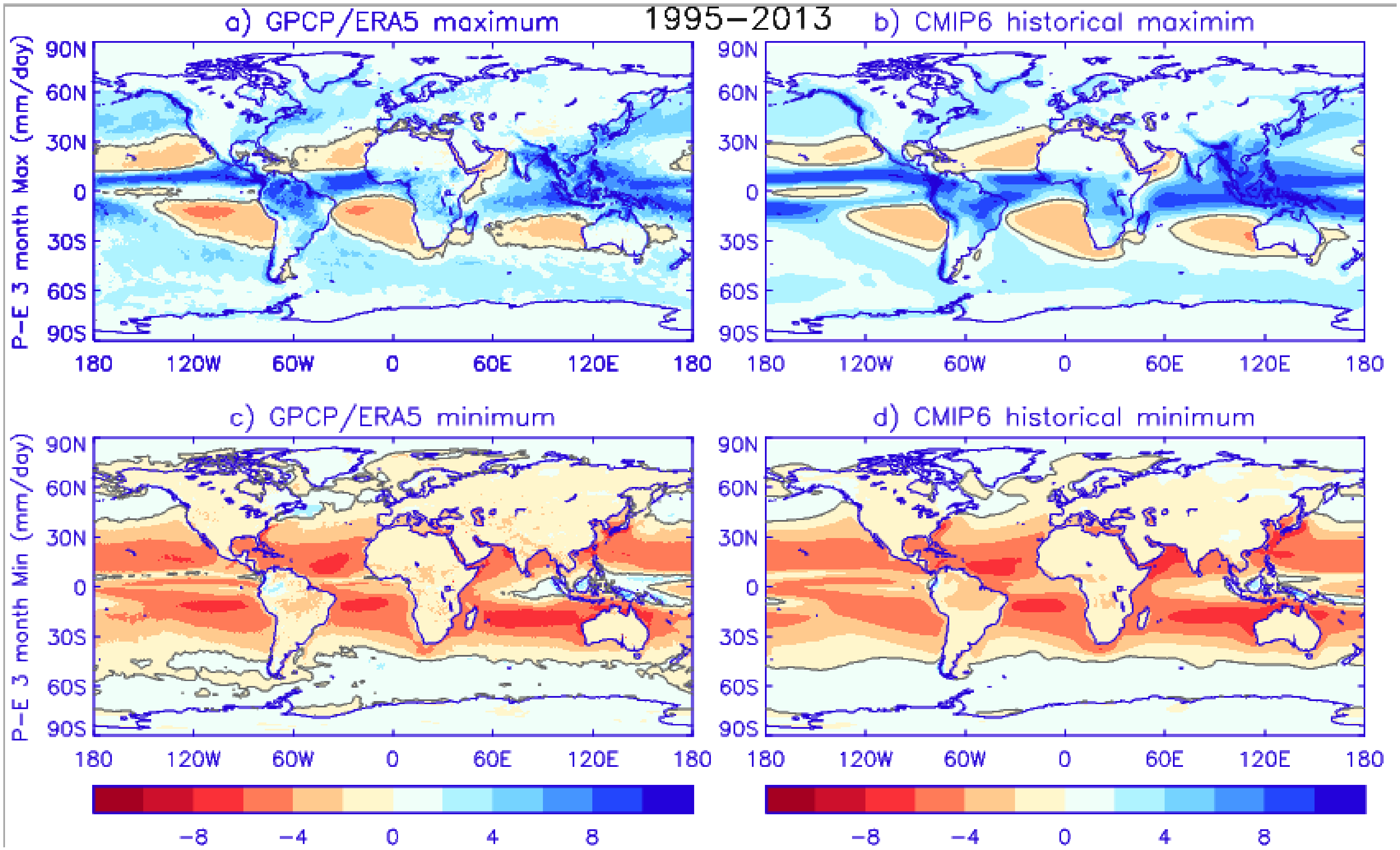
Scale ocean E so ∫(P – E) = 0

- ocean dominant
- observing system changes
- land changes looked suspect when scaled



