Under what conditions do the global warming responses of drought indices and land-surface models agree?

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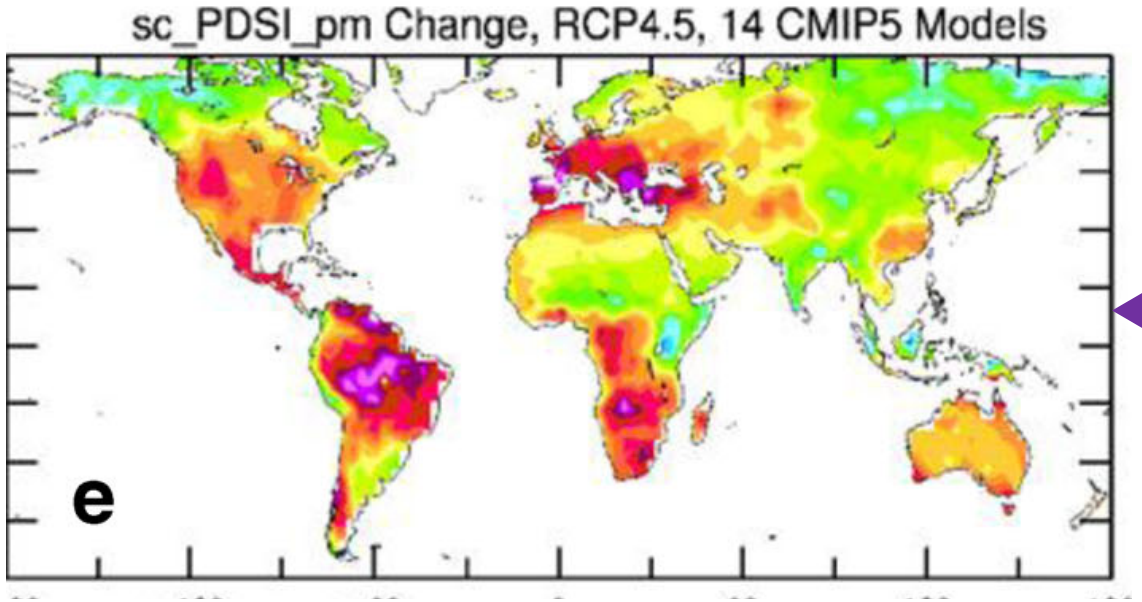
Abstract

The regional to global responses of the Standardized Precipitation-Evapotranspiration Index, Palmer Drought Severity Index, and Aridity Index to future global warming tend to be much more pervasively and strongly negative than the responses of comprehensive land model runoff and bulk soil-moisture outputs to the same warming. We term these systematic differences "index-impact gaps." Some studies have assumed that these gaps arise because land-surface models include water-saving CO2-plant effects that the dryness indices do not, but recently published work makes clear that the gaps largely persist even in model simulations in which these effects are switched off. Thus, the main reason(s) for the index-impact gaps are still unclear, making it difficult to trust either the common dryness indices or the comprehensive land-surface models under climate change. In this study, we are investigating several postulated causes of these index-impact gaps using sensitivity experiments with the state-of-the-art Community Land Model version 5.0. In addition to CO2-plant effects, we are testing the roles of stomatal closure driven by high vapor-pressure deficits, short-term runoff enhancement due to sharper concentration of rain in time with warming, and annual-scale runoff enhancement due to changes in the seasonality of precipitation and/or infiltration with warming. If CLM5.0's runoff and bulk soil-moisture responses start to agree with the dryness-index responses much more after eliminating these pathways, it will imply that the dryness indices are in fact a useful theoretical baseline for understanding the comprehensive model responses. However, if the index-impact gaps still remain wide, it will imply either that dryness-index responses are fundamentally different from runoff and soil-moisture responses to climate change, or else that CLM5.0's evapotranspiration is not sensitive enough to rising temperatures. Further experiments will be required in that case.

Under what conditions do the global warming responses of dryness indices and land-surface models agree?



