Past warm climates inform the future South Asian summer monsoon

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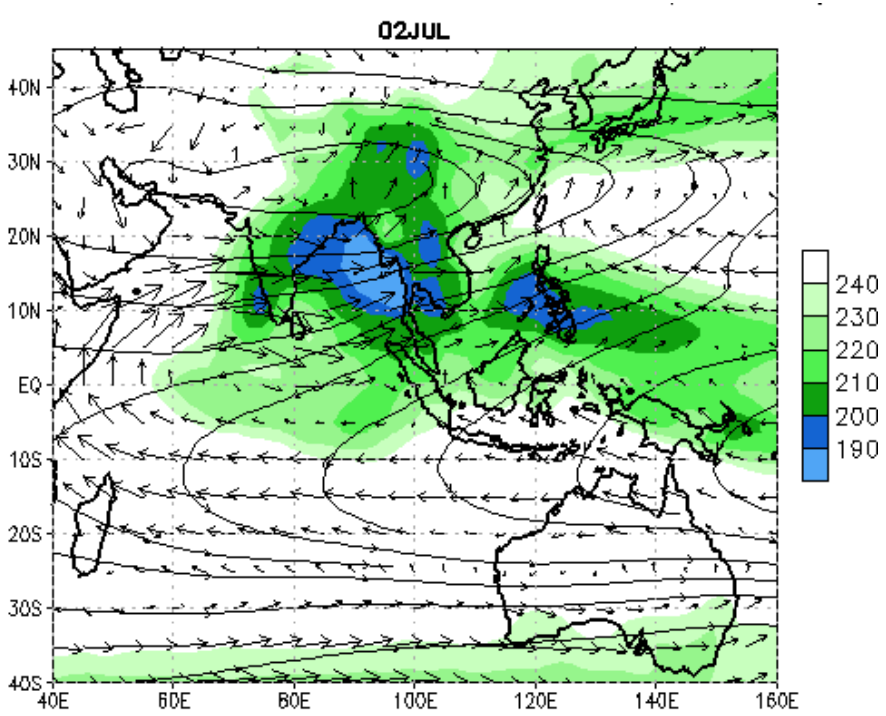
EGU26, Session AS1.27 “Monsoon systems: processes, prediction, and climatic changes in the past and future”

Wed, 06 May, 14:00–17:55 (CEST), Room M2. Vienna, Austria

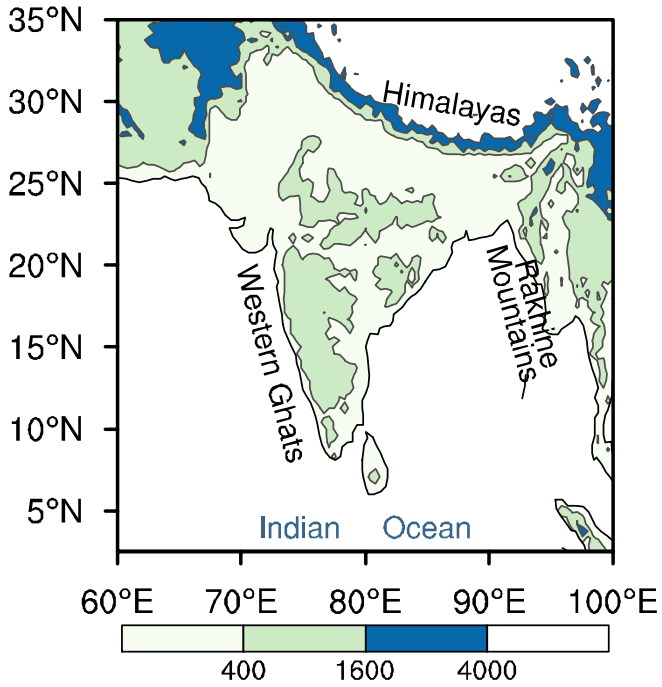
South Asian summer monsoon (SASM)

OLR, 200hPa streamlines and 850hPa wind
Climatology (annual cycle)

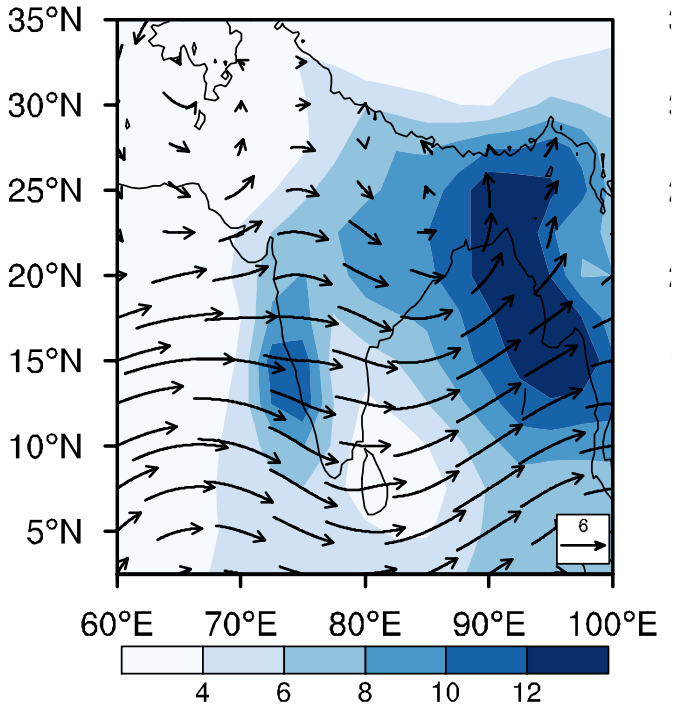


From NOAA
Data source: NESDIS, NCEP

Topography



Precipitation and 850hPa wind climatology
(Jun to Sep)



Data source: GTOPO30, ERA5, GPCP

Impacts of anomalous SASM behavior

Floods due to excessive monsoon rainfall

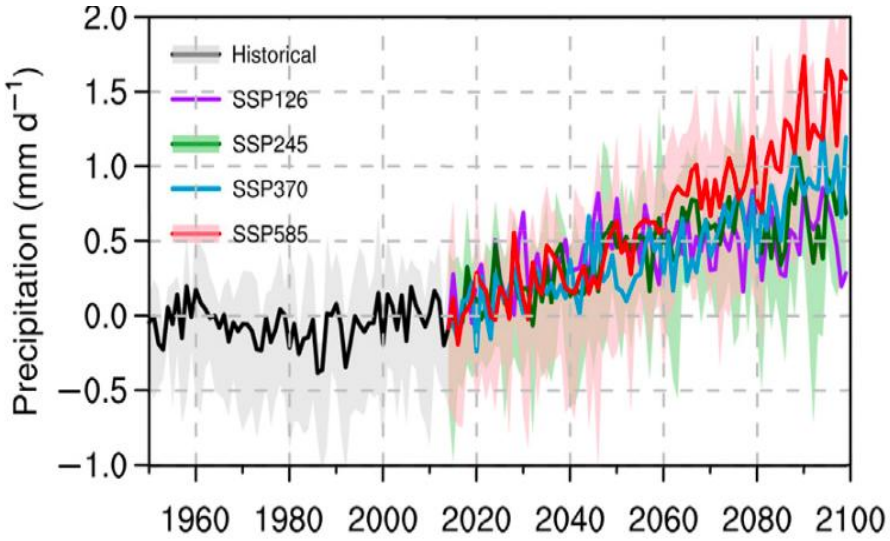
Photo by Press Trust of India

Droughts due to monsoon breaks

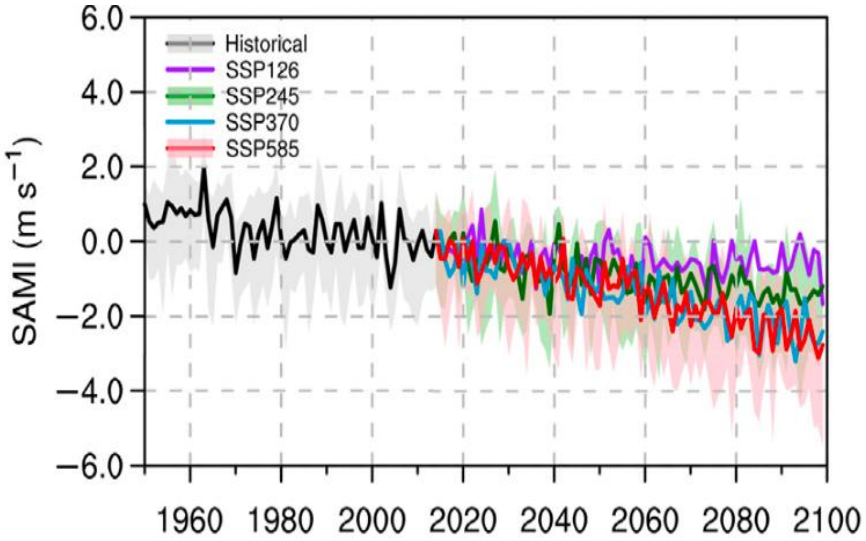
Photo by Christopher Michel

Future Projection of South Asian Summer Monsoon (SASM)

