XVIII World Water Congress
International Water Resources Association (IWRA)

Does the hook structure constrain future precipitation extremes and floods?

Dr. Jiabo Yin
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In collaboration with Prof. Pierre Gentine, Prof. Louise Slater and Prof. Shenglian Guo

1 Background

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Save reefs to rescue all ecosystems

An approach that tackles the underlying causes of coral-reef decline could be applied to other habitats, argue Tiffany H. Morrison, Terry P. Hughes and colleagues.

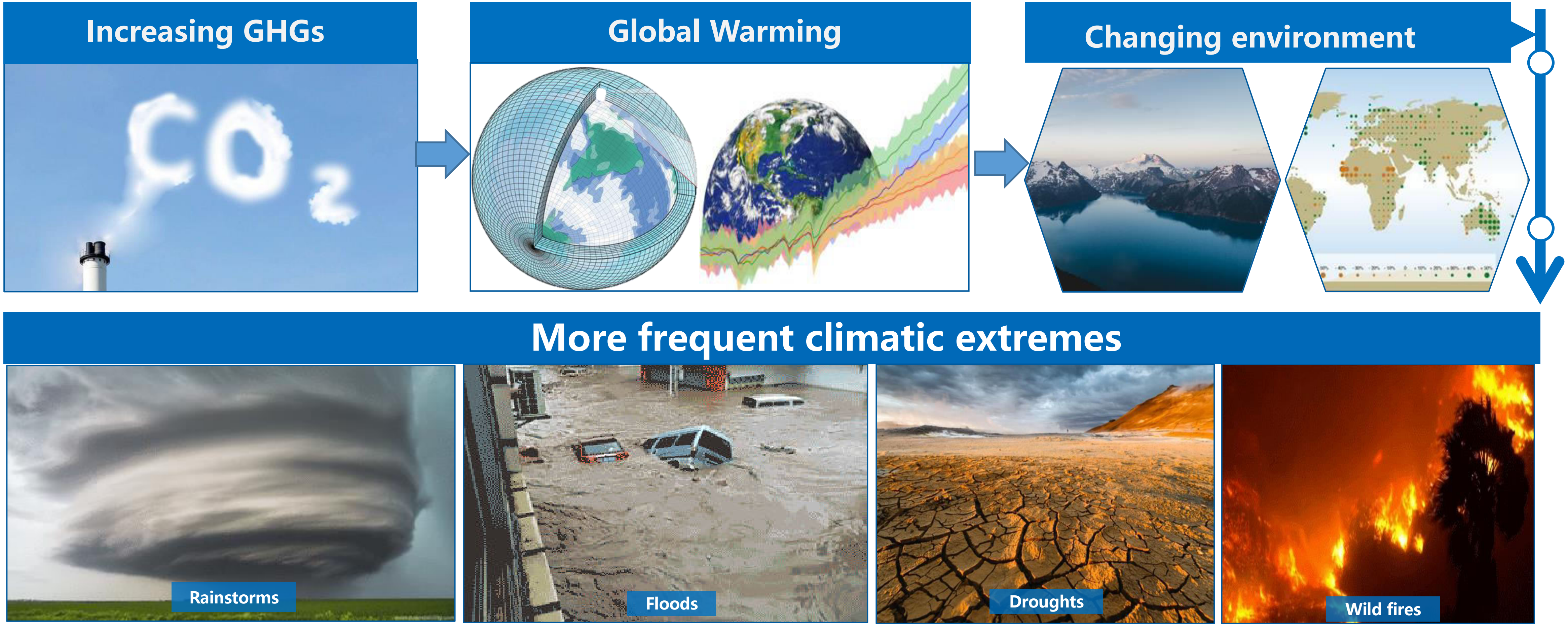
Nature Alert: All the coral reefs in the world might be gone by 2070 if global heating continues on its current path.

Climate Warming

2019-2020: Australian wildfires have killed half a billion animals and plants.