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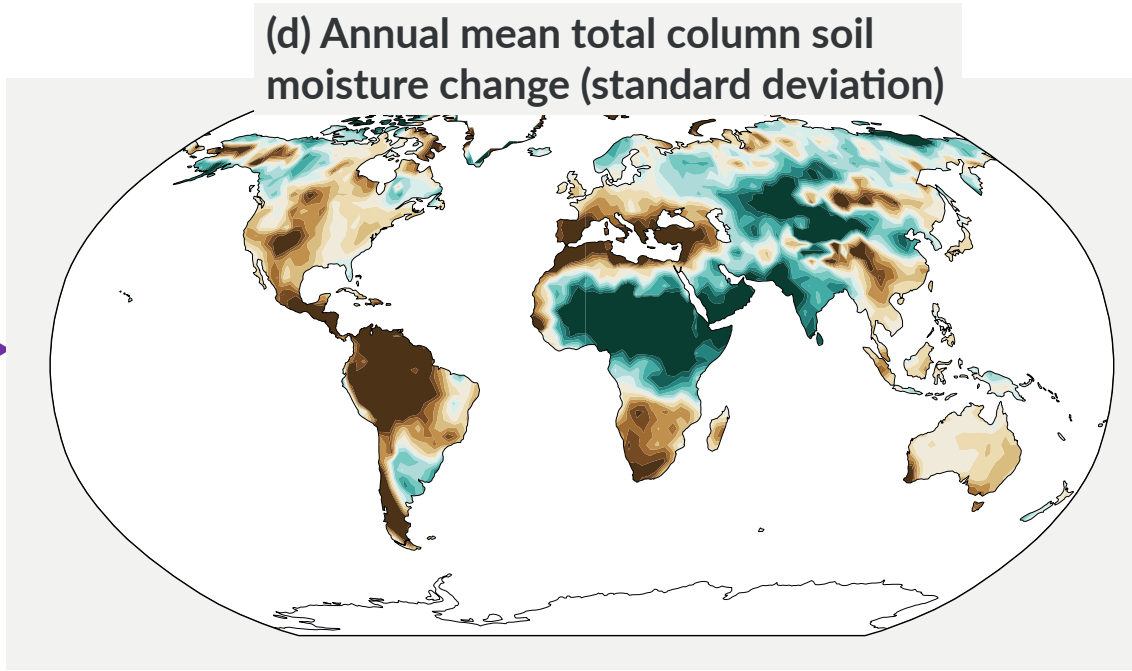

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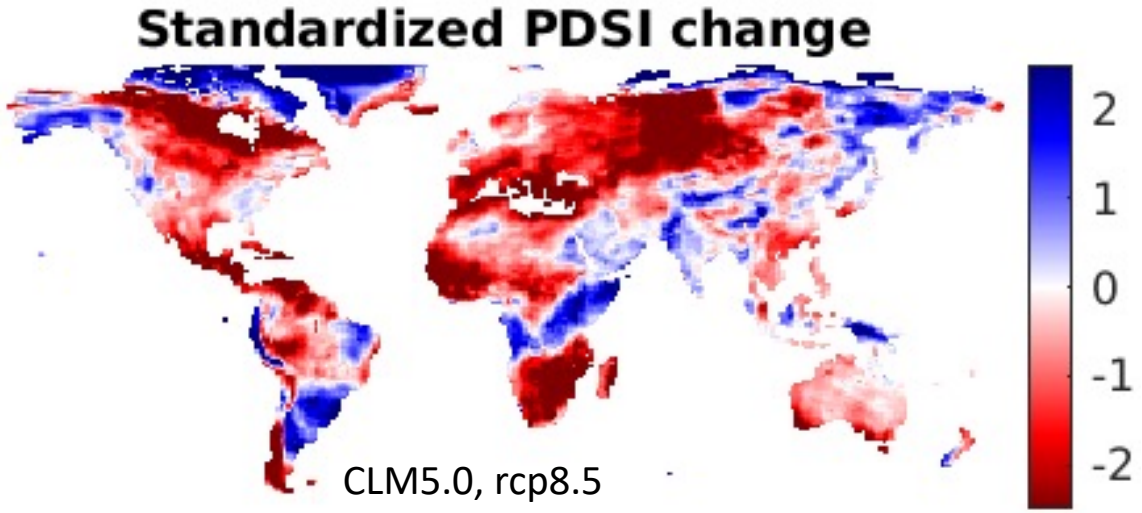
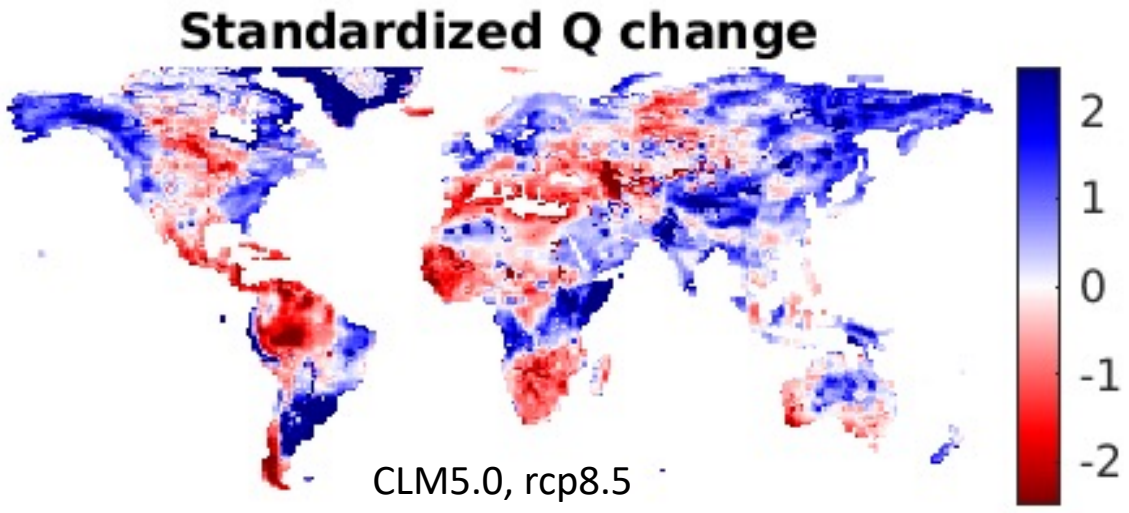
In prep, *Earth's Future*