Monsoon rainfall changes



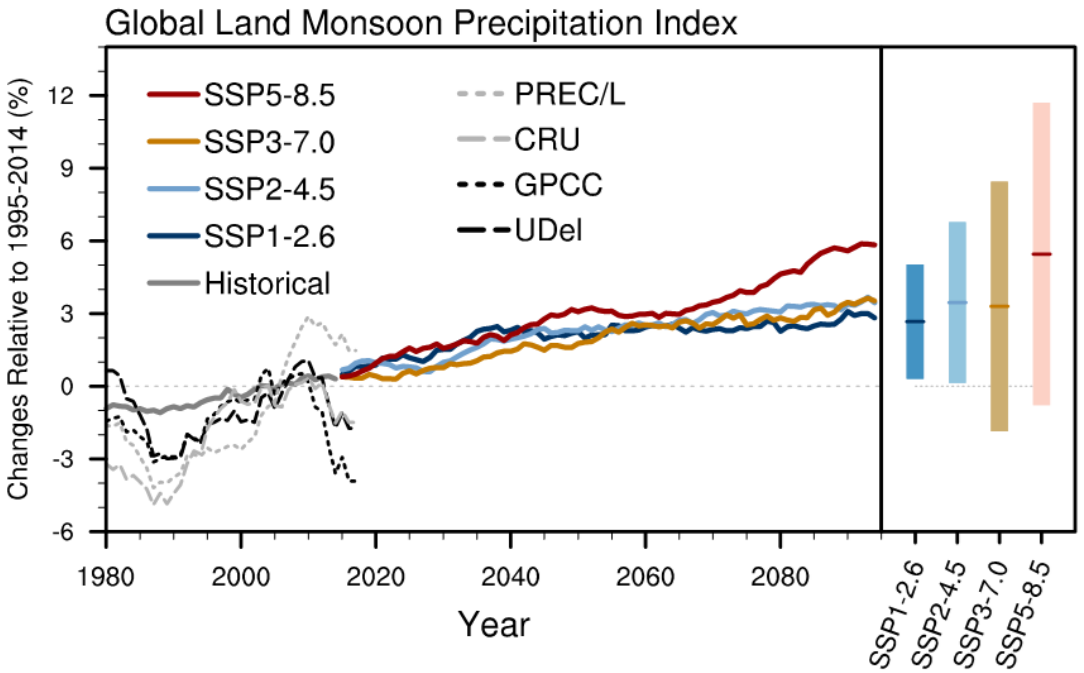
Monsoon circulation changes

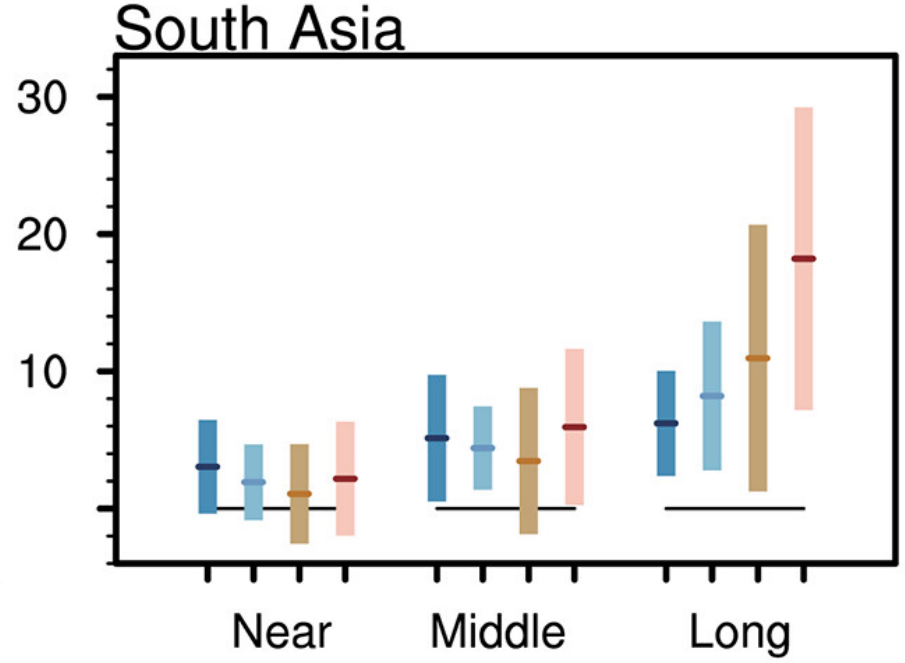


- Projection paradox of South Asian summer monsoon: rainfall increases, but circulation weakens

Wu et al. 2022, *ACCR;* *Kitoh et al. 2013, JGR, doi:10.1002/jgrd.50258*

Spread in monsoon rainfall projection



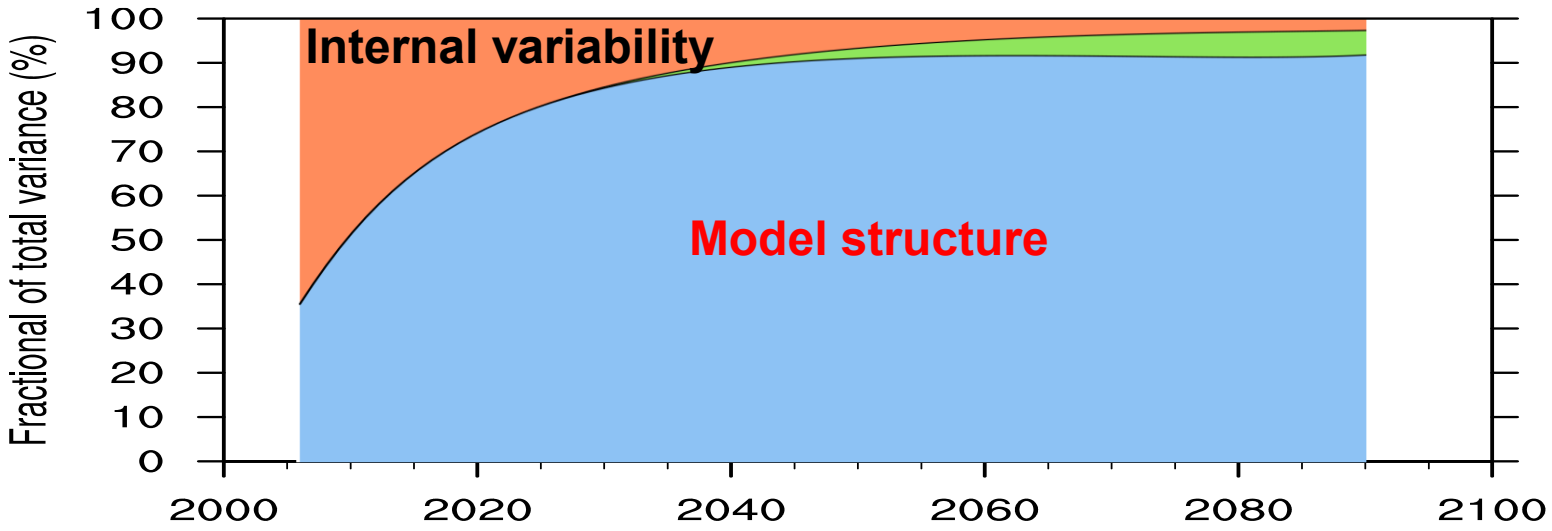


5

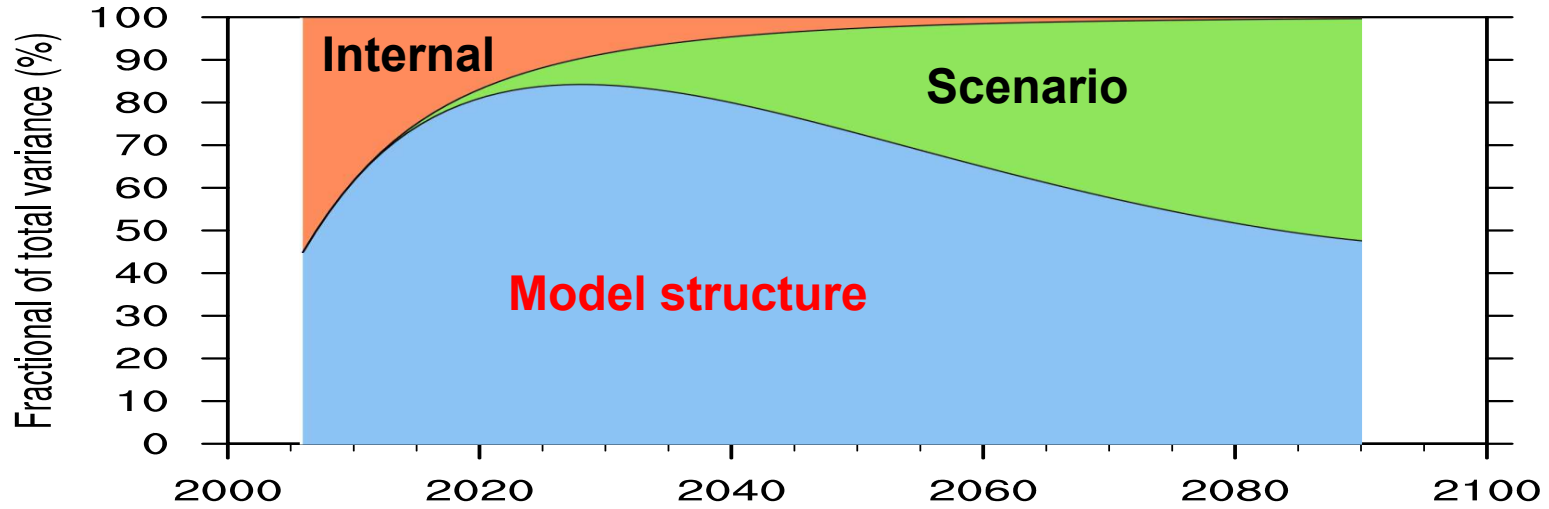
SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5

Chen, Z., Zhou T.* et al. (2020). Global land monsoon precipitation changes in CMIP6 projections. *Geophysical Research Letters*, 47, e2019GL086902

The sources of uncertainty in monsoon rainfall projection: Fraction of total variance



Mean prcp: Pav

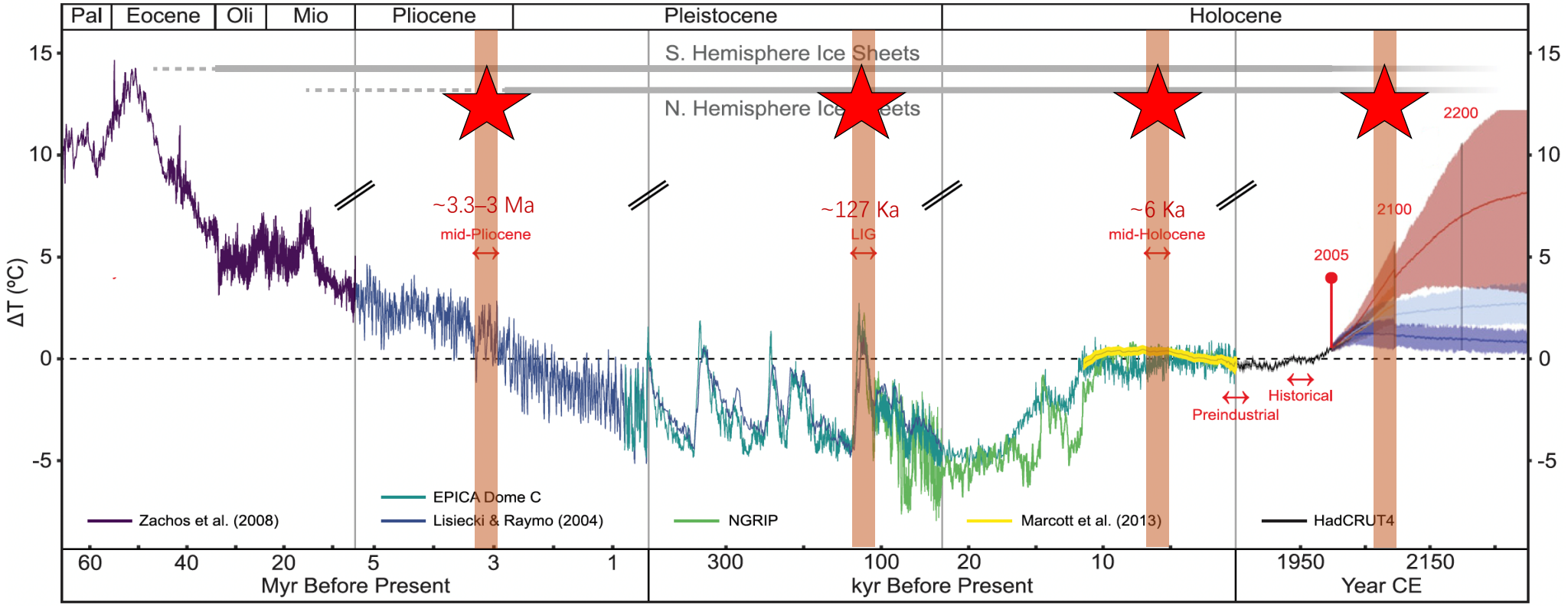


Extreme prcp: RX5day

Zhou T.* et al. 2020: The Sources of Uncertainty in the Projection of Global Land Monsoon Precipitation. *Geophysical Research Letters*, 47, e2020GL088415