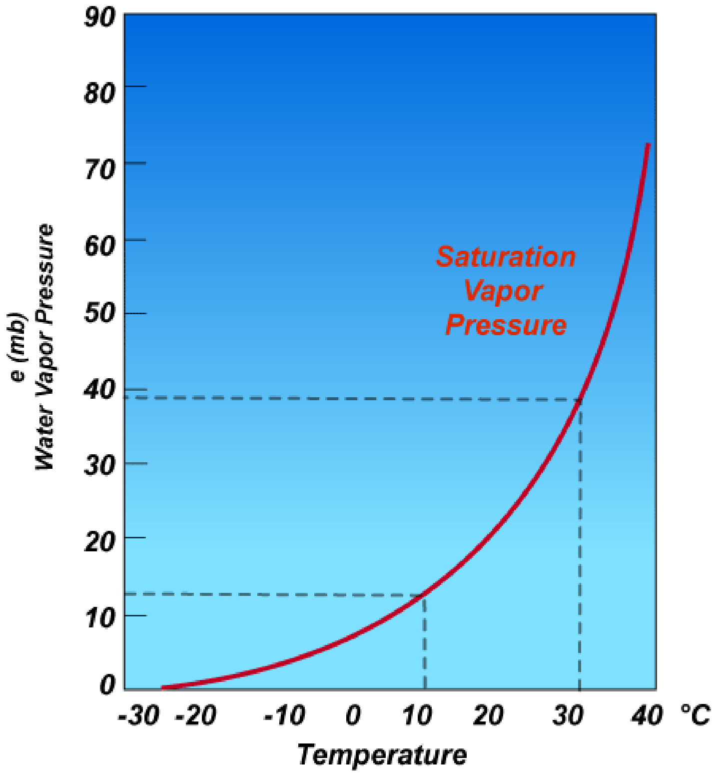
1 Background

- **Anthropogenic warming due to increasing greenhouse gas emission has altered the climate system and water-carbon cycle**



2 Hook structure of extreme precipitation and storm runoff

Atmospheric water vapor holding capacity should increase with rising temperature



Clausius-Clapeyron

Latent heat of vaporization

$$e_s(T) = e_{s0}\exp\left(\frac{L_v}{R_v}\left[\frac{1}{T_0} - \frac{1}{T}\right]\right)$$

saturated vapor pressure

Vapor gas constant

$$\frac{de_s}{e_s dT} = \frac{L_v}{R_v T^2}$$

(1) saturation vapor pressure is dependent solely on temperature

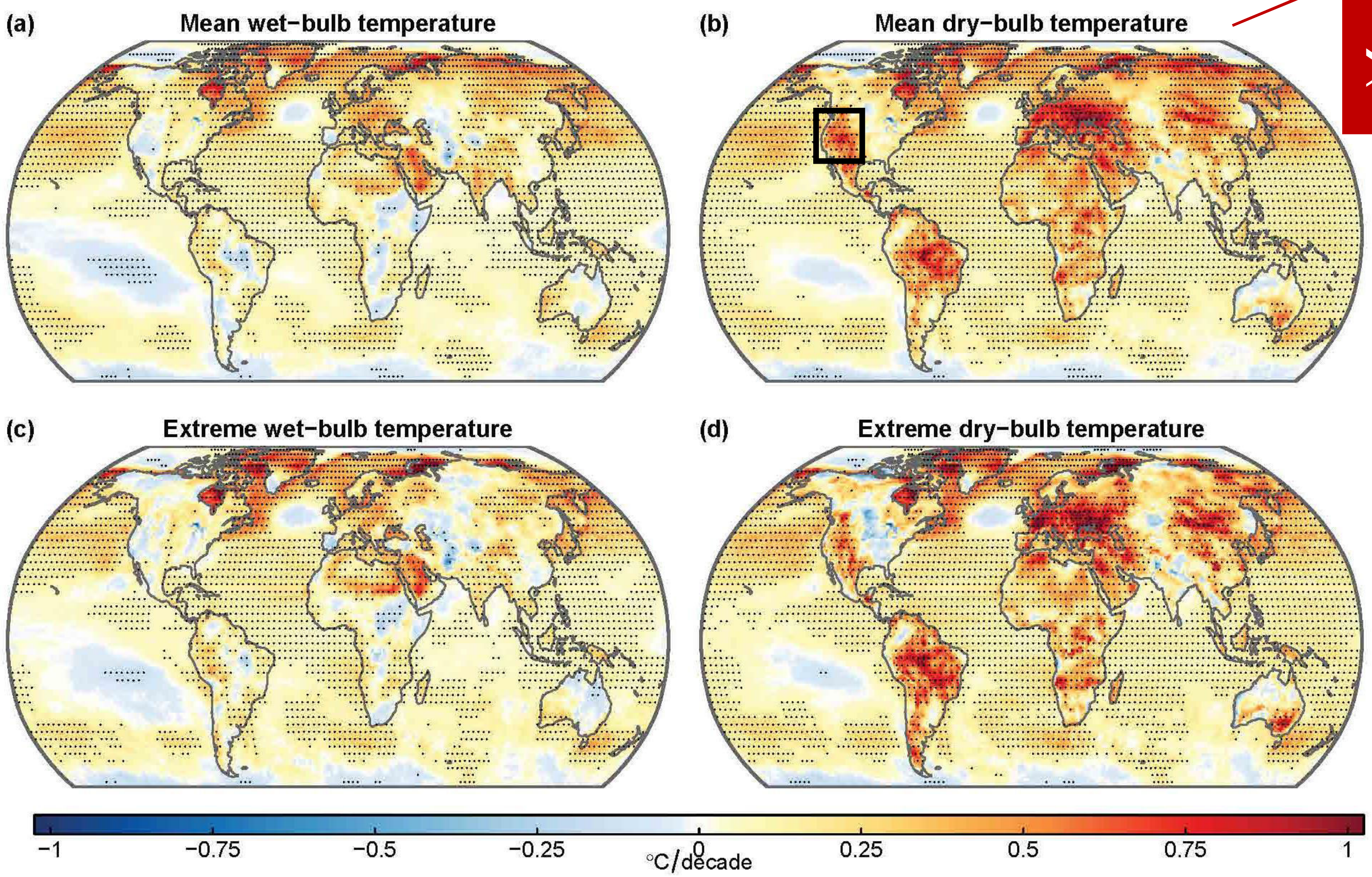
(2) 6.8 %/K at 25 °C (usually called as C-C scaling)