Artistic interlude

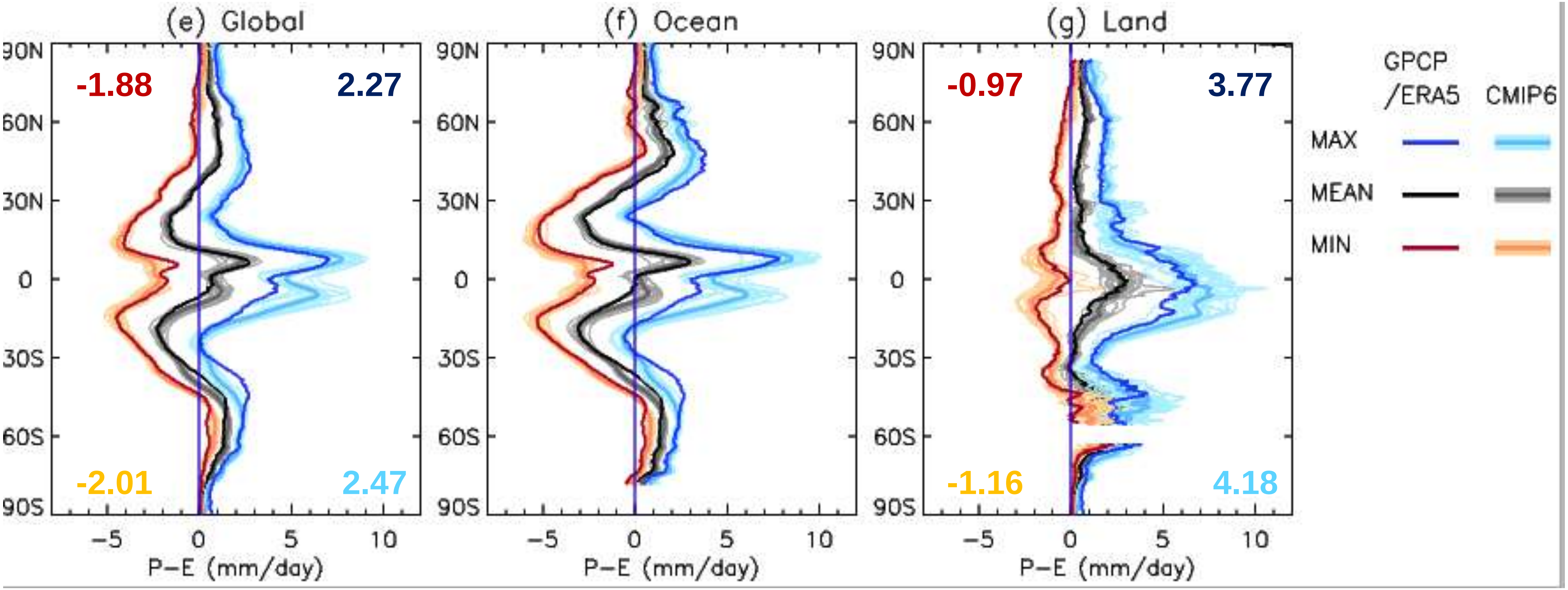


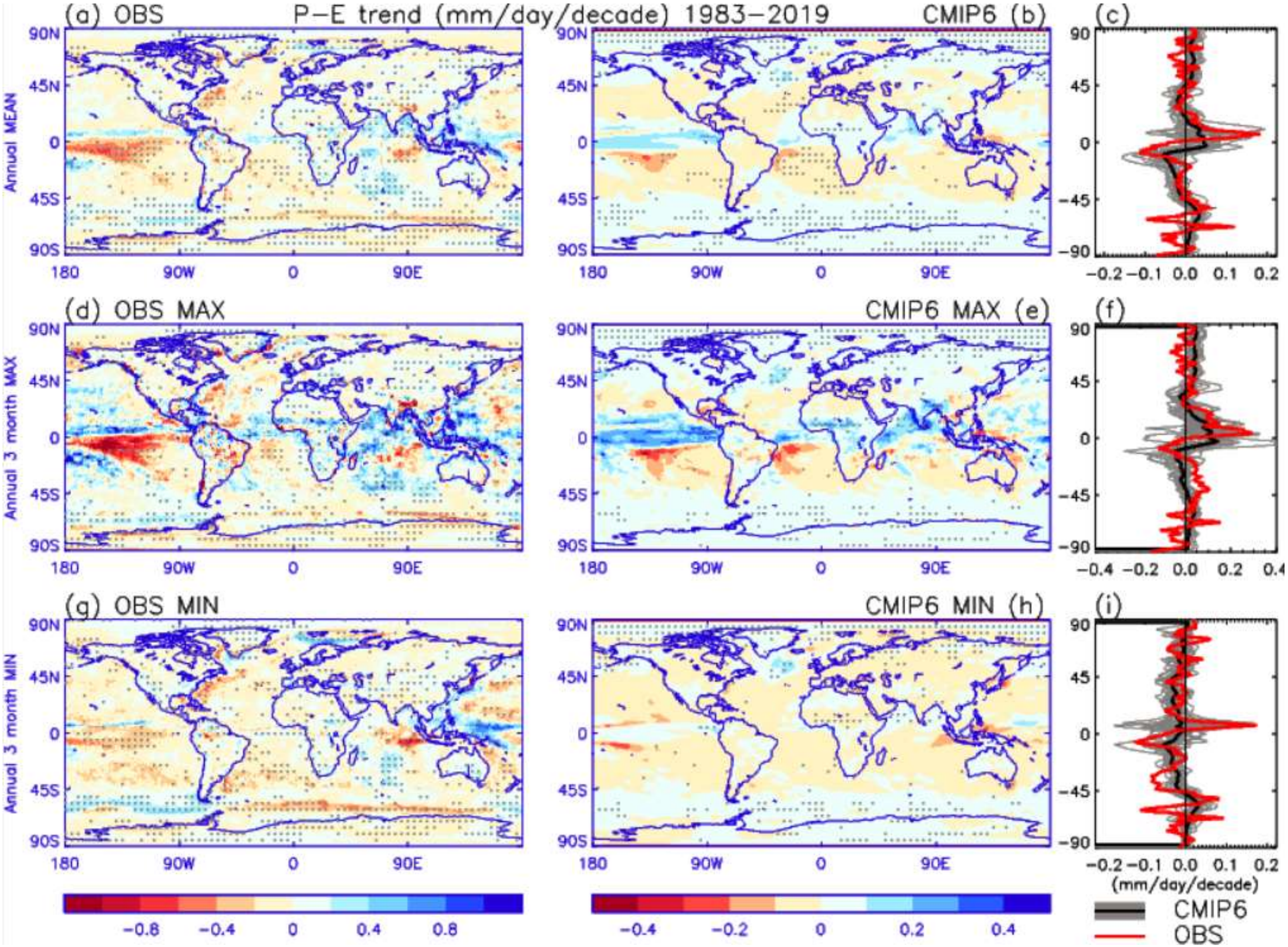


Annual maximum & minimum P-E

(1995-2013 average, 3-month annual max & min)

Zonal mean of seasonal Max/Min & annual **Mean** P-E





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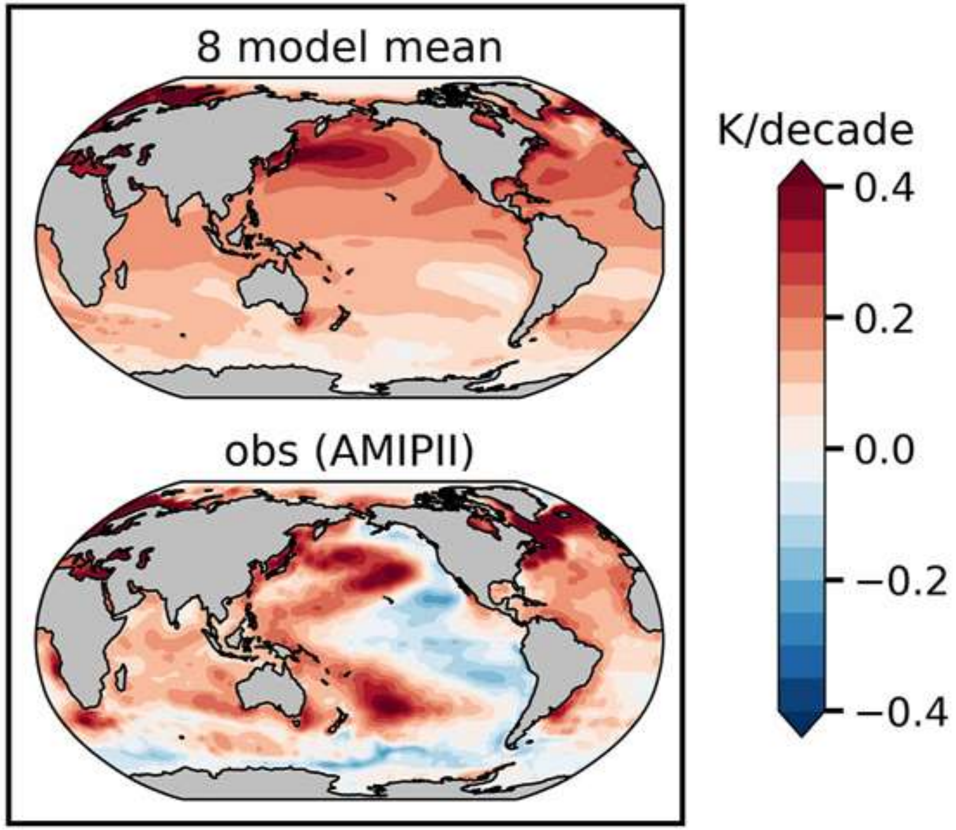
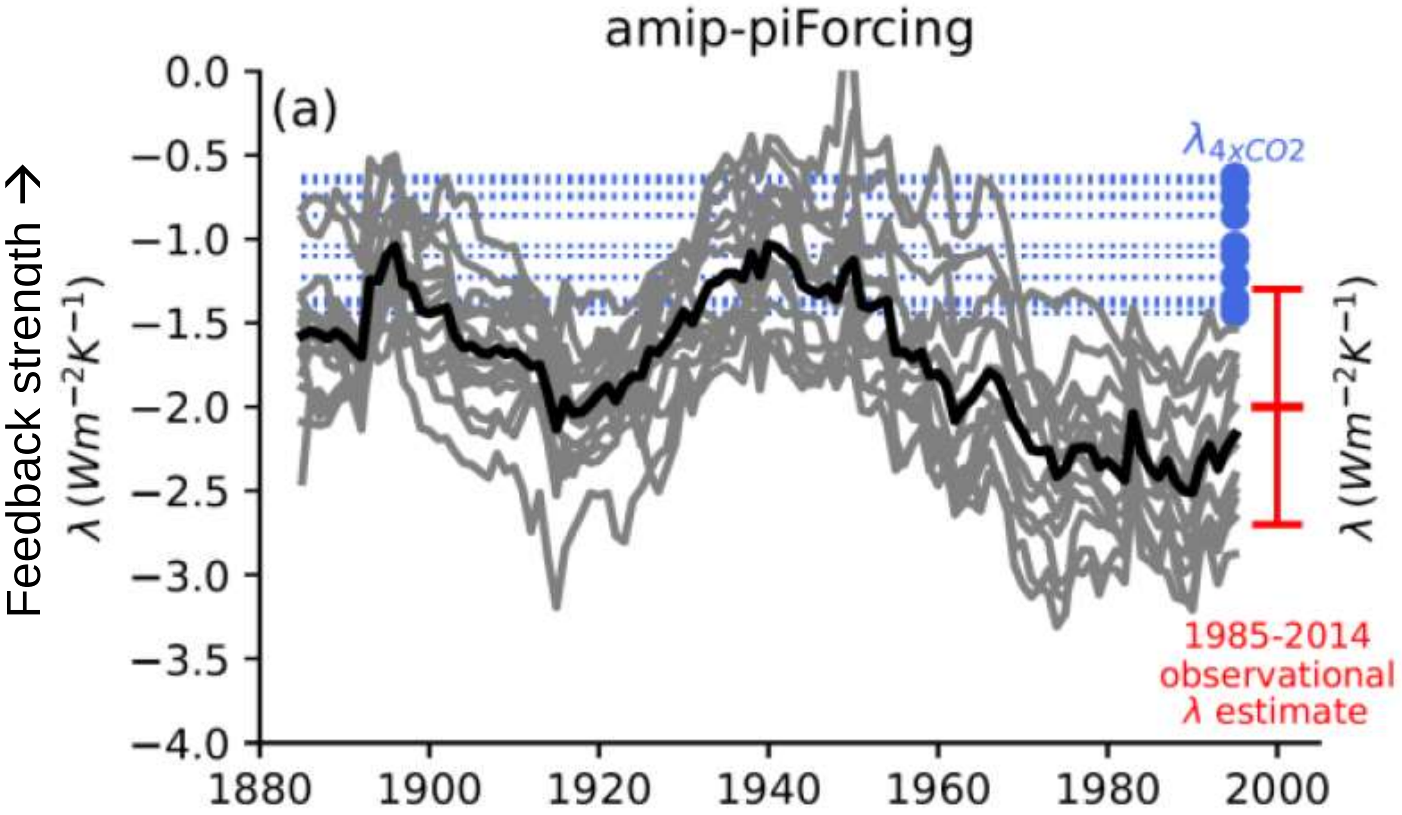
P-E Trends:
Seasonal
1983-2019