Past warm climates as future analogs

Cenozoic evolution of global mean surface temperature



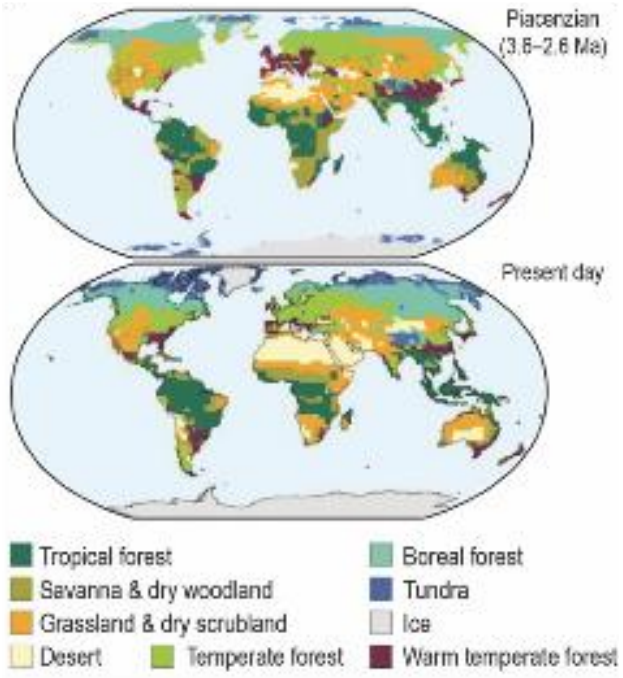
Burke et al. 2018, *PNAS*

- PMIP4 warm intervals as future analogs: mid-Pliocene, Last Interglacial, mid-Holocene

Past warm climates as future analogs

Mid-Pliocene

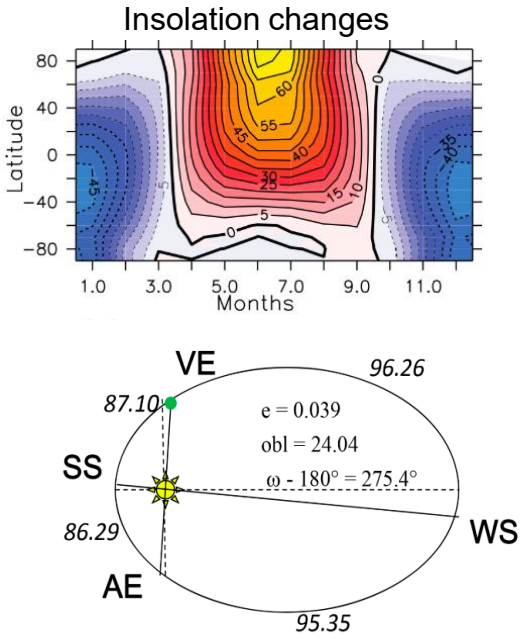
vegetation and ice sheet patterns



Arias et al. 2021

Last interglacial

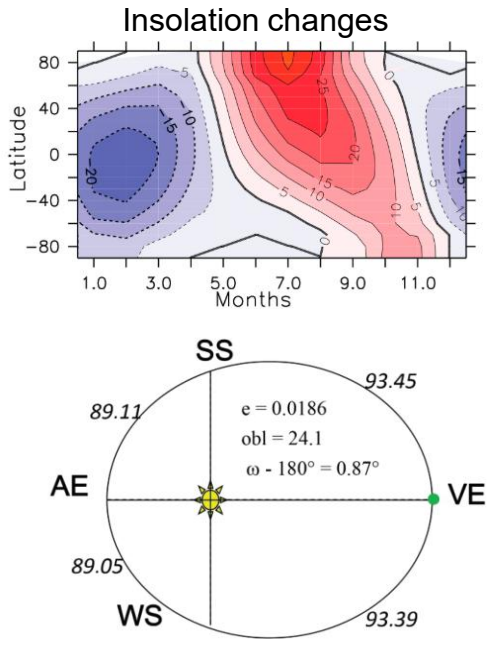
Insolation changes



Otto-Bliesner et al. 2017, *GMD*

Mid-Holocene

Insolation changes



- Elevated CO_2 and its long-term feedback
- Perihelion near the summer solstice
- Perihelion near the autumn equinox

Earth's orbital configuration

Research Question 1

Can past warm climates serve as analogs for the future monsoon?

Proxy records and model data

Details of proxy records during past warm intervals

Period	Site	Lat (°N)	Lon (°E)	Interpretation	Proxy
Last interglacial	Hoti cave	23.08	57.35	Wetter	Speleothems
	Xiaobailong cave	24.2	103.35	Wetter	Speleothems
	Mawmluh Cave	25.26	91.88	Wetter	Stalagmite
	Heqin basin	26.56	100.17	Wetter	Sediment composition
	Thar Desert	27	71	Wetter	Other/unspecified
	Namco	30.3	91	Wetter	Pollens, lake sediments
	Bittoo cave	30.79	77.78	Wetter	Speleothems
	Tianmen cave	30.92	90.67	Wetter	Speleothems
mid-Holocene	Gujjar Hut	30.9	78.8	No change	Peat
	Siling Co	31.75	89	Wetter	Underwater lake cores
	Tso Kar	33.16	78	Wetter	Underwater lake cores
mid-Pliocene	Chandigarh	30.73	76.77	Wetter	Floral and Faunal Remains
	Subathu and Kangra	32.09	76.26	Wetter	Soil Carbonate

- Thirty-one proxy records indicate generally wetter conditions, especially along the Himalayan foothills.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Proxy records and model data

Details of CMIP6 simulations during warm intervals

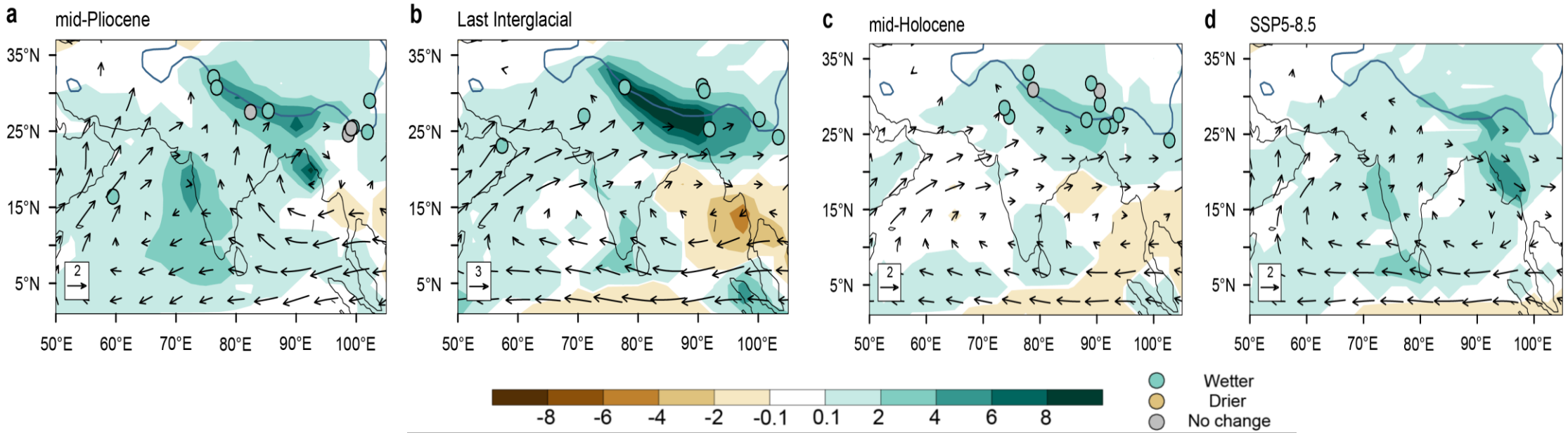
No	mid-Pliocene	Last Interglacial, mid-Holocene	Pre-industrial period	SSP2-4.5, SSP3-7.0, SSP5-8.5	lon × lat
1	CESM2	CESM2	CESM2	CESM2	288 × 192
2	EC-Earth3-LR	EC-Earth3-LR	EC-Earth3-LR/ EC-Earth3	EC-Earth3	320 × 160/ 512 × 256
3	GISS-E2-1-G	GISS-E2-1-G	GISS-E2-1-G	GISS-E2-1-G	144 × 90
4	HadGEM3-GC31-LL (only precipitation)	HadGEM3-GC31-LL (only precipitation)	HadGEM3-GC31-LL	HadGEM3-GC31-LL	192 × 144
5	IPSL-CM6A-LR	IPSL-CM6A-LR	IPSL-CM6A-LR	IPSL-CM6A-LR	144 × 143
6	NorESM1-F	NorESM1-F	NorESM1-F/ NorESM2-LM	NorESM2-LM	144 × 96/ 144 × 96

- Forty-two model simulations (six model groups across seven climate backgrounds).
- Calendar adjustment for the Last interglacial and mid-Holocene.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Consistent SASM changes in warm climates

Monsoon rainfall and 850hPa wind changes



Despite regional differences, the SASM is characterized by:

- an overall increase in monsoon rainfall
- weakening over the Bay of Bengal, and strengthening over the northern Arabian Sea

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Research Question 2

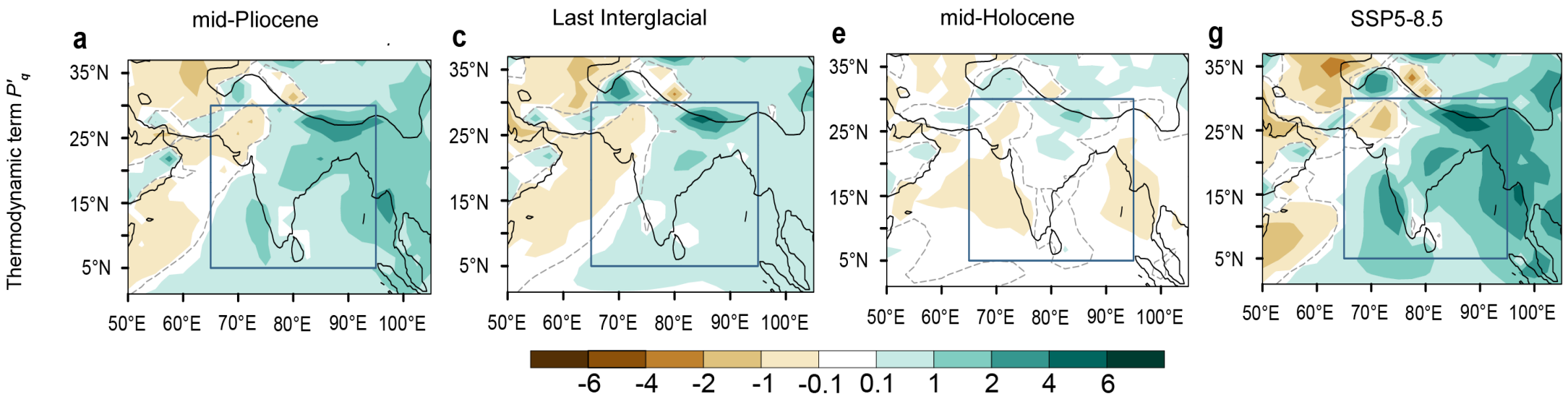
WHY can past warm climates serve as analogs for the future monsoon?