2 Hook structure of extreme precipitation and storm runoff

In many regions, temperature is rising, while precipitation extremes are declining

+Trend of T_{max}

>90%

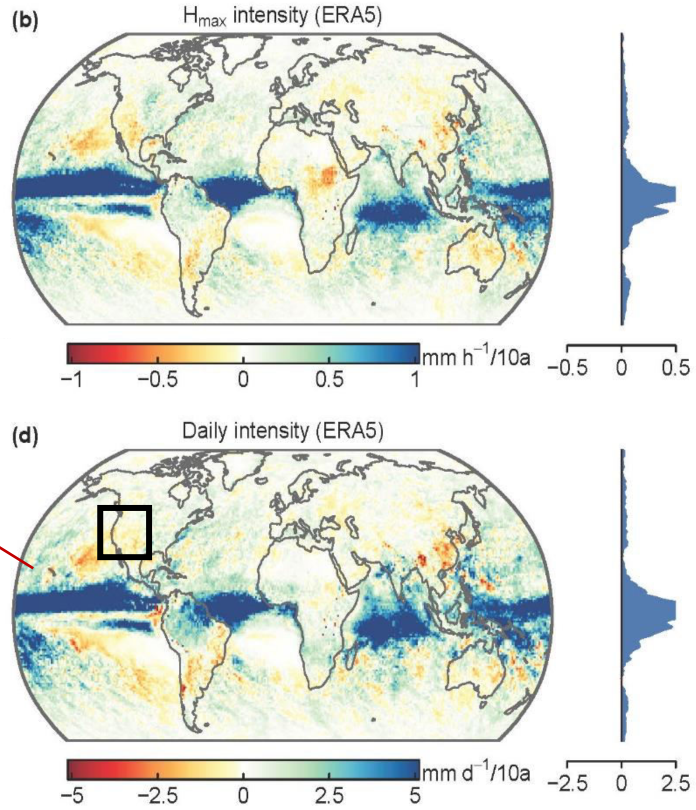


Global trend of mean and extreme temperatures during 1979-2021

Yin J, et al. GRL (2022)

+Trend of P_{max}

>60%



Trends of precipitation extremes during 1979-2021

Yin J, et al. Science China Earth Sciences (2023)