OBS CMIP6

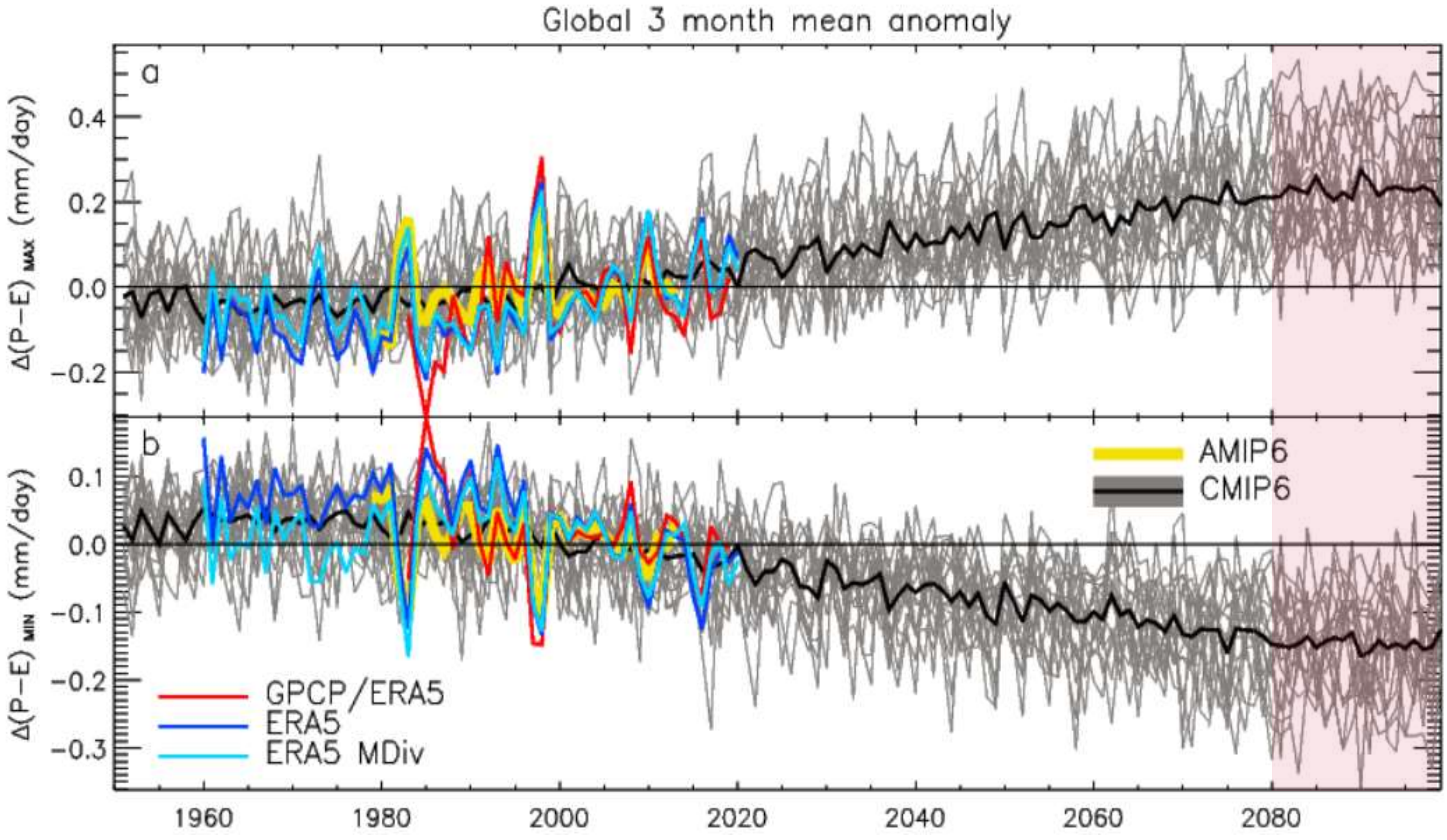
Aside: Warming Pattern Effect





Pattern of observed warming (1979-2014) is unexpected!
Dong et al. (2021) GRL

Observed pattern of global warming has weakened climate feedbacks relative to coupled models
(Andrews et al. 2022 JGR)