Background

- Global warming strongly increases temperature
- But only weakly changes precipitation (at least over mid- to low latitude land)
- Thus, climatic dryness indices (PDSI, SPEI, P/E_0) obtain **widespread, temperature-driven drying** when applied to RCP projections
- Yet, land-surface models simulate much more **mixed** responses in Q, deep-layer SM, etc when driven by those same projections!

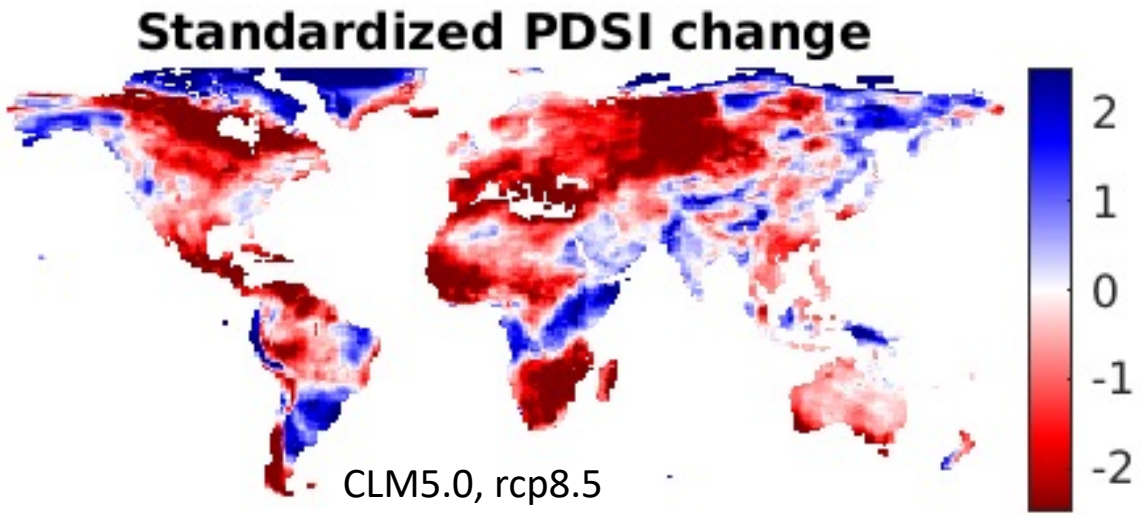


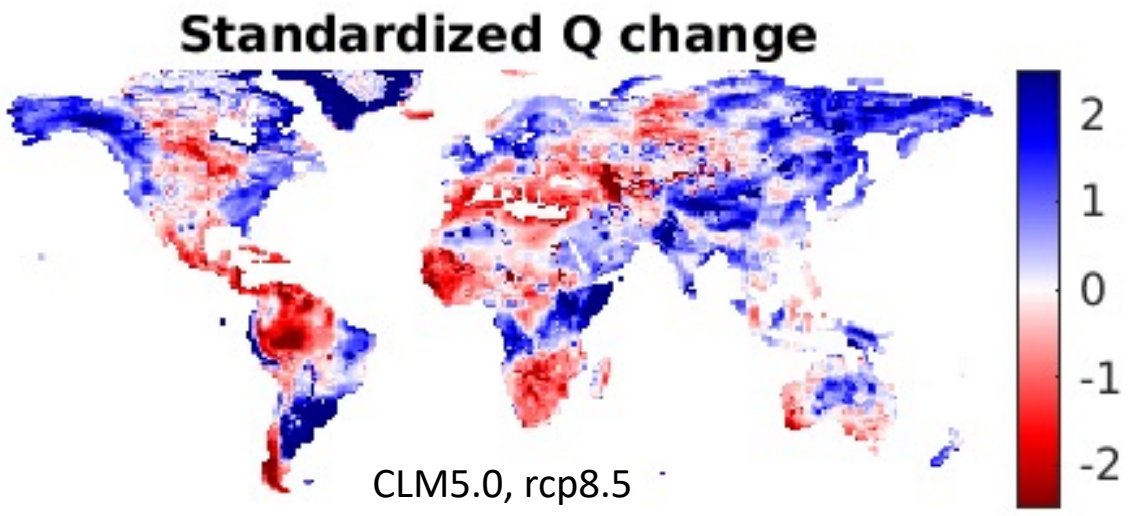


Background

- **Which picture are we to believe in practice??**