YES, but WHY

Roles of atmospheric moisture and circulation

$$P' \approx P'_q + P'_\omega = -\left\langle \bar{\omega}\frac{\partial q'}{\partial p} \right\rangle - \left\langle \omega'\frac{\partial \bar{q}}{\partial p} \right\rangle .$$

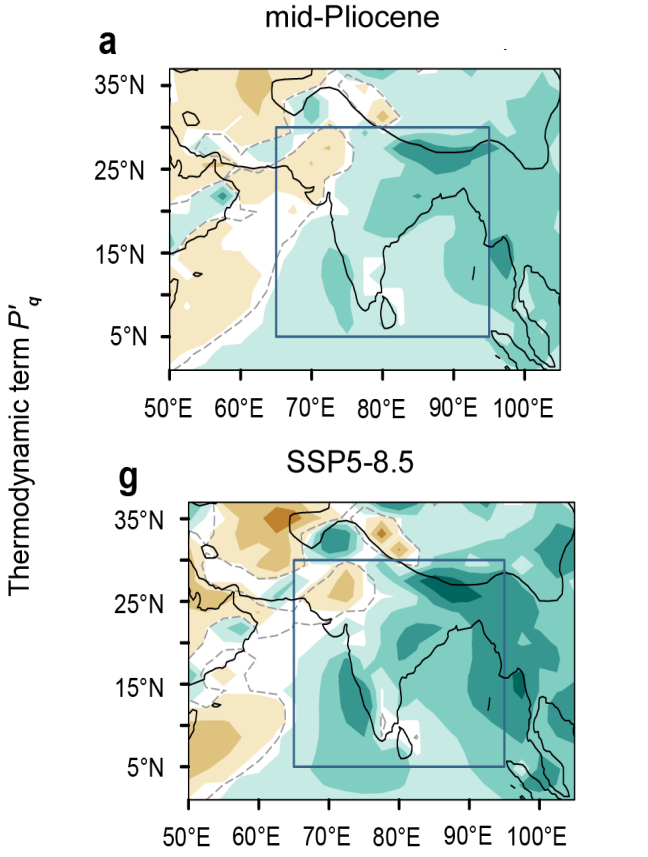
Role of atmospheric moisture (thermodynamics)



- The thermodynamic effect follows the "wet gets wetter, dry gets drier" paradigm.
- The mid-Holocene thermodynamic effect is weaker due to weaker summer warming.

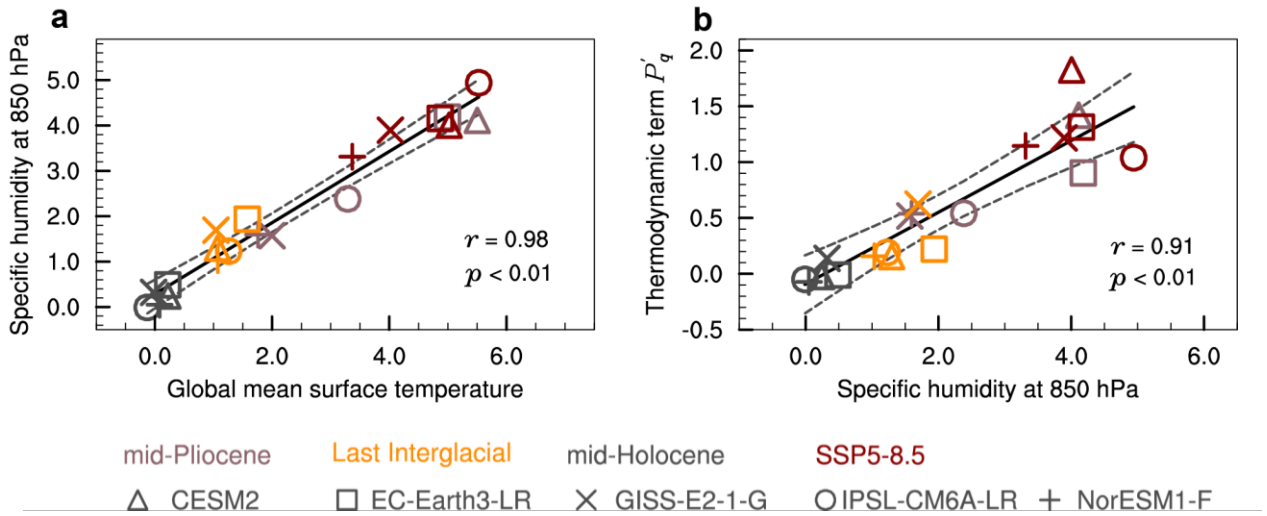
He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Controls of warming level in thermodynamics



$$P' \approx P'_q + P'_\omega = -\left\langle \bar{\omega} \frac{\partial q'}{\partial p} \right\rangle - \left\langle \omega' \frac{\partial \bar{q}}{\partial p} \right\rangle .$$

Scatterplots of atmospheric variables related to thermodynamics



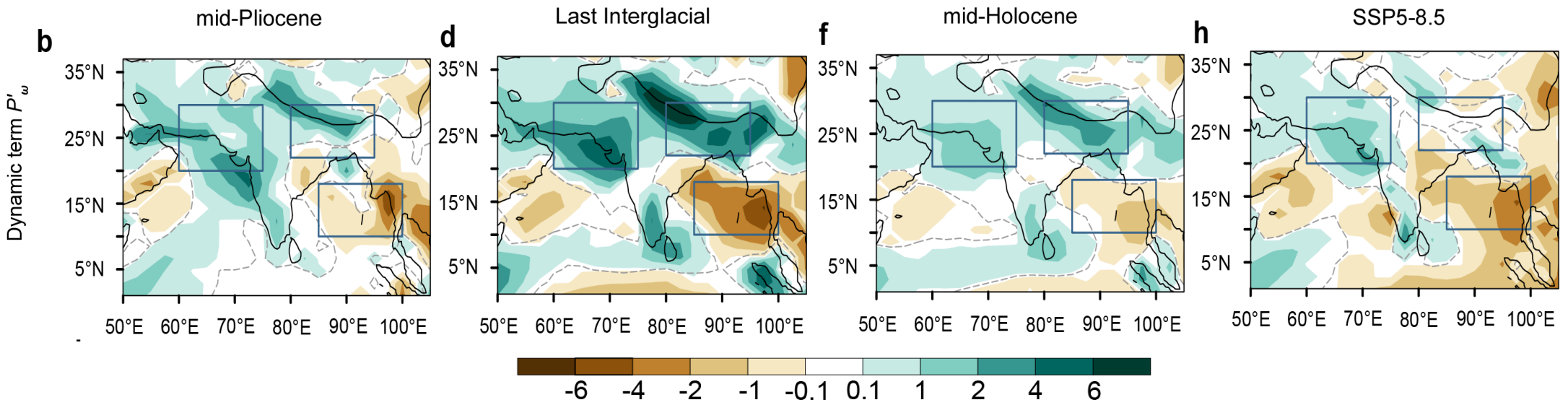
- A higher global mean surface temperature favors moister air over South Asia, leading to increased monsoon rainfall.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Roles of atmospheric moisture and circulation

$$P' \approx P'_q + P'_\omega = -\left\langle \bar{\omega}\frac{\partial q'}{\partial p} \right\rangle - \left\langle \omega'\frac{\partial \bar{q}}{\partial p} \right\rangle .$$

Role of atmospheric circulation (dynamics)

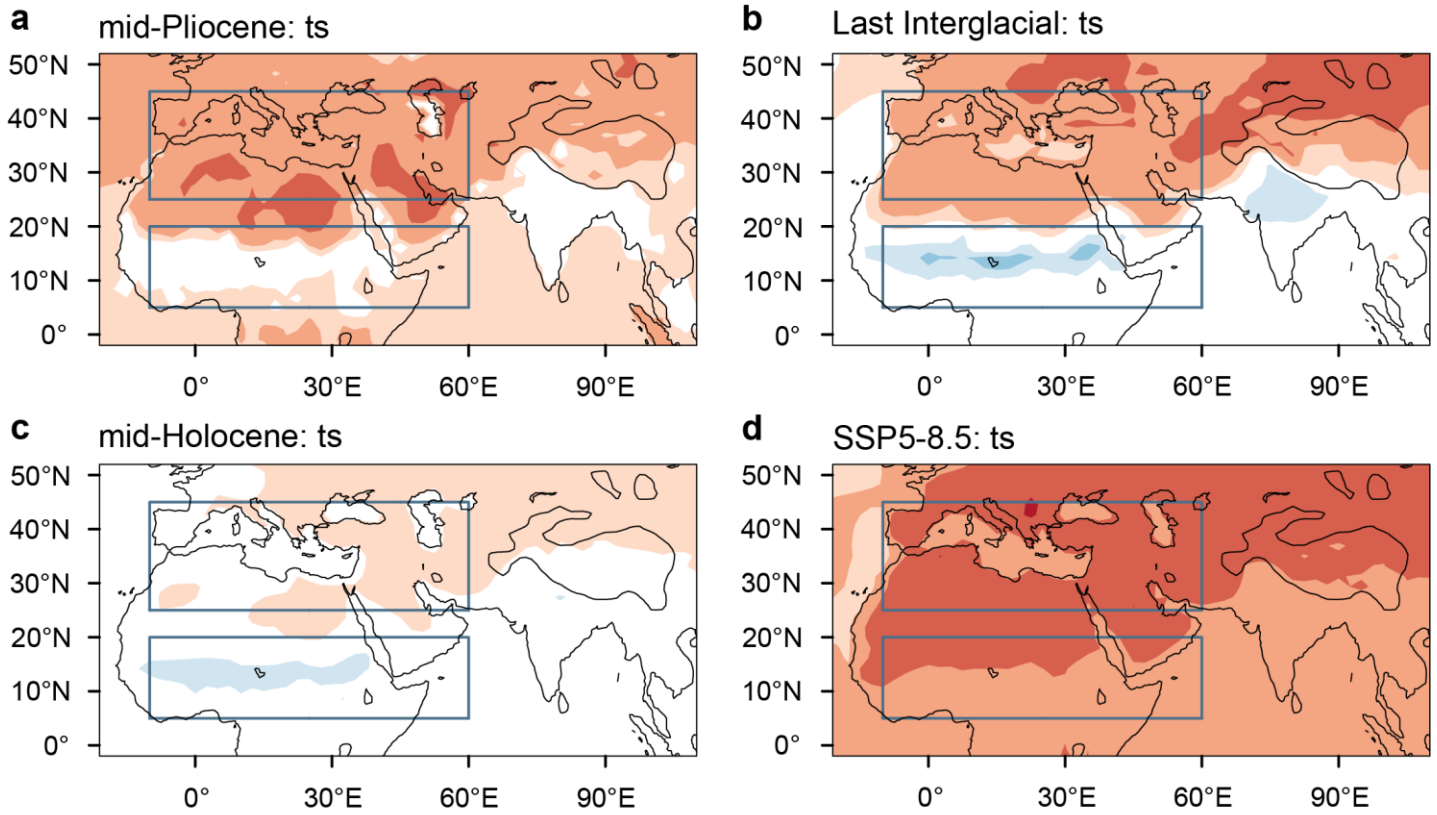


- The dynamic effect is spatially non-uniform, with south drying and north wetting.
- The non-uniform dynamic effect helps explain why the monsoon circulation appears to strengthen in the past but weaken in the future when measured by regional-mean vertical motion.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Controls of warming pattern in dynamics