UKESM1-0-LL

+0.23 mm/day

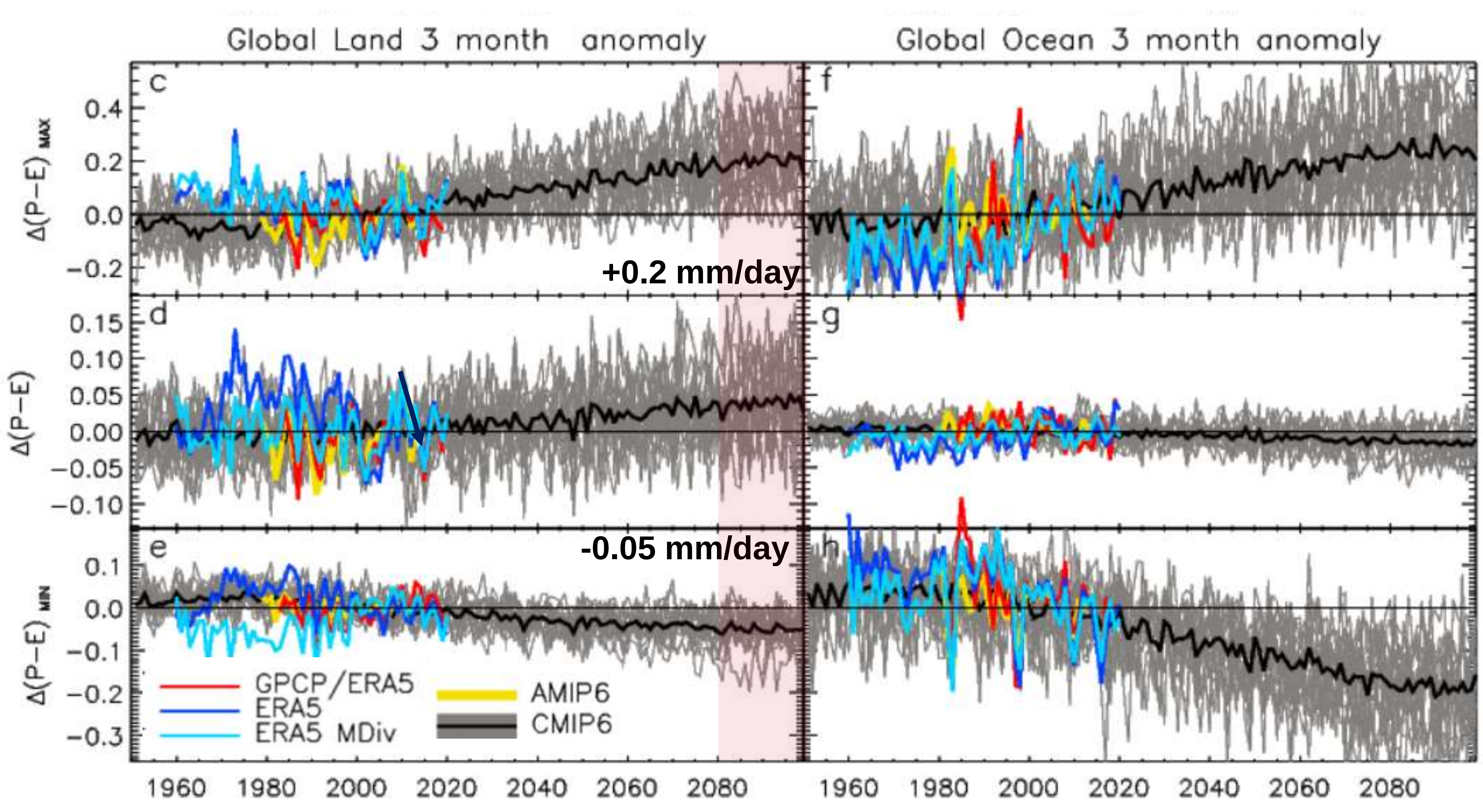
INMCM; MICROC6

INMCM; MICROC6

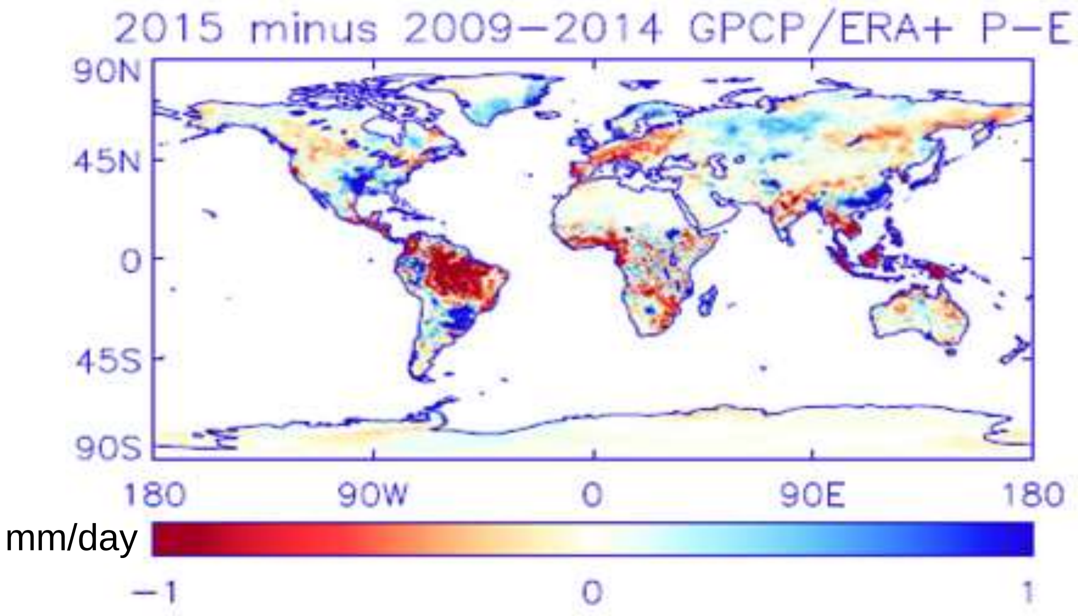
-0.15 mm/day

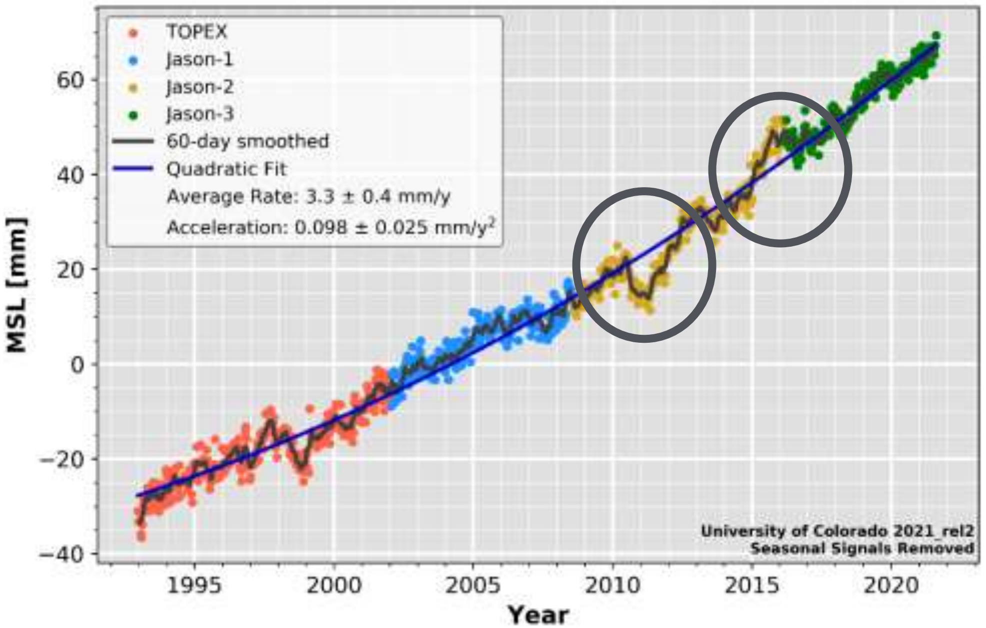
UKESM1-0-LL

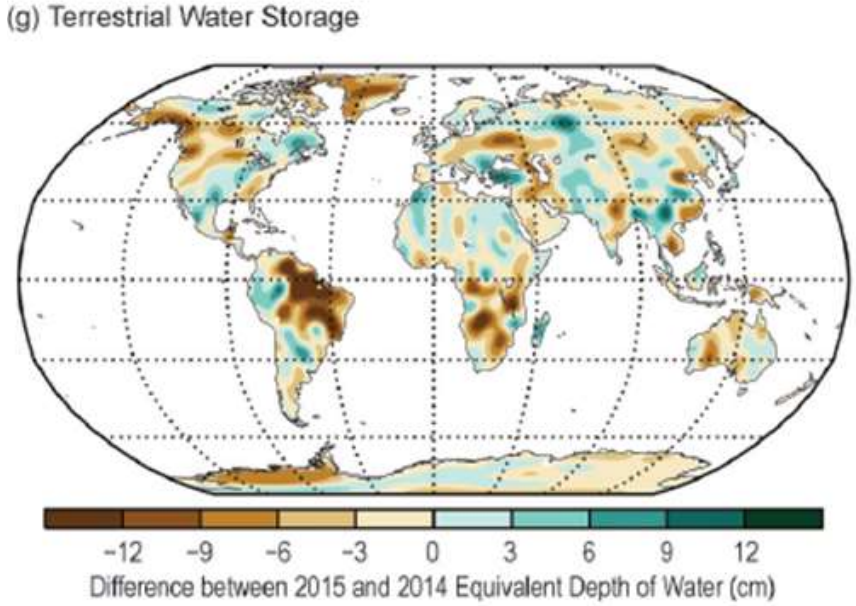
Similar to changes in wettest vs driest regions precip Liu & Allan (2013) ERL

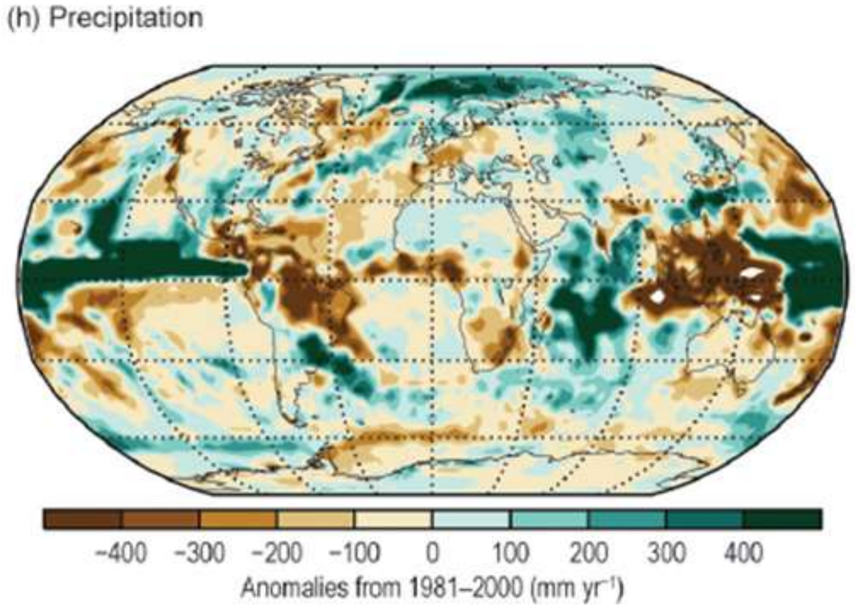

Global Land 3 month anomaly
Global Ocean 3 month anomaly
c
d
e
f
g
h
Δ(P−E) MAX
Δ(P−E)
Δ(P−E) MIN
+0.2 mm/day
-0.05 mm/day
GPCP/ERA5
ERA5
ERA5 MDiv
AMIP6
CMIP6
1960
1980
2000
2020
2040
2060
2080