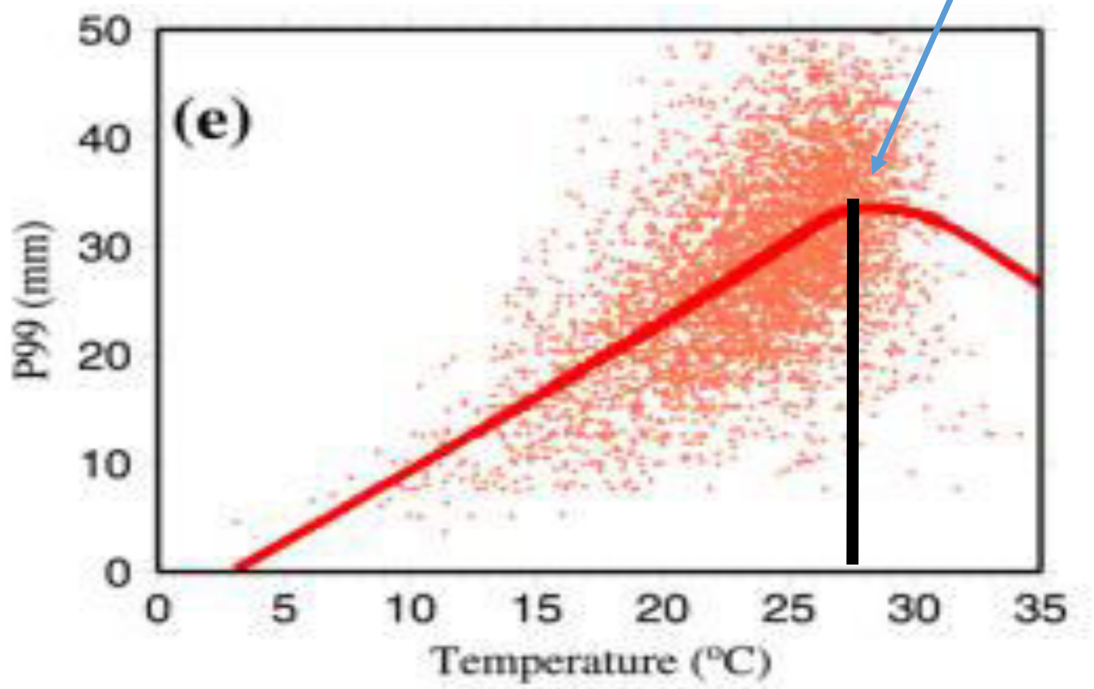
2 Hook structure of extreme precipitation and storm runoff

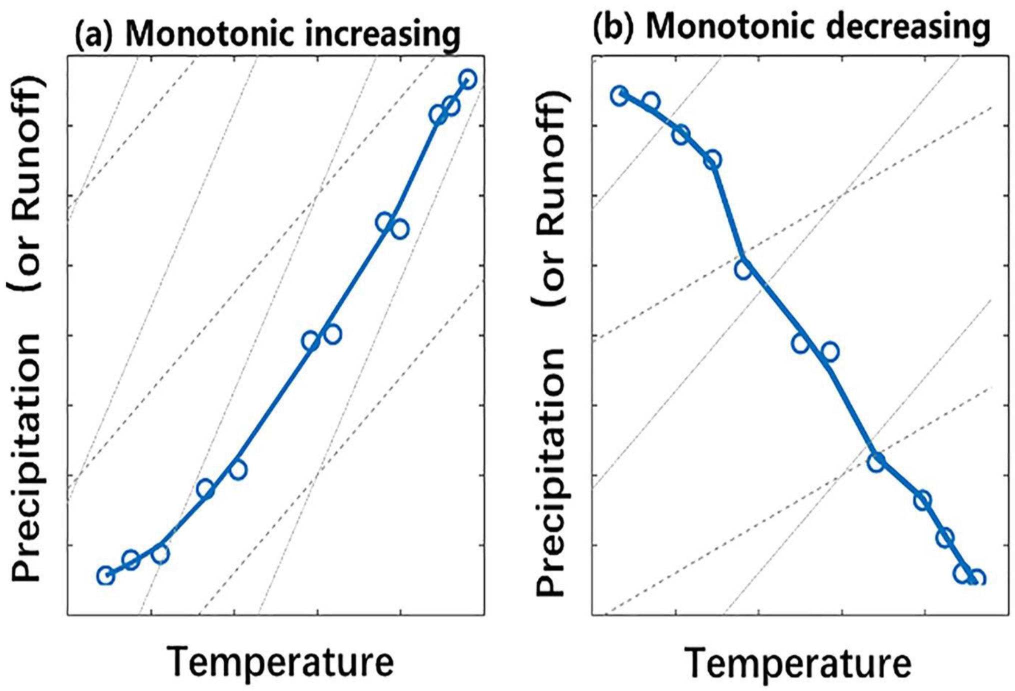
Unlike the thermodynamic expectations, we find a hook structure between precipitation/runoff extremes and temperatures