Surface temperature changes

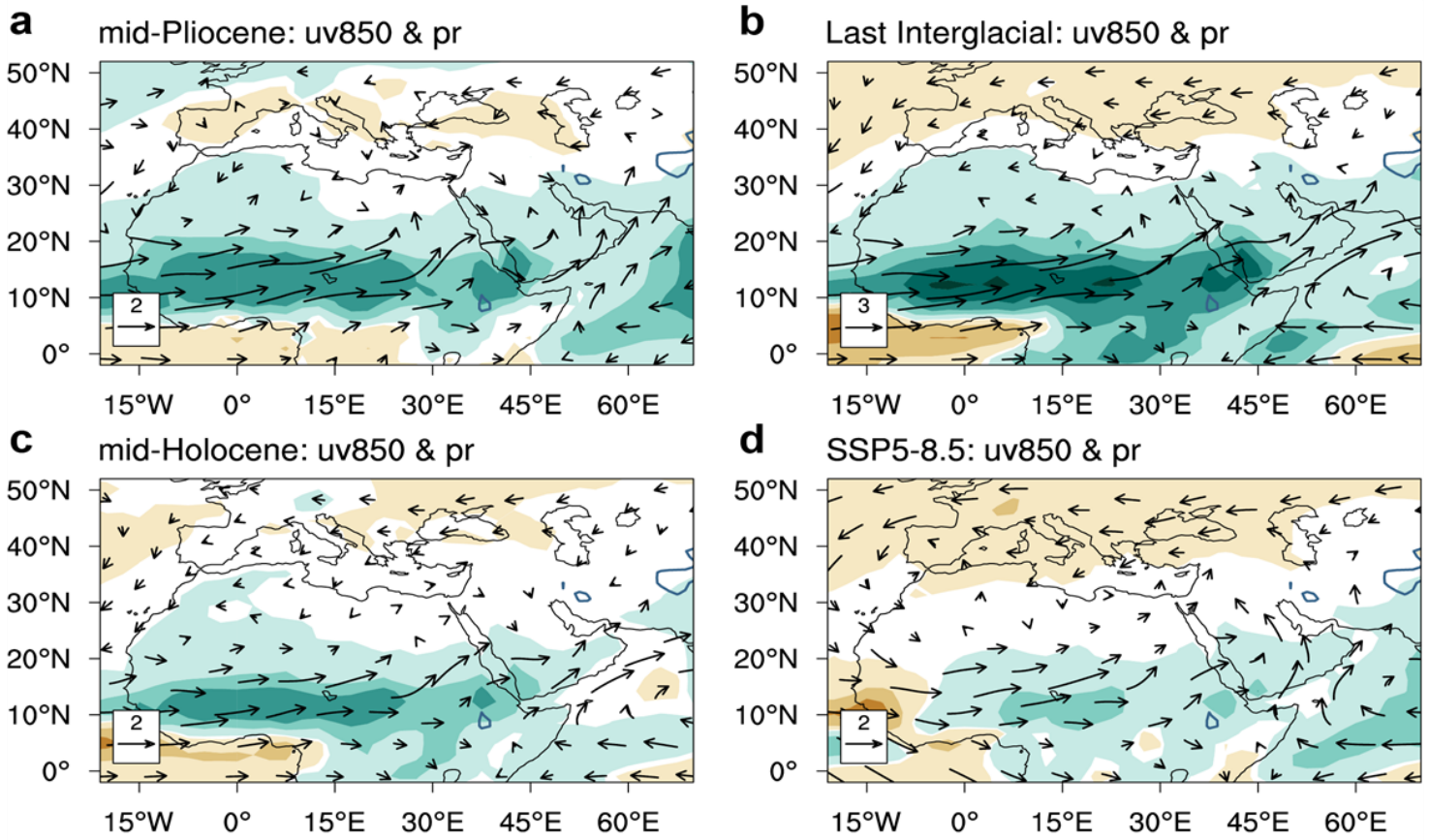


- Consistent warming pattern: Enhanced subtropical land warming relative to tropical Africa.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Controls of warming pattern in dynamics

Rainfall and 850hPa wind changes

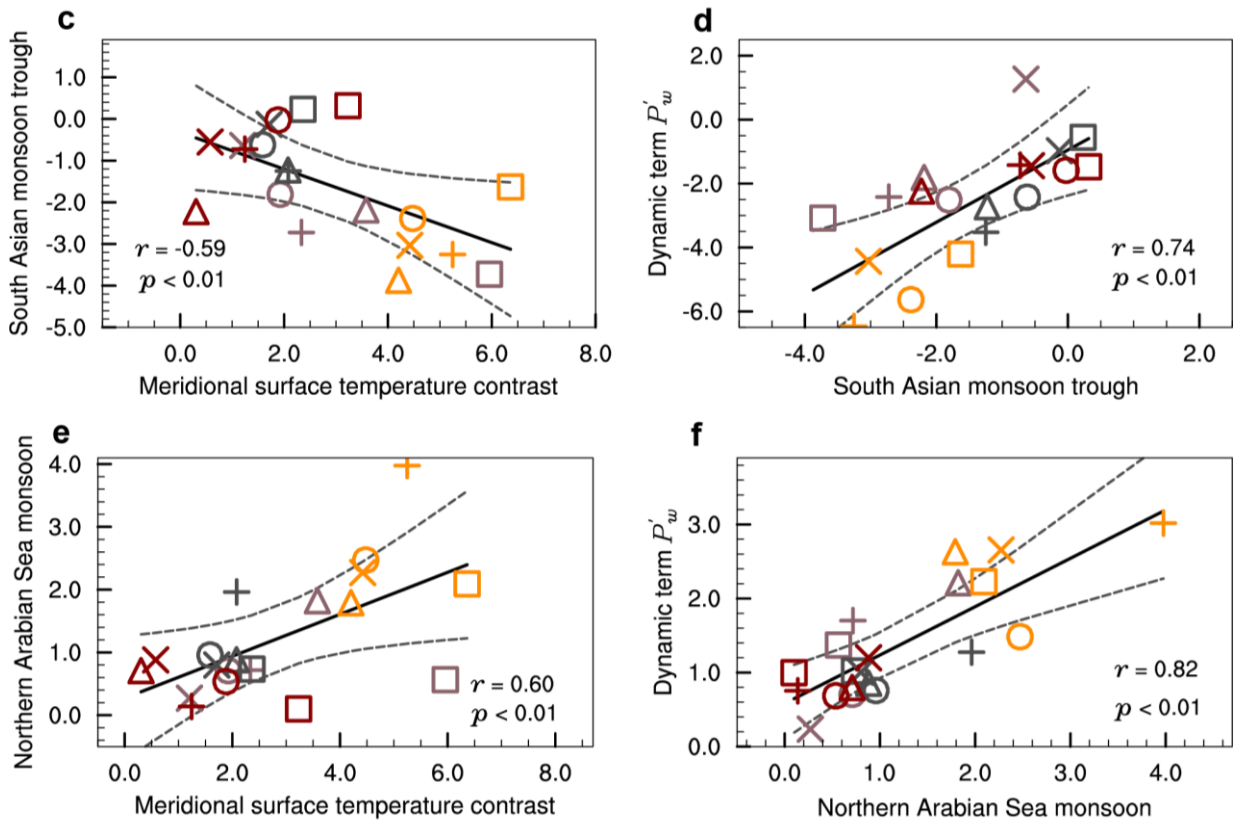


- Warming induces a westerly–easterly dipole over South Asia linked to stronger West African monsoon.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Controls of warming pattern in dynamics

Scatterplots of atmospheric variables related to dynamics



- A stronger meridional temperature contrast favors weakened monsoon circulation over the Bay of Bengal, enhanced circulation over the northern Arabian Sea, and a "south drying and north wetting" rainfall pattern.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Controls of warming pattern in dynamics

Model: CAM5
Resolution: ~2°
Integration: 30 years

Details of the atmospheric model experiments

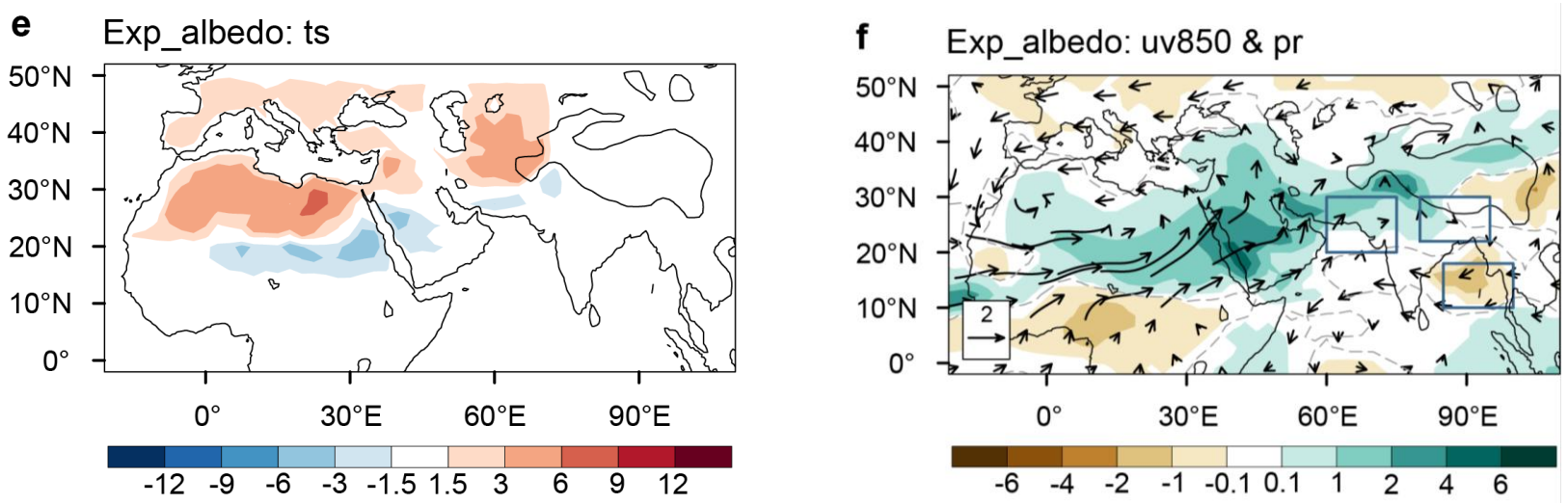
No	Experiment name	Experiment design	Experiment purpose
1	*Exp_control*	Standardized atmospheric experiment forced by modern observational sea surface temperature	Simulate the present-day climate
2	*Exp_albedo*	Same as *Exp_control* but with a 60% reduction in land surface albedo over (20°–50°N, 20°W–70°E) from June to September	Examine the effect of meridional temperature contrast
3	*Exp_vegice*	Same as *Exp_control* but with the surface type in the mid-Pliocene	Examine the role of surface type changes
4	*Exp_orbit*	Same as *Exp_control* but with orbital parameters in the Last interglacial	Examine the role of increased insolation
5	*Exp_CO_2*	Same as *Exp_control* but with the atmospheric CO_2 concentration in the SSP5-8.5	Examine the role of atmospheric CO_2
6	*Exp_sst*	Same as *Exp_control* but with the modern observational SST plus anomalies of the multi-model mean in the SSP 5-8.5	Examine the role of CO2-induced SST