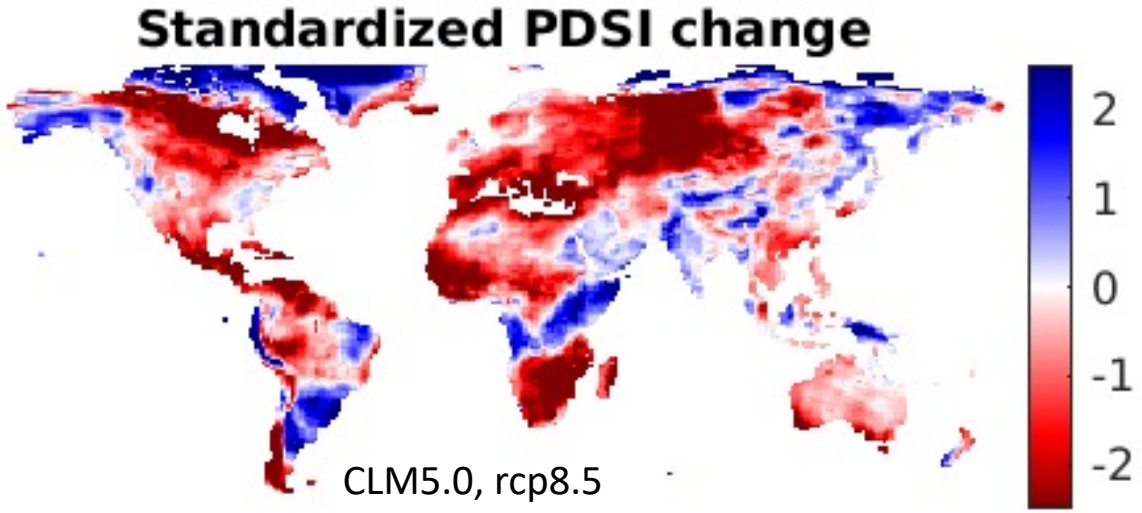
- Do we trust the simple dryness indices, or do we trust the land-surface models' complex runoff schemes (or neither?)

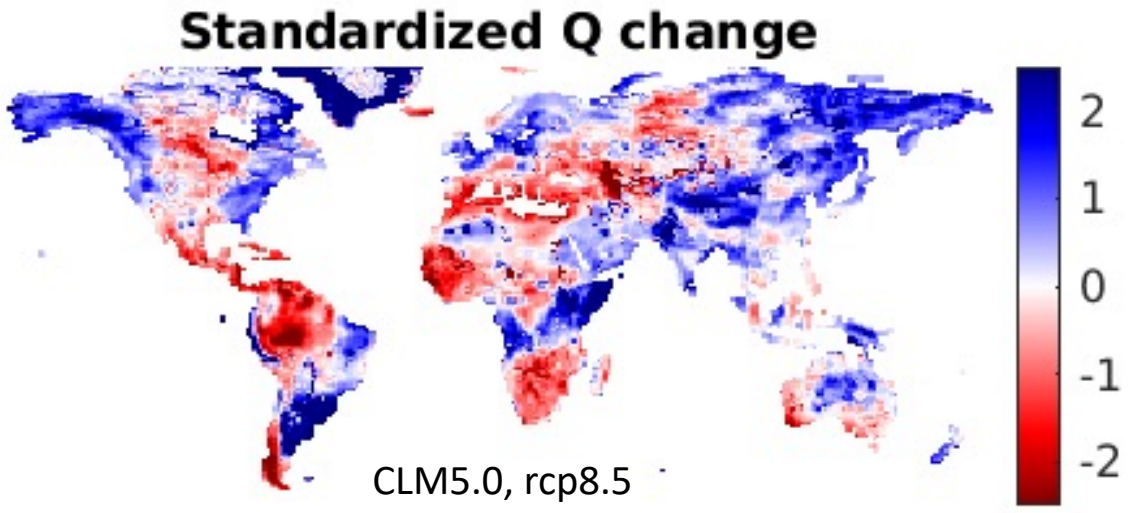




Background

- It would be helpful to know **why** they differ!
- Roderick et al (2015), Milly and Dunne (2016), Swann et al (2016), etc. assumed it's due to CO_2 closing leaf stomates in the models
- But Scheff et al (2021, *ERL*) showed most of the gaps **persist** in CMIP simulations in which CO_2-plant effects are switched off
- CO_2 effects can't be the main reason for the gaps