Binning Scaling

$$EPS = (\exp^{\frac{\ln P_b - \ln P_a}{T_b - T_a}} - 1) \times 100\%$$

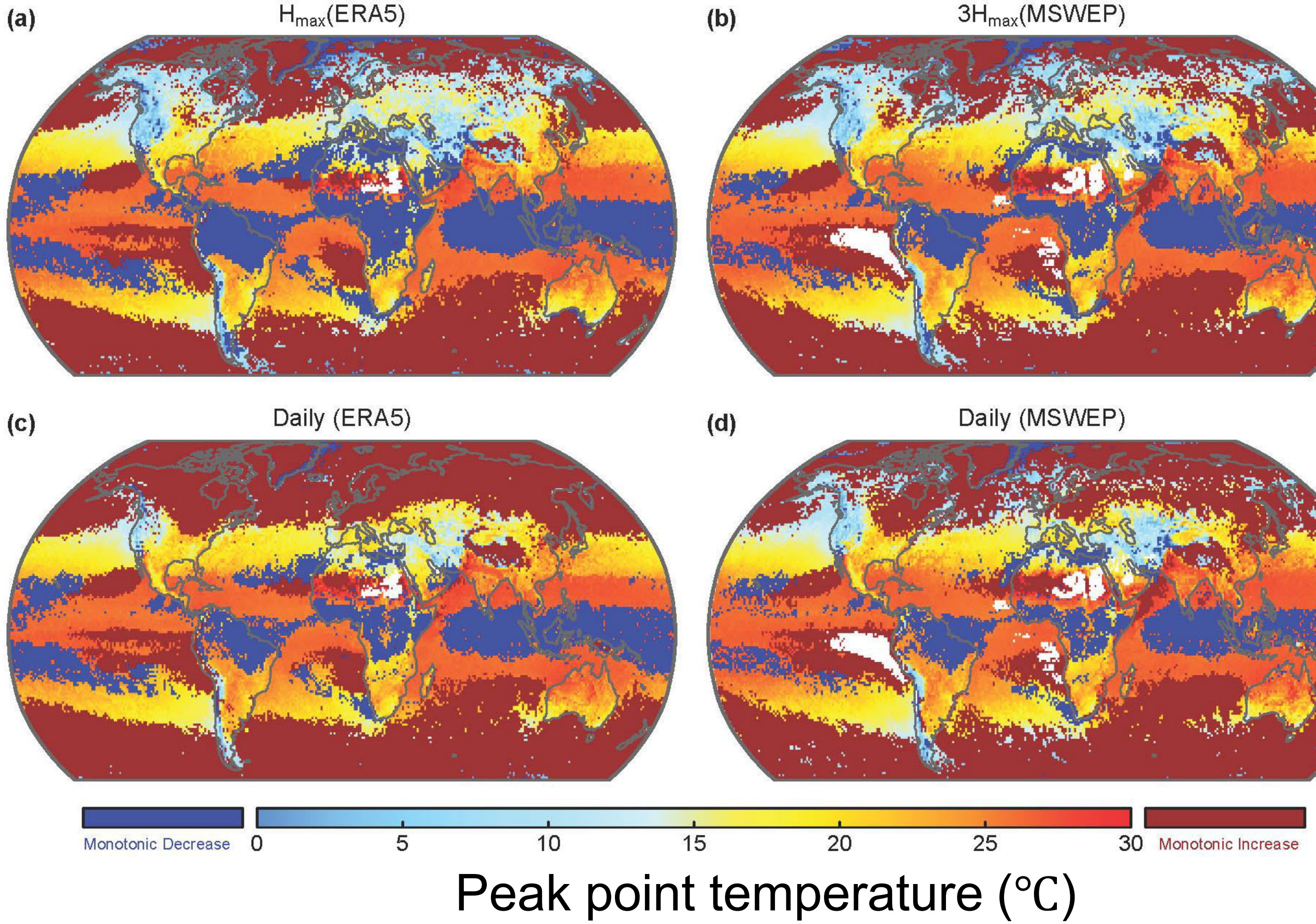
Hook structure: Extremes strengthen with rising temperature up to a peak point (T_{pp}) and decline thereafter