Chasing water through 2015/16 El Niño









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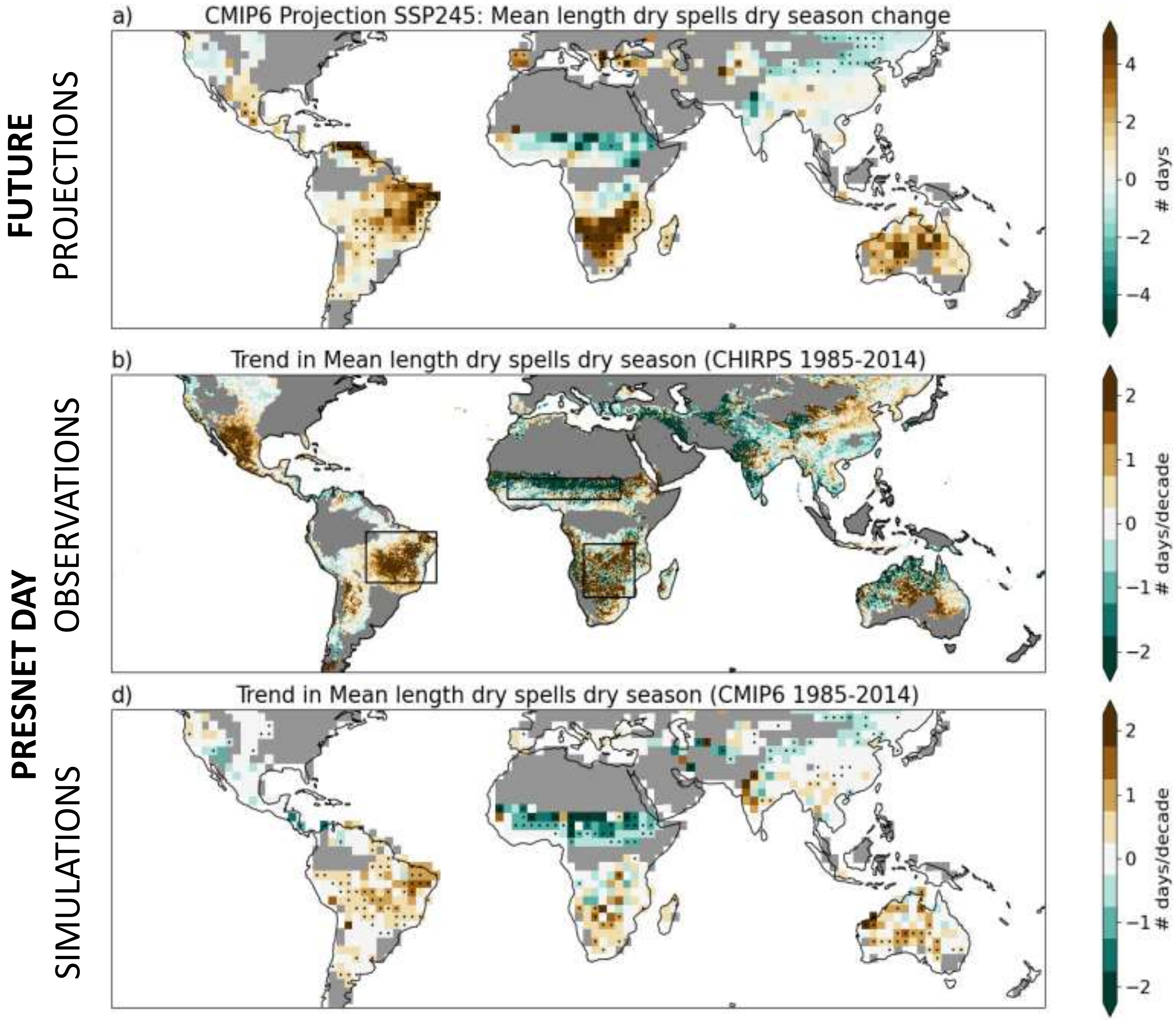
← BAMS state of the climate 2015

Boening et al. (2012) GRL: The 2011 La Niña so strong, the oceans fell

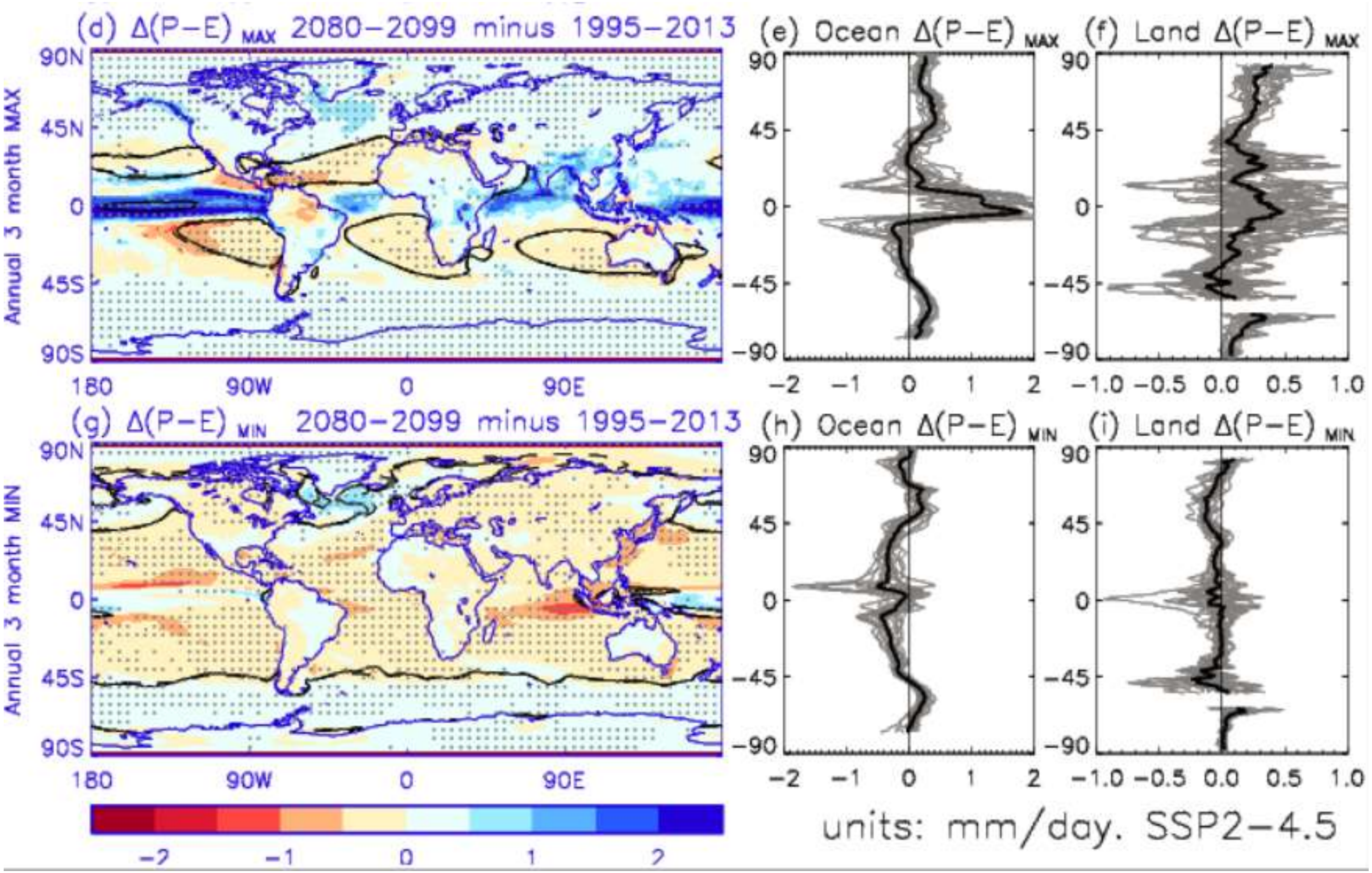
Emerging signals

- Emerging signals of more intense dry seasons over eastern Brazil, southern Africa and Australia (opposite in Sahel)