This study

- Here we test four alternative explanations for the dryness index-impact gaps in NCAR's Community Land Model v5.0 (CLM5.0).

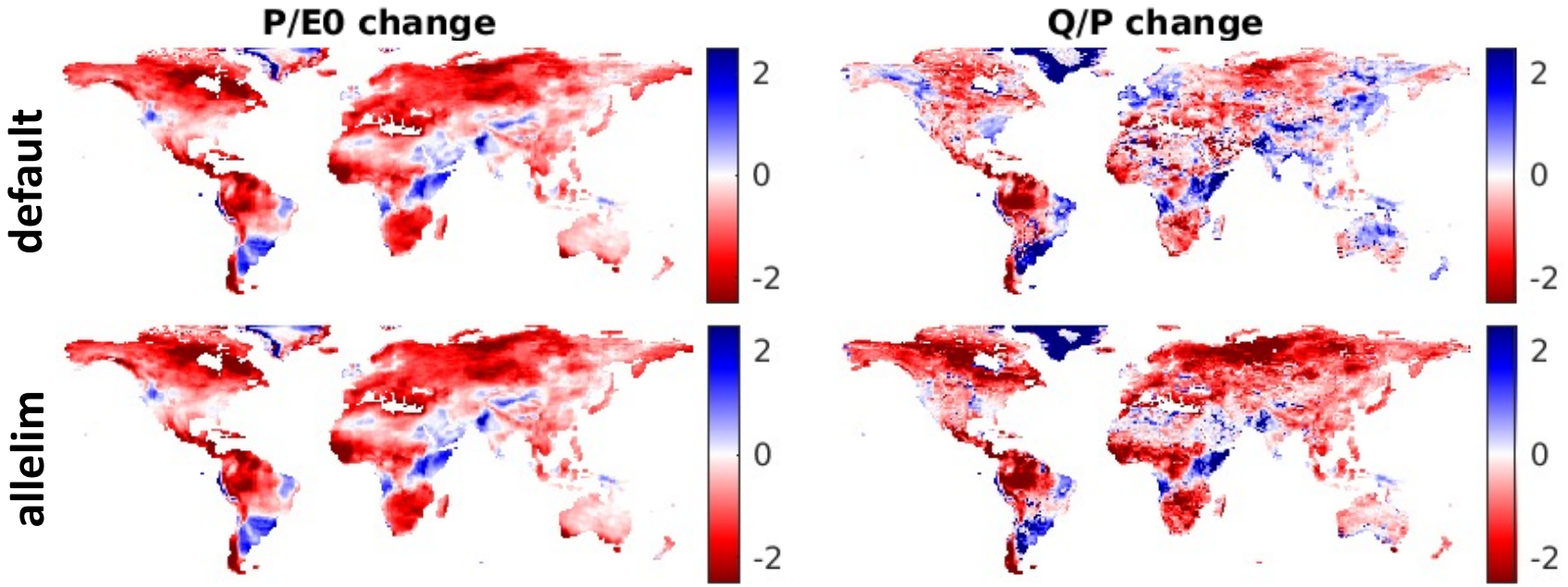
- Closure of leaf stomates by high CO_2
- Closure of leaf stomates by high VPD (Novick et al. 2016, etc)
- Concentration of precip into "flashier" events (Pendergrass and Hartmann 2014, Dai et al 2018, Mankin et al 2018, etc)
- Movement of precip into the existing wet season (Allen and Anderson 2018, Chou et al 2013, etc)
- All would increase annual Q and/or SM but not PDSI, SPEI or P/E_0

Model runs

- 6 pairs of offline CLM5.0 simulations driven by saved historical (1985-2014) and rcp8.5 (2071-2100) coupler output from CESM2
- ‘default’: all the usual settings
- ‘fixedCO2’: CO_2 held to 370 ppmv
- ‘medlynconst’: VPD seen by the stomatal code held to 1.5 kPa
- ‘noflash’: rcp8.5 coupler output replaced by “pseudo-rcp8.5” = historical coupler output scaled to match rcp8.5’s seasonal climate
- ‘noflashnoseas’: like noflash, but precip scaled to match rcp8.5’s *annual* climate only (so precip seasonality stays historical)
- ‘allelim’: fixedCO2, medlynconst, and noflashnoseas *simultaneously*

Results

- First: gap between P/E_0 (aridity index) and Q/P (runoff ratio)
- Most concerning of the gaps, since Budyko says P/E_0 drives Q/P
- Largely gone in allelim!