- To confirm the warming pattern effect, we designed idealized albedo experiments.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Controls of warming pattern in dynamics

Idealized warming pattern and its effects

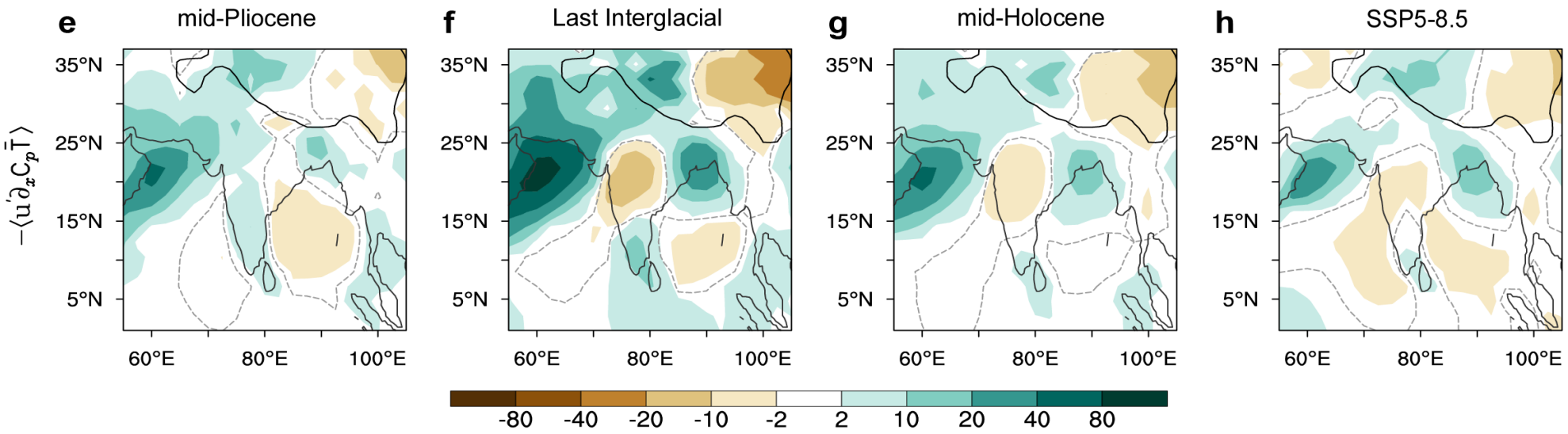


- The atmospheric general circulation experiments with reduced surface albedo confirm that the warming pattern can effectively drive the dynamic effect of SASM.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Monsoon rainfall dynamics driven by zonal winds

Zonal wind changes-induced sensible heat advection



$$\left\langle \omega \frac{\partial h}{\partial p} \right\rangle' \approx -\left\langle u \frac{\partial (L_v q + C_p T)}{\partial x} \right\rangle' - \left\langle v \frac{\partial (L_v q + C_p T)}{\partial y} \right\rangle' + F'_{net},$$

$$-\omega' \propto -\left\langle u' L_v \frac{\partial \bar{q}}{\partial_x} \right\rangle - \left\langle u' C_p \frac{\partial \bar{T}}{\partial_x} \right\rangle.$$

- According to the moist static energy framework, the spatially non-uniform monsoon rainfall dynamics related to zonal wind changes are primarily driven by sensible heat advection.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

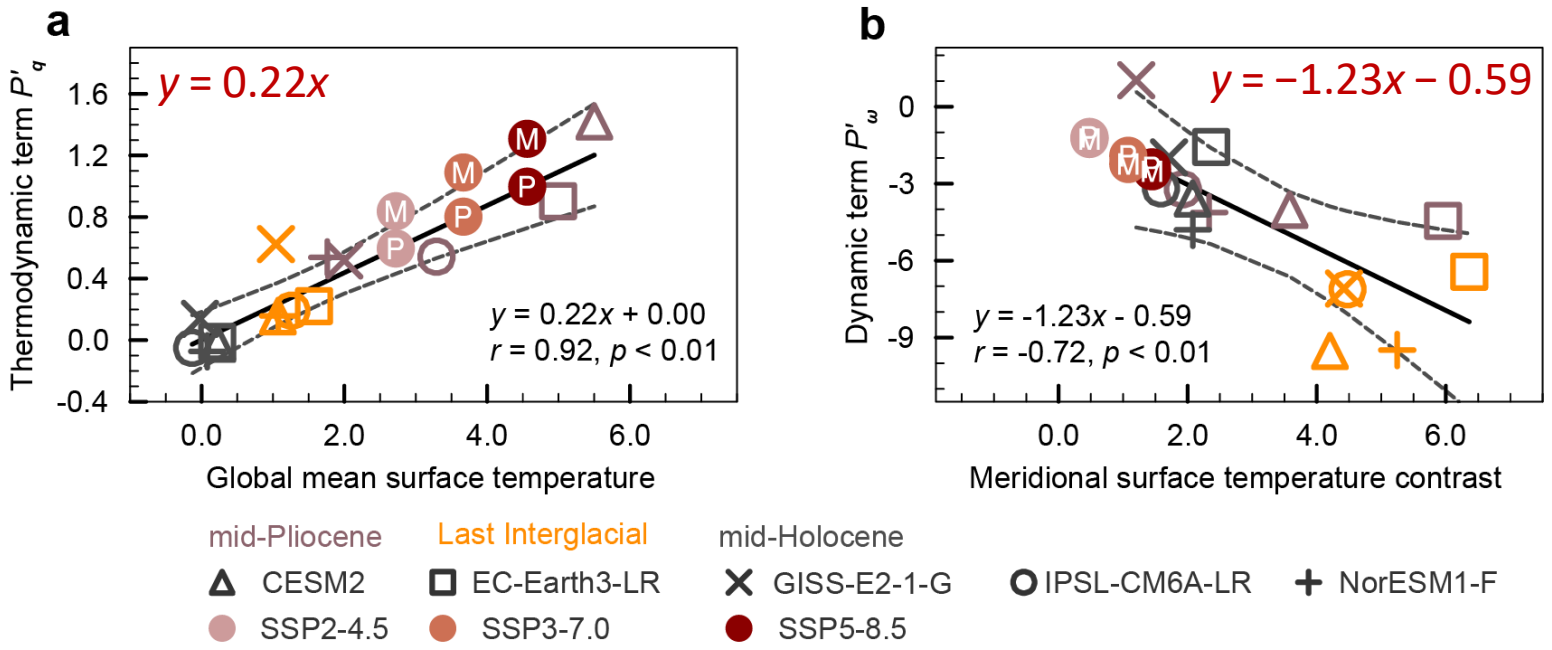
Research Question 3

HOW do past warm climates serve as analogs for the future monsoon?

Prediction based on analogue: Regression model

Future prediction using past information

Future prediction of SASM thermodynamics and dynamics



- To demonstrate that past can inform future, we construct physics-based regression models using past information.
- Regression predictions are generally consistent with climate model projections.

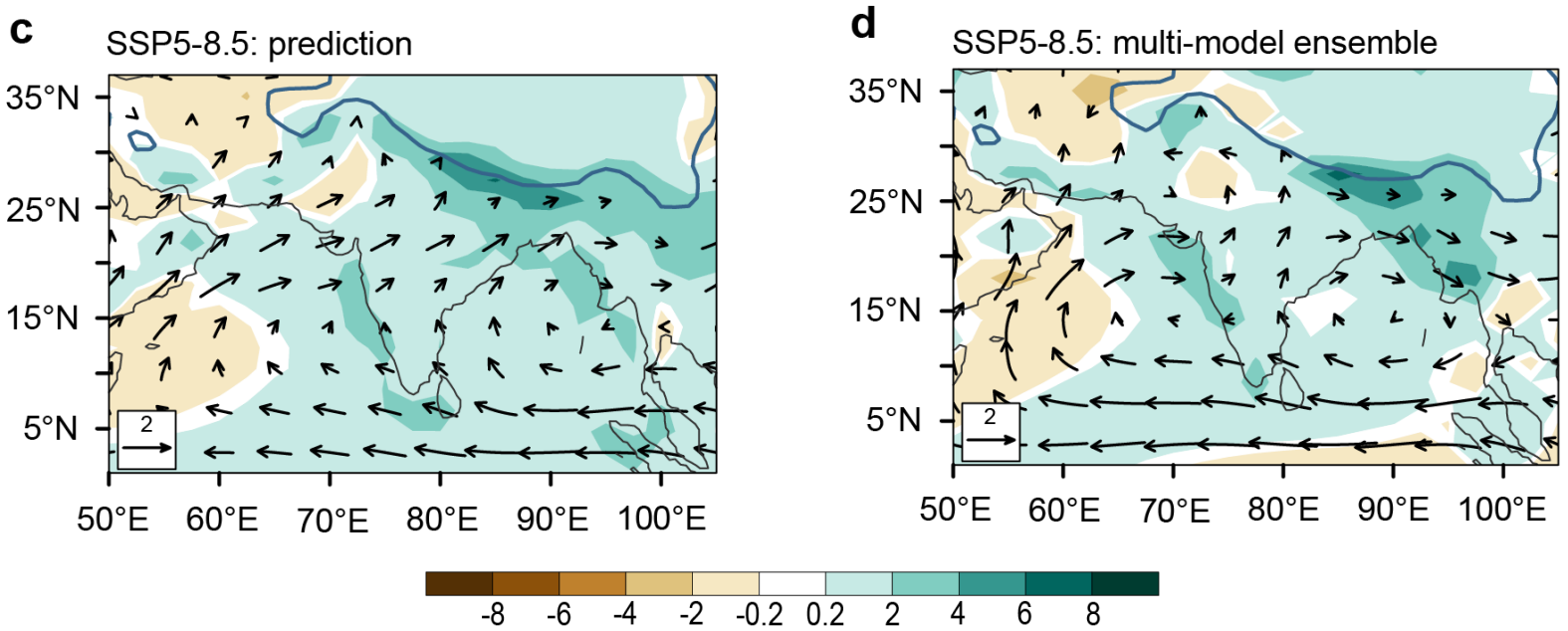
He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Future prediction using past information

Future prediction of SASM rainfall and circulation

Regression models

Climate models



- Spatial pattern correlations between regression-based predictions and climate model projections: 0.80 for monsoon circulation and 0.70 for monsoon rainfall.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Key Takeaways

- Within a unified research framework, we identify consistent SASM responses to warming ranging from the past to the future, governed by a tug-of-war between the thermodynamic and dynamic effects.
- Thermodynamically, it follows the wet-get-wetter paradigm determined by the global mean temperature. Dynamically, it is dominated by the monsoon circulation driven by the regional meridional temperature contrast.
- Building on this, we have developed a physics-based regression model using past climate information, which predicts the future monsoon well as projected by climate models.
- This suggests that past warm climates can inform the future South Asian summer monsoon, although driven by different forcing agents.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

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NEWS AND VIEWS | 14 May 2025

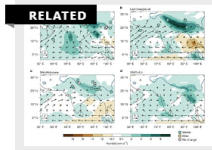
Earth's climatic past illuminates future South Asian monsoon patterns

An analysis of warm periods in Earth's history helps to clarify an apparent anomaly in projections of the future behaviour of the South Asian summer monsoon.