Wainwright et al. (2022) GRL →



FUTURE CHANGE



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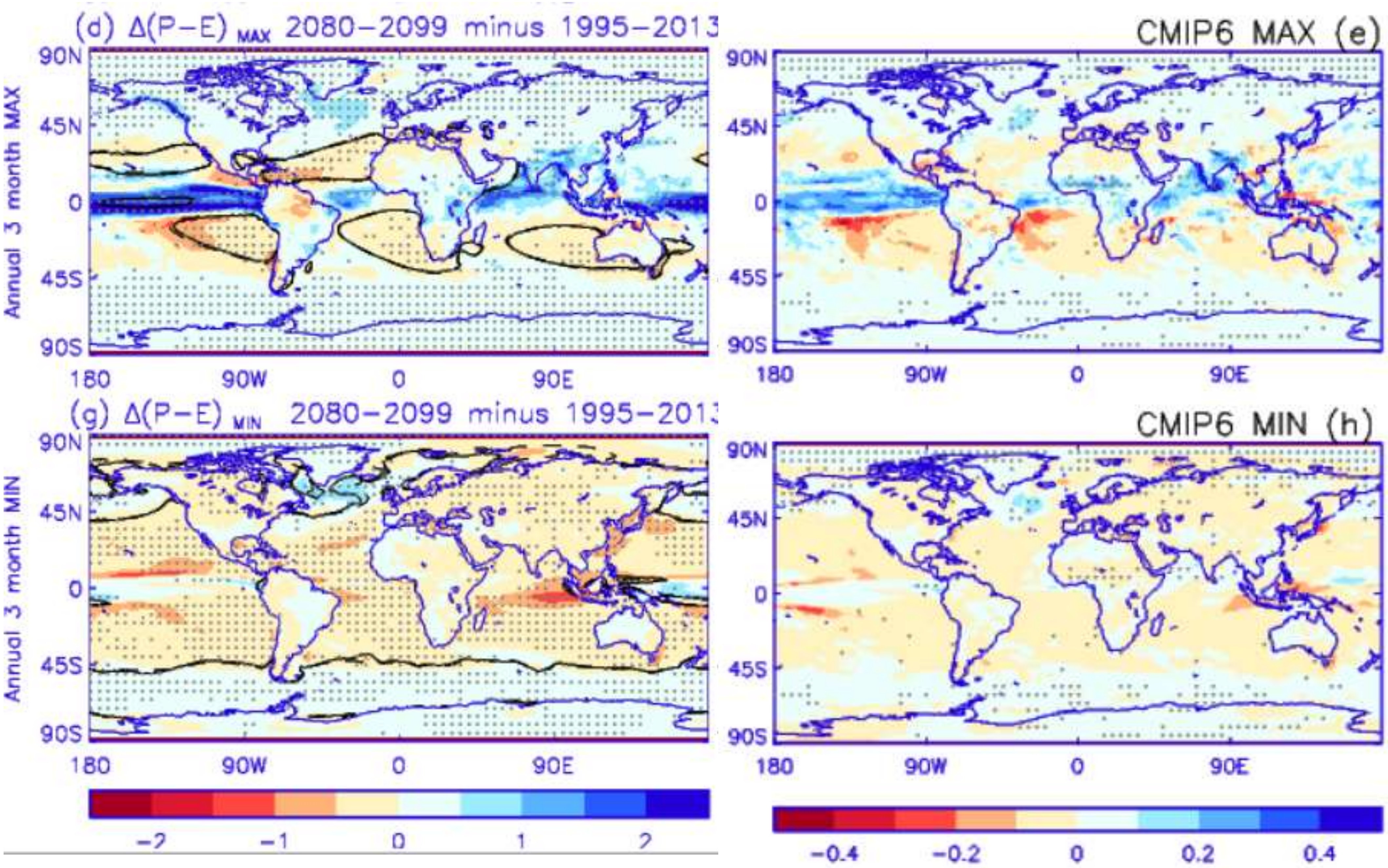
MAX

MIN

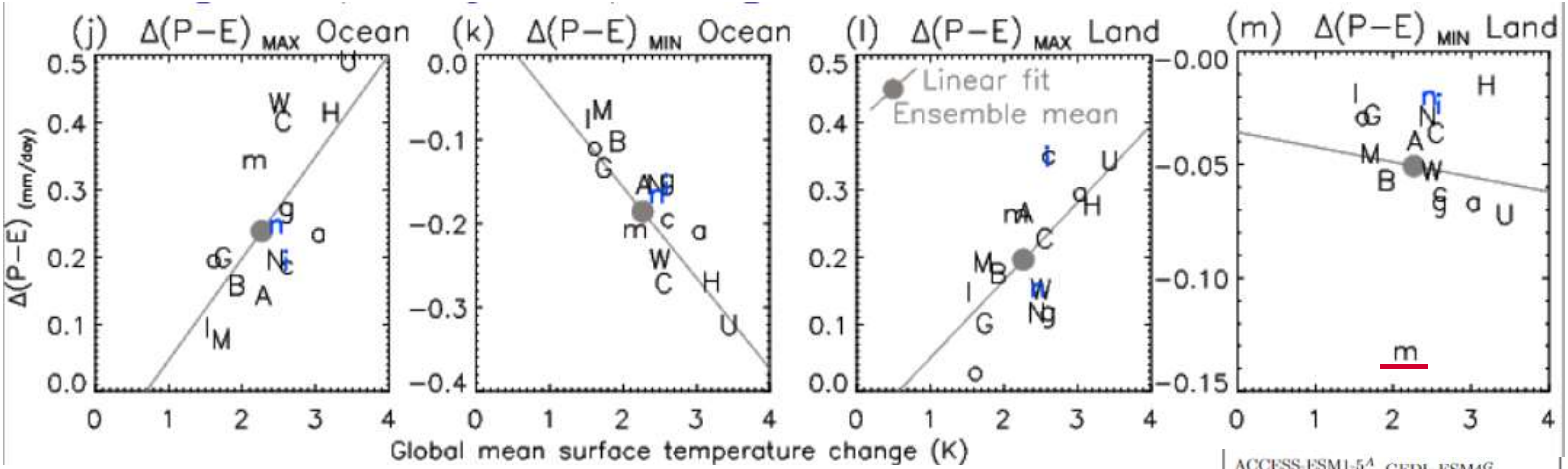
FUTURE CHANGE PRESENT TRENDS



MAX

MIN

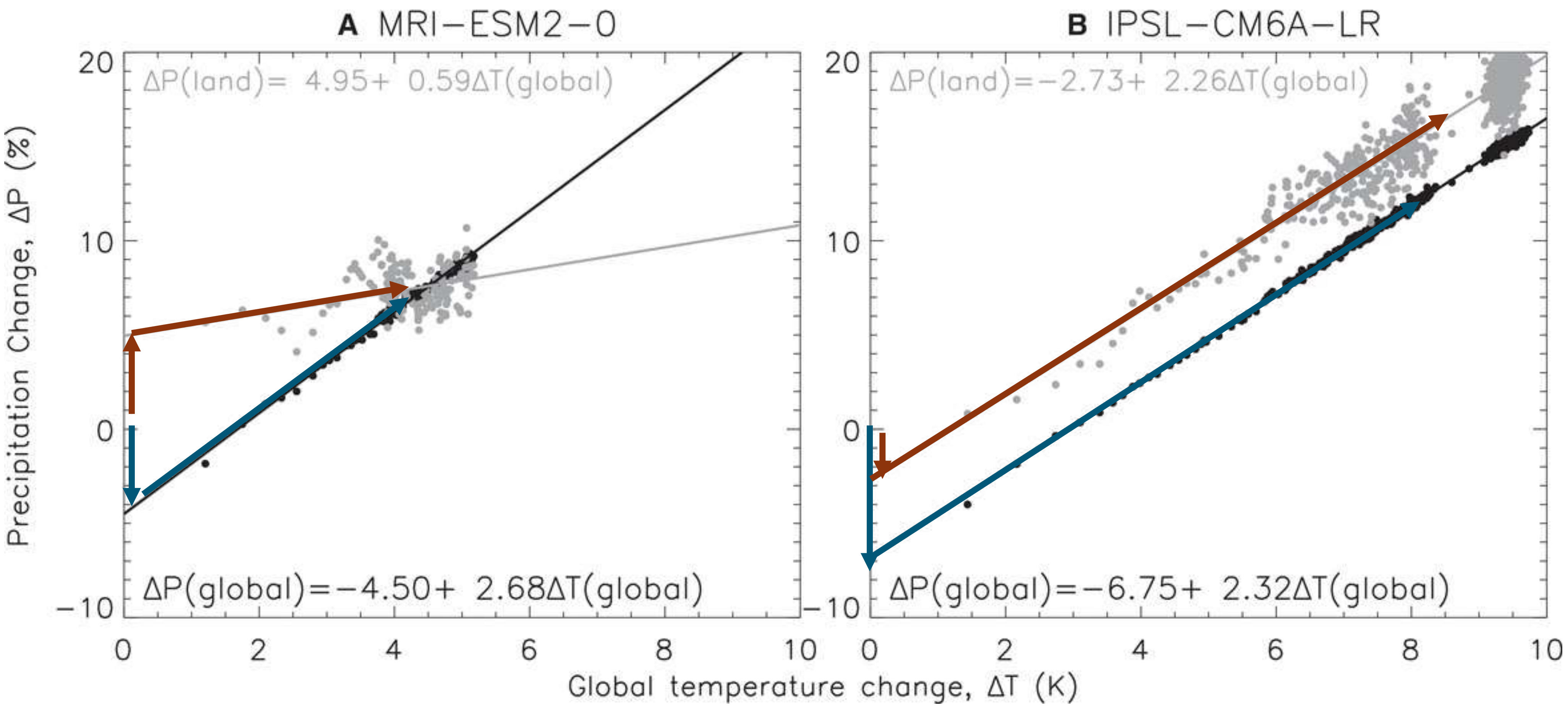
Thermodynamic amplification of P-E



ACCESS-ESM1-5[A]	GFDL-ESM4[G]
BCC-CSM2-MR[B]	GISS-E2-1-G[g]
BCC-ESM1[b]	HadGEM3-GC31-LL[H]
CanESM5[a]	INM-CM5-0[I]
CESM2[C]	IPSL-CM6A-LR[i]
CESM2-WACCM[W]	MIROC6[M]
CMCC-CM2-SR5[C]	MRI-ESM2-0[m]
CNRM-CM6-1[N]	NorESM2-LM[o]
CNRM-ESM2-1[n]	UKESM1-0-LL[U]