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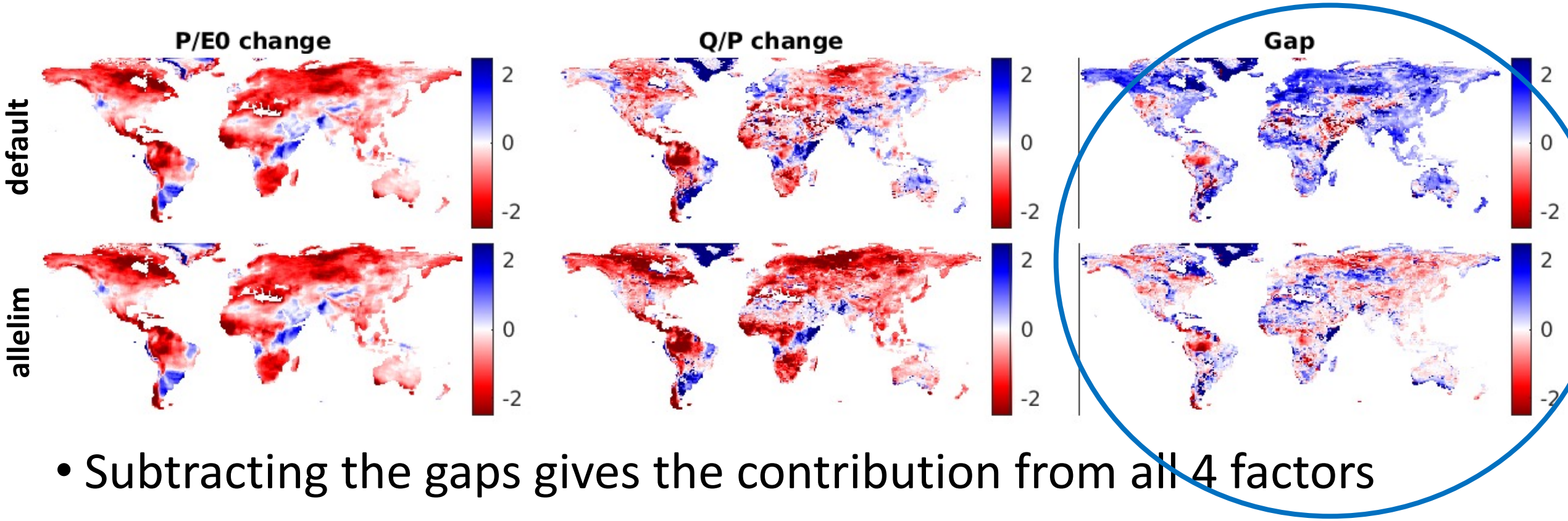
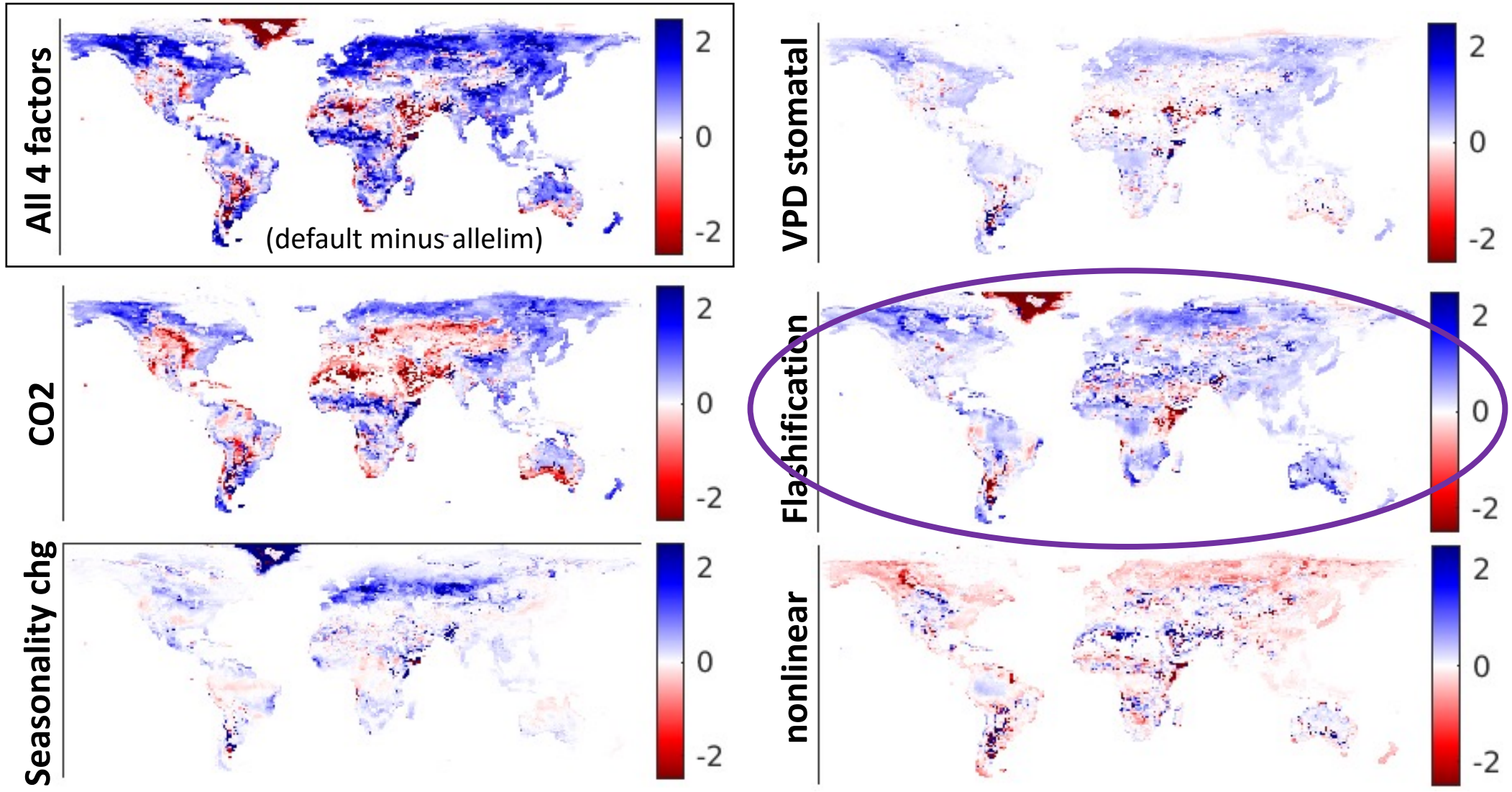