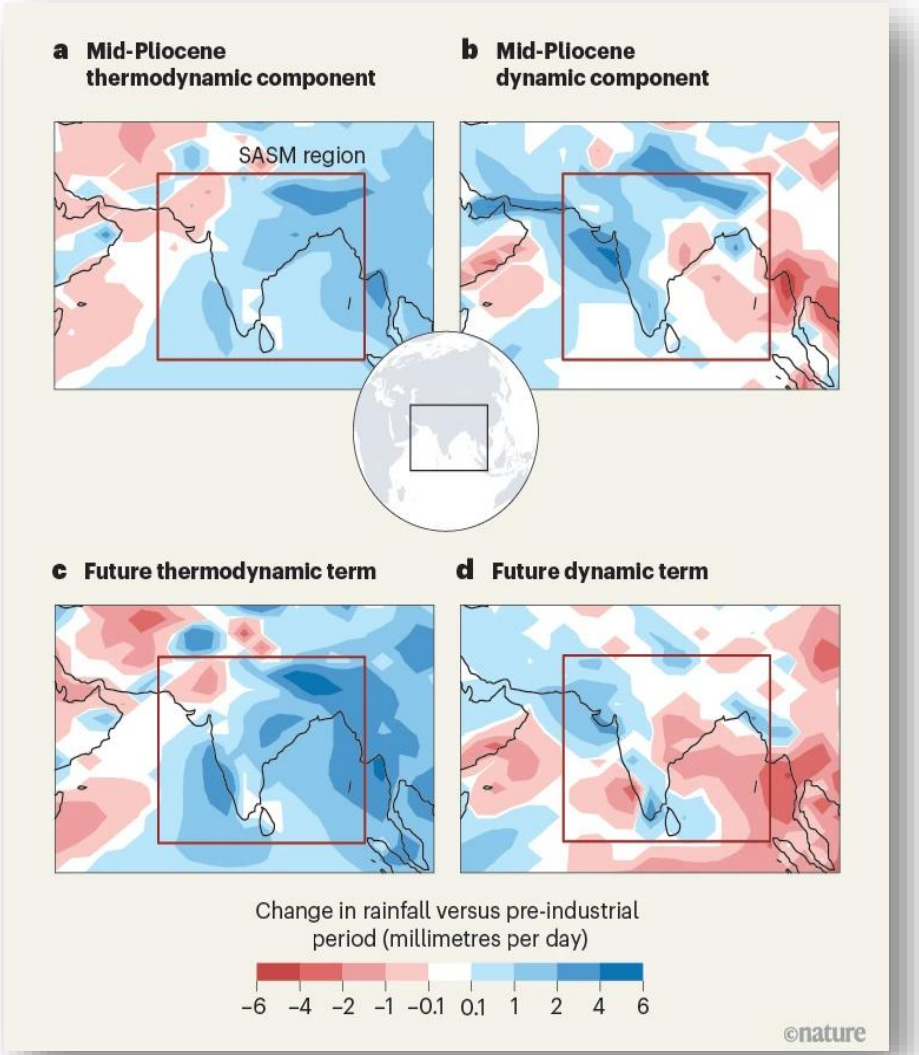
By Francesco S. R. Pausata & Thejna Tharammal

The South Asian summer monsoon (SASM) is vital for more than one billion people because it delivers approximately 80% of their annual rainfall[1,2], sustaining agriculture and the livelihoods of numerous communities. It is therefore crucial to understand how the SASM will be affected by global warming, but climate models project a paradox: as temperatures rise, SASM rainfall is expected to increase even as the atmospheric circulation that drives it weakens[2,3]. Writing in *Nature*, He *et al.*[4] explain this paradox by turning to Earth's climatic past. The authors reveal consistent patterns that underpin past and future monsoon behaviour — an advance that improves predictions for one of the world's most consequential weather systems.

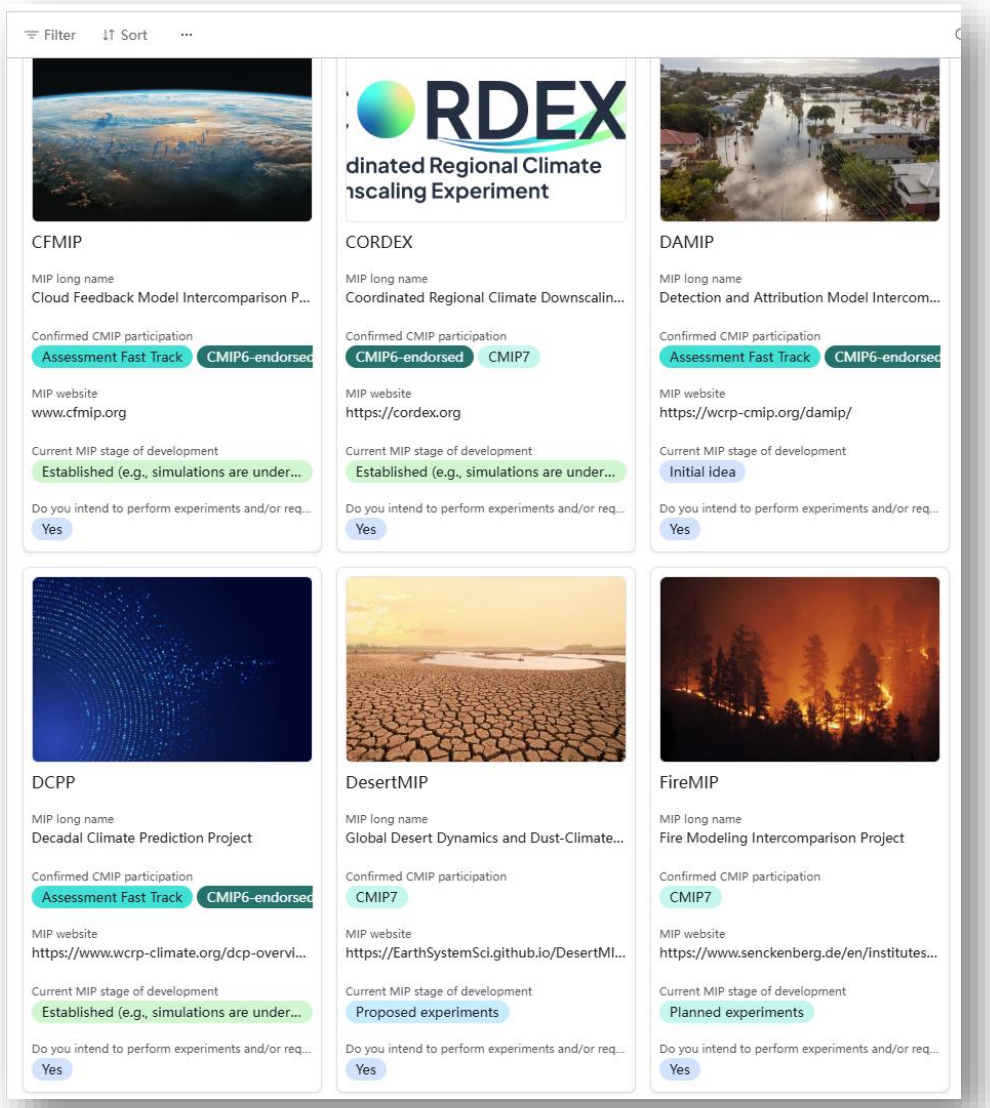
RELATED



In South Asia, the summer monsoon season typically occurs from June to September and is characterized by the reversal of trade winds, resulting in the transport of vast amounts of moisture from the Indian Ocean and the Arabian Sea to the land. As a crucial component of the global monsoon system[5], the SASM is influenced by various factors, including variations in



Next steps: GMMIP going forward from CMIP6 to CMIP7



https://wcrp-cmip.org/mips

CMIP6:

1. Model skill in simulating the climatology and interannual-to-multidecadal variability of global monsoons forced by the sea surface temperature during historical climate period;
2. The roles of the Interdecadal Pacific Oscillation and Atlantic Multidecadal Oscillation in driving variations of the global and regional monsoons;
3. The effects of large orographic terrain on the establishment of the monsoons

CMIP7:

1. From palaeoclimate monsoons to future climate change
2. Analogues of future projection and narrow down uncertainty
3. Process understanding: internal variability versus anthropogenic and natural external forcing agents
4. Immediate future and near-term prediction
5. Monsoon stability, variability, and reversibility in past and future climate, including potential tipping point

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Roles of individual forcing agents in dynamics

Model: CAM5
Resolution: ~2°
Integration: 30 years

Details of the atmospheric model experiments

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3	*Exp_vegice*	Same as *Exp_control* but with the surface type in the mid-Pliocene	Examine the role of surface type changes
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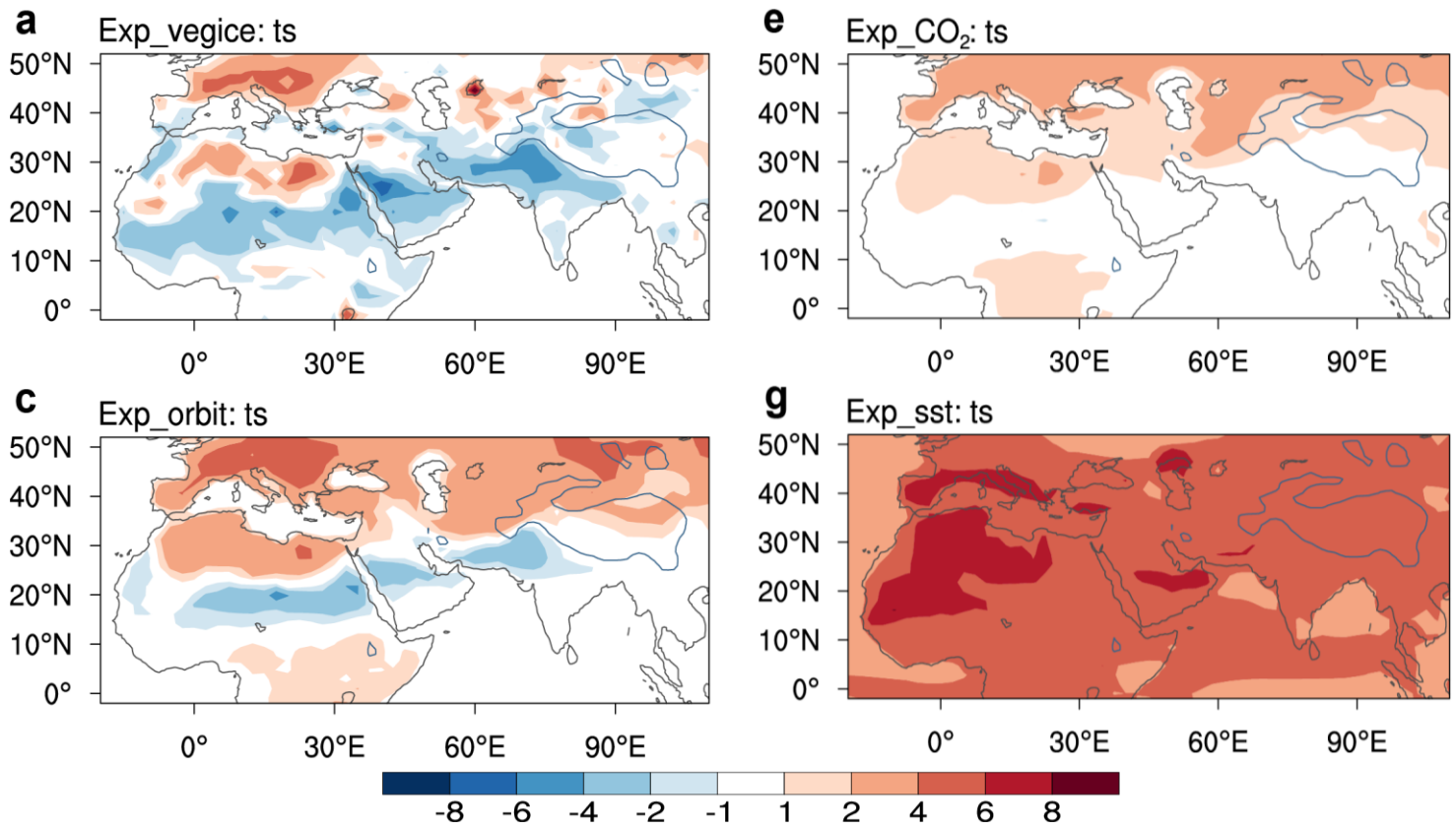
5	*Exp_CO_2*	Same as *Exp_control* but with the atmospheric CO_2 concentration in the SSP5-8.5	Examine the role of atmospheric CO_2
6	*Exp_sst*	Same as *Exp_control* but with the modern observational SST plus anomalies of the multi-model mean in the SSP 5-8.5	Examine the role of CO2-induced SST