- Thermodynamic amplification of seasonal P-E with warming
- Changes over land across models less coherent (right)

Fast & slow global precipitation responses to $4xCO_2$

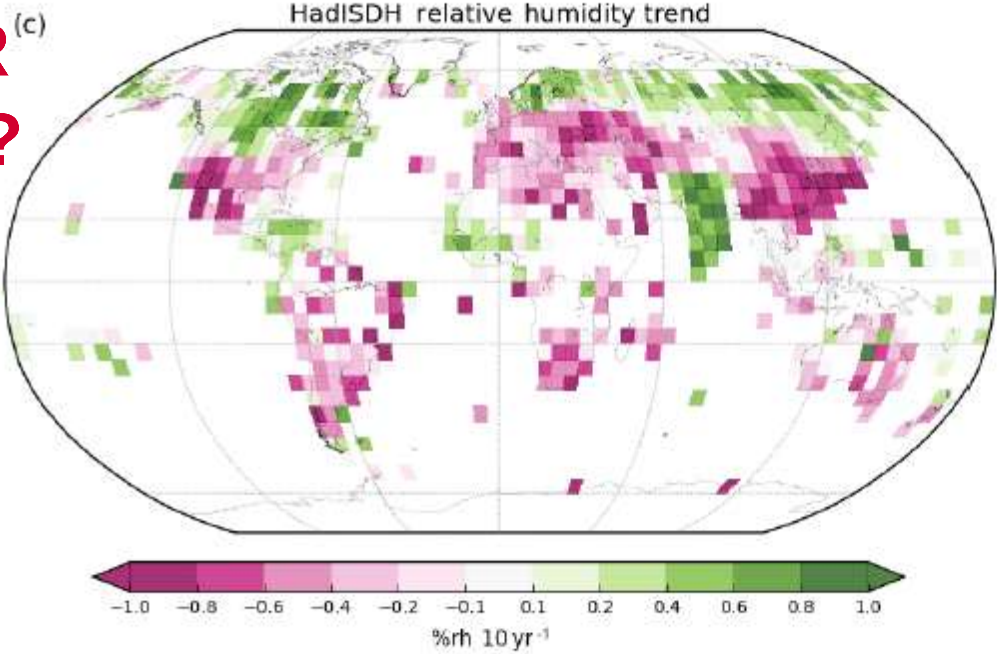


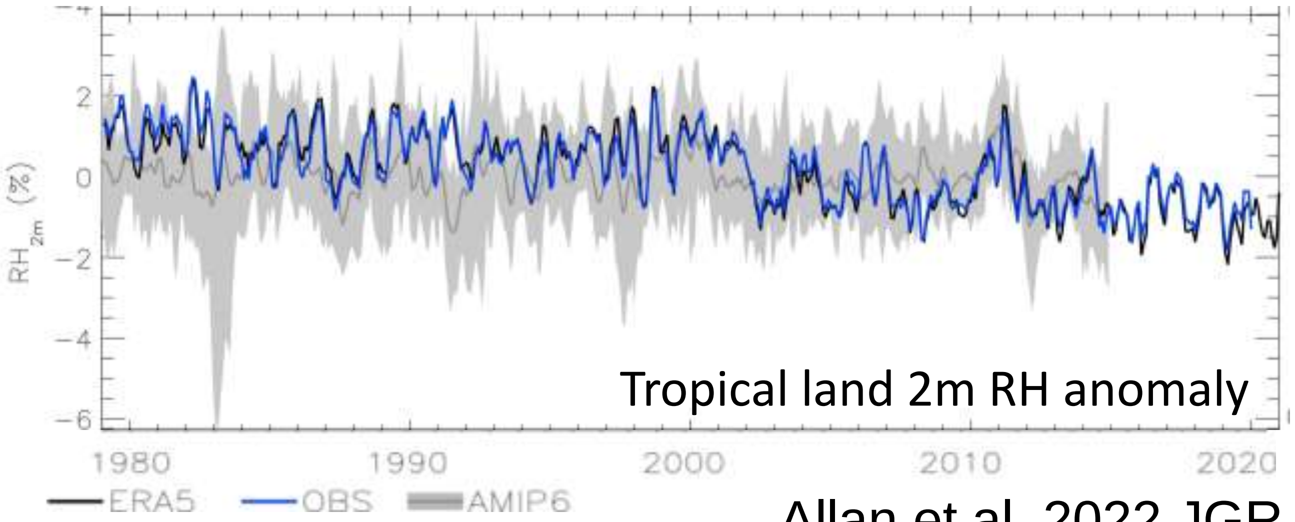
Allan et al. (2020) NYAS

Global: rapid decline, consistent slow increase with warming (2-3%/^{o}C)
Land: model-dependent rapid response & suppressed(?) increase per ^{o}C warming
e.g. **Andrews et al. (2009) J Climate**; **Samset et al. (2018) Clim. Atmos. Sci.**:

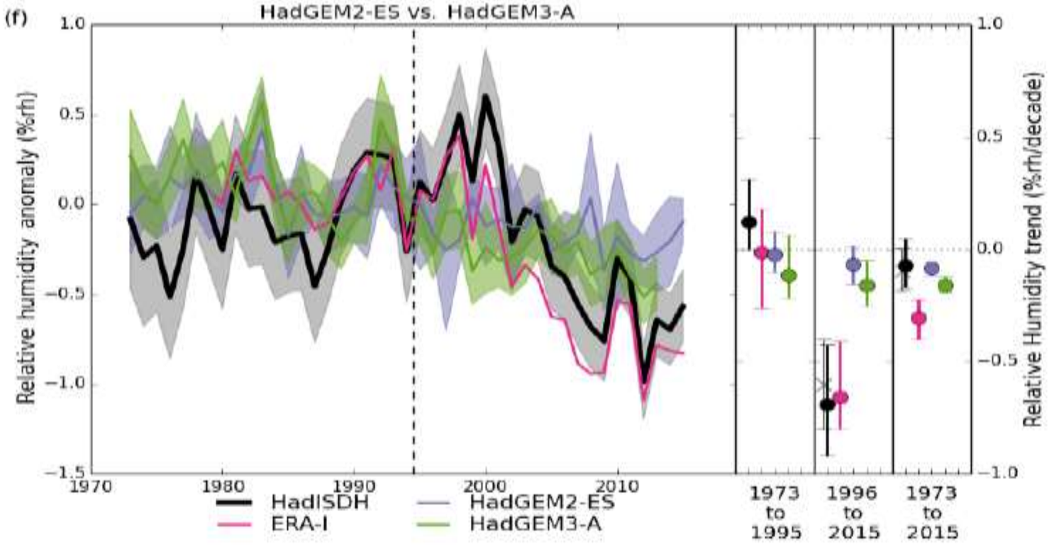
IS RELATIVE HUMIDITY DECLINE OVER LAND UNDERESTIMATED BY MODELS?

- Declining Relative Humidity over land
- Consistent with larger warming over land than sea e.g. O'Gorman & Byrne (2018) PNAS
- Not captured by CMIP5/6 simulations even when forced with observed SST
  e.g. Allan et al. 2022 JGR, Dunn et al. 2017 ESD