- Subtracting the gaps gives the contribution from all 4 factors

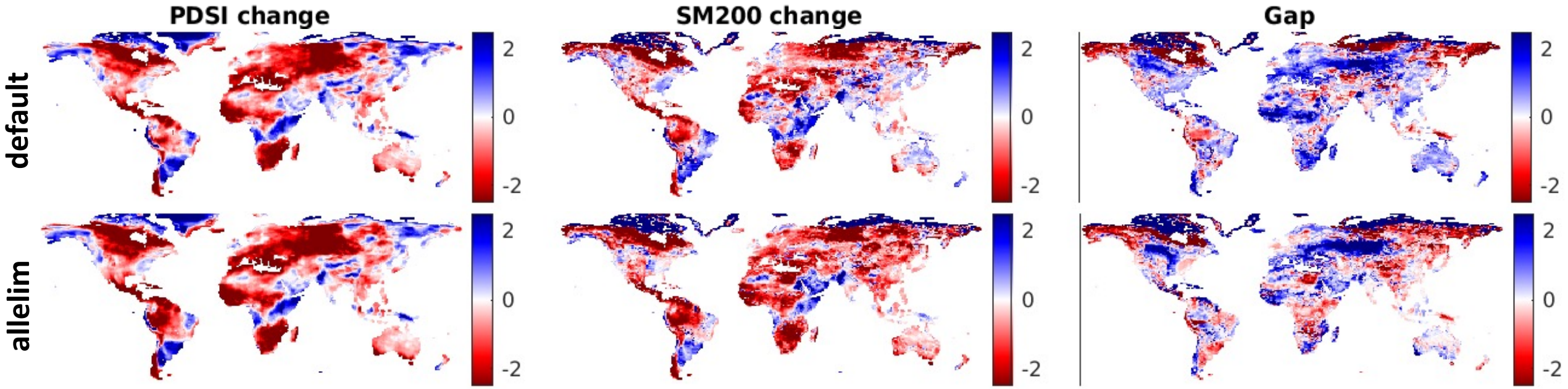
Results

- Contributions to the Q/P - P/E_0 gap from:



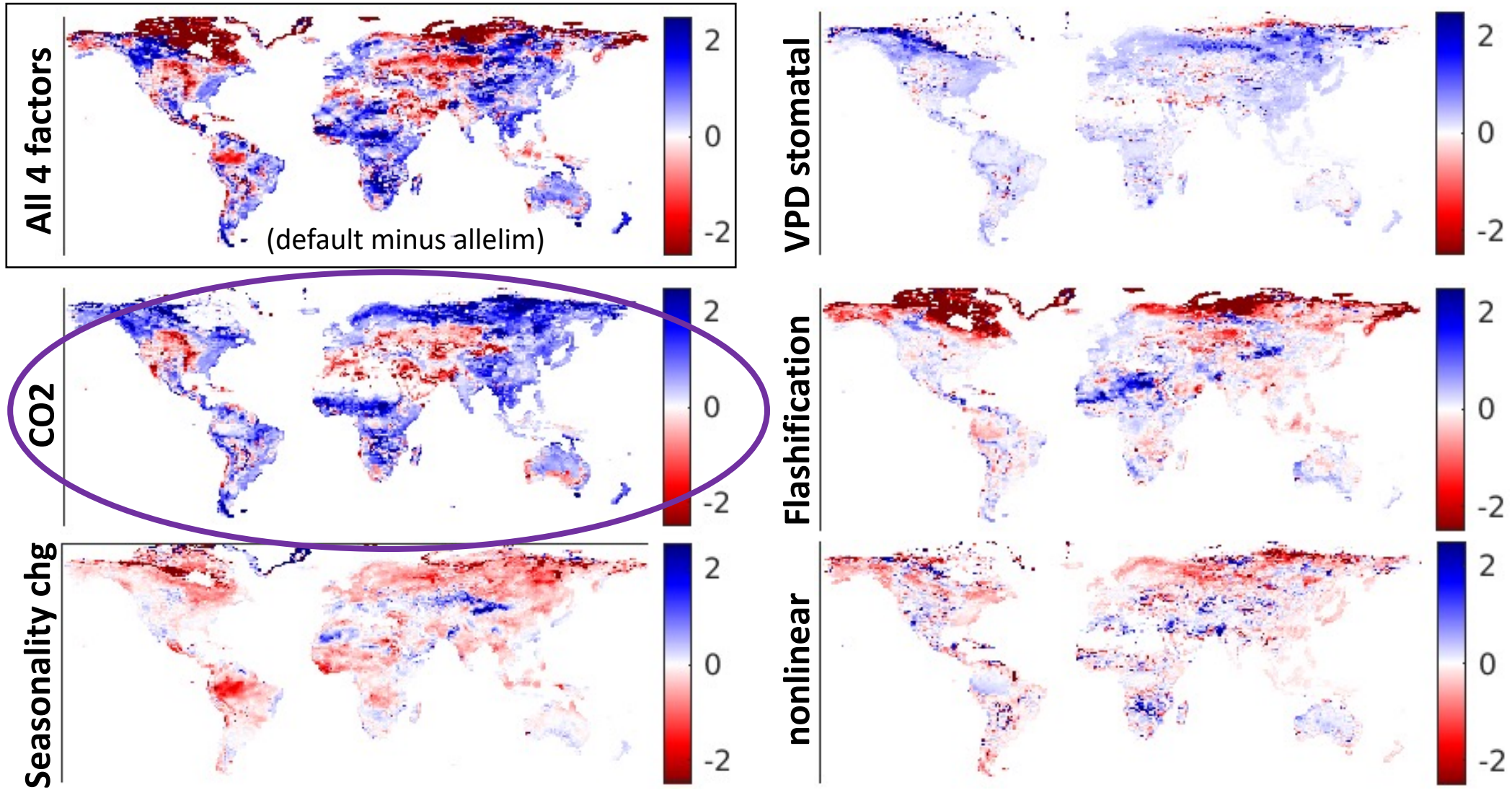
Results

- SM200 - PDSI gap: both signs, but generally SM200 increasing more
- In allelim, though, relative increases and decreases are more equal
- SM200 qualitatively resembles PDSI more in allelim



Results

- Contributions to the SM200 - PDSI gap from:



Summary

- *When physiological, "flashification", and seasonality effects are cut,* P/E_0 change does look like Q/P change under global warming
- And PDSI change does look like SM200 change (roughly)
- Indices work as designed! Not "useless" for understanding
- Gaps are mainly due to flashification (for P/E_0) and CO_2 (for PDSI)

- However **runoff itself (Q)** still increases much more strongly than any of the above quantities. [Q = (Q/P) * P]
- These indices are not directly relevant for runoff, despite working well for their intended purposes.