- To isolate the role of individual forcing agents in monsoon rainfall dynamics, we designed a set of single-forcing experiments.

He, L., Zhou, T.* & Guo, Z. Past warm intervals inform the future South Asian summer monsoon. ***Nature*** 641, 653–659 (2025).

Roles of individual forcing agents in dynamics

Surface temperature responses to individual forcing agents



- The individual forcing agents—including mid-Pliocene surface types, LIG127k orbital parameters, and direct radiative forcing from SSP585 CO_2—can drive enhanced land warming over subtropical western Eurasia and northern Africa, except for the indirect radiative forcing of CO_2.

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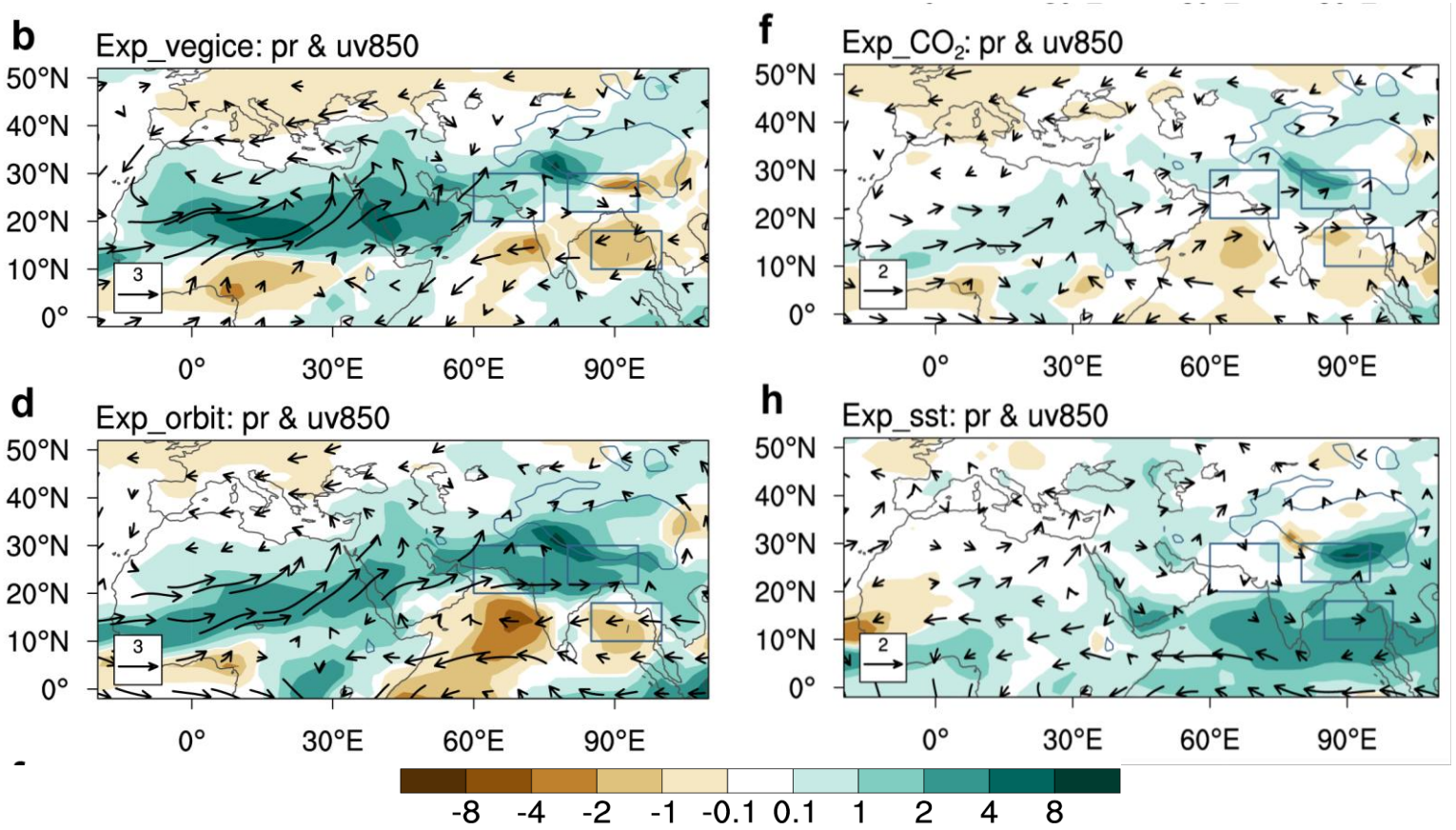
Roles of individual forcing agents in dynamics

Rainfall and 850hPa wind responses to individual forcing agents



- Given the warming pattern, these forcing agents further induce a dipolar pattern of monsoon circulation and rainfall anomalies over South Asia, whereas the indirect radiative forcing of CO_2 leads to a more uniform wetting dominated by thermodynamics.

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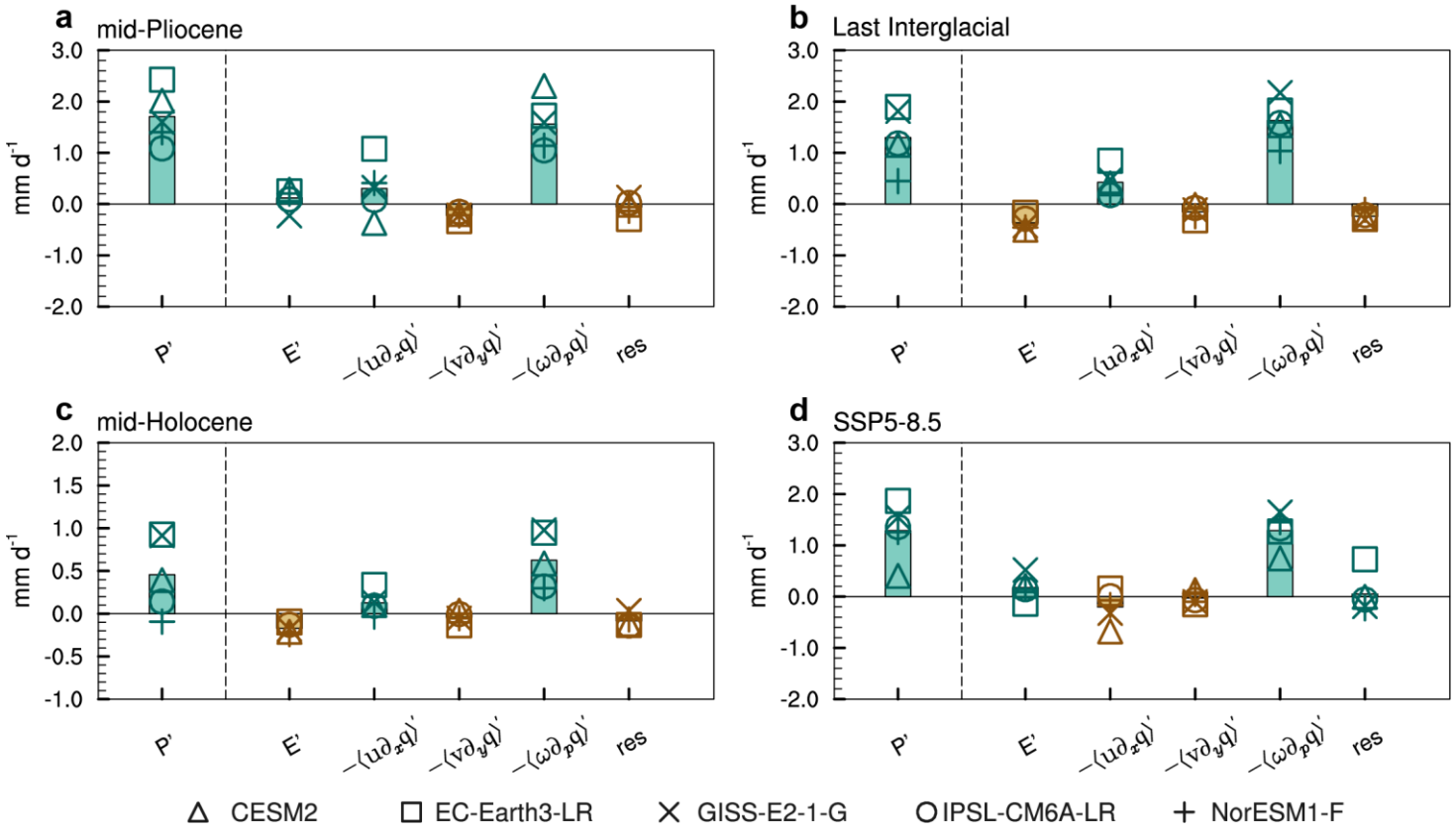
Consistent SASM changes in warm climates

Atmospheric moisture budget equation



- Increased monsoon rainfall is dominated by changes in the vertical moisture transport.

$$P' = E' - \left\langle u\frac{\partial q}{\partial x}\right\rangle' - \left\langle v\frac{\partial q}{\partial y}\right\rangle' - \left\langle \omega\frac{\partial q}{\partial p}\right\rangle' + \text{res},$$

- It can be further decomposed into the effects of atmospheric moisture and circulation.

$$P' \approx P'_q + P'_\omega = -\left\langle \overline{\omega}\frac{\partial q'}{\partial p}\right\rangle - \left\langle \omega'\frac{\partial \overline{q}}{\partial p}\right\rangle.$$

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