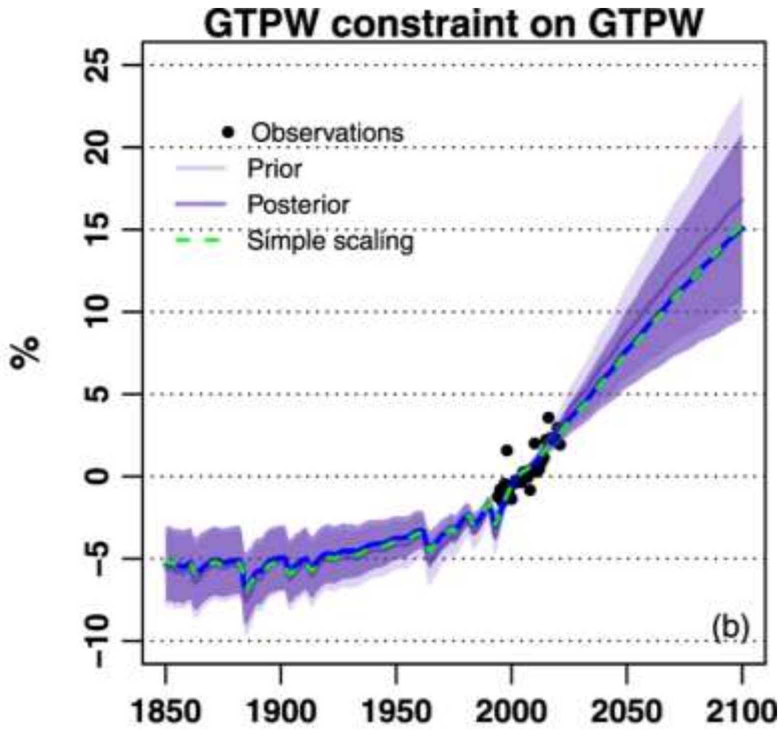
Allan et al. 2022 JGR

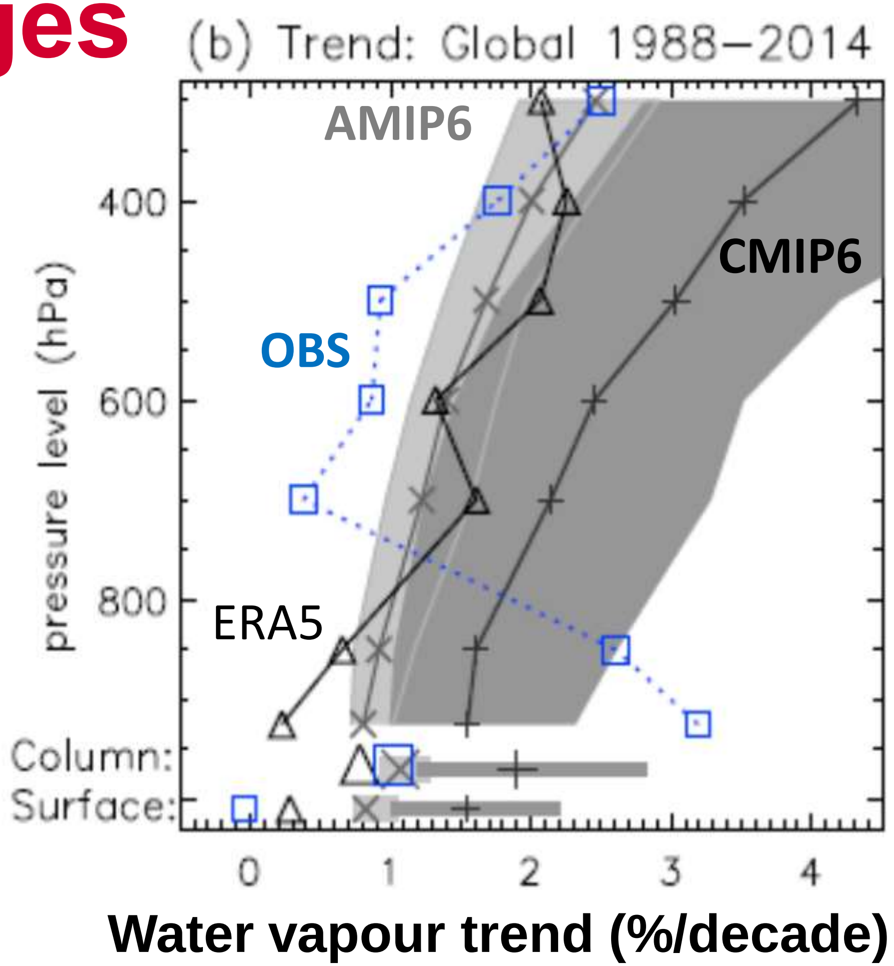


Dunn et al. 2017 ESD

Can current water cycle changes constrain future projections?

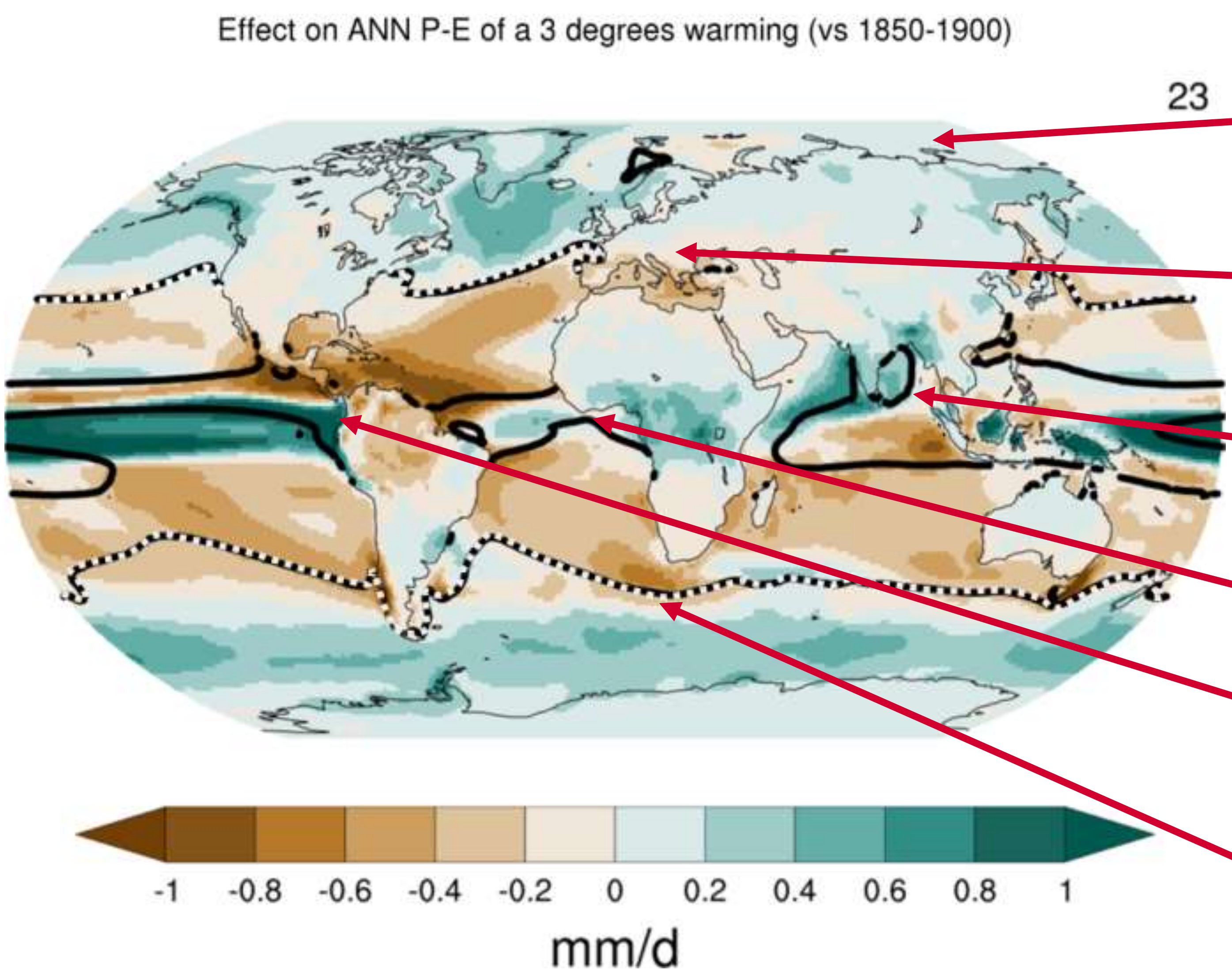
- Douville et al. (2022) Comm. Earth & Env. water vapour observations constrain future projections ~ 7% per ^{o}C increase in column moisture





- But observed warming/moistening smaller than CMIP6 (e.g. Allan et al. 2022 JGR) due to warming pattern (internal variability?)

What circulation-related changes are robust?



Douville et al. (2021) IPCC, Ch 8 , Figure 8.21

- Uncertain role of Arctic amplification on high latitude weather systems e.g. Henderson et al. 2018; Tang et al. 2014
- Poleward migration of subtropical belt over ocean, complex effects over land Grise & Davis 2020; Byrne & O'Gorman 2015
- Slowing tropical circulation supresses thermodynamic intensification of monsoons e.g. IPCC AR5
- Contraction and intensification of ITCZ e.g. Byrne & Schneider, 2016; Su et al., 2020
- Region dependent shifts in ITCZ e.g. Dong & Sutton 2015; Dunning et al. 2018; Mamalakis et al. 2021.
- Poleward, complex migration of storm tracks/contrasting hemispheric forcing Watt-Meyer et al., 2019; Zhao et al., 2020

Conclusions

- Amplification of P-E signal over ocean well understood
- P-E changes over land not well understood
- Seasonal amplification of P-E patterns?
  - Wet season P > E; Dry season (onset) E > P
  - Intensification of wet season (+4.2 → +4.4 mm/day global land)
  - More intense dry season onset over northern continents but not apparent over tropics? (-1.15 → -1.2 mm/day global land)
  - See also IPCC (2021) TS Box 8.2; Chapter 8, Section 8.2
- Emerging regional signals of hydrological change? e.g. Wainwright et al. (2022) GRL
- Changing atmospheric circulation crucial but low confidence e.g. IPCC (2021) Fig. 8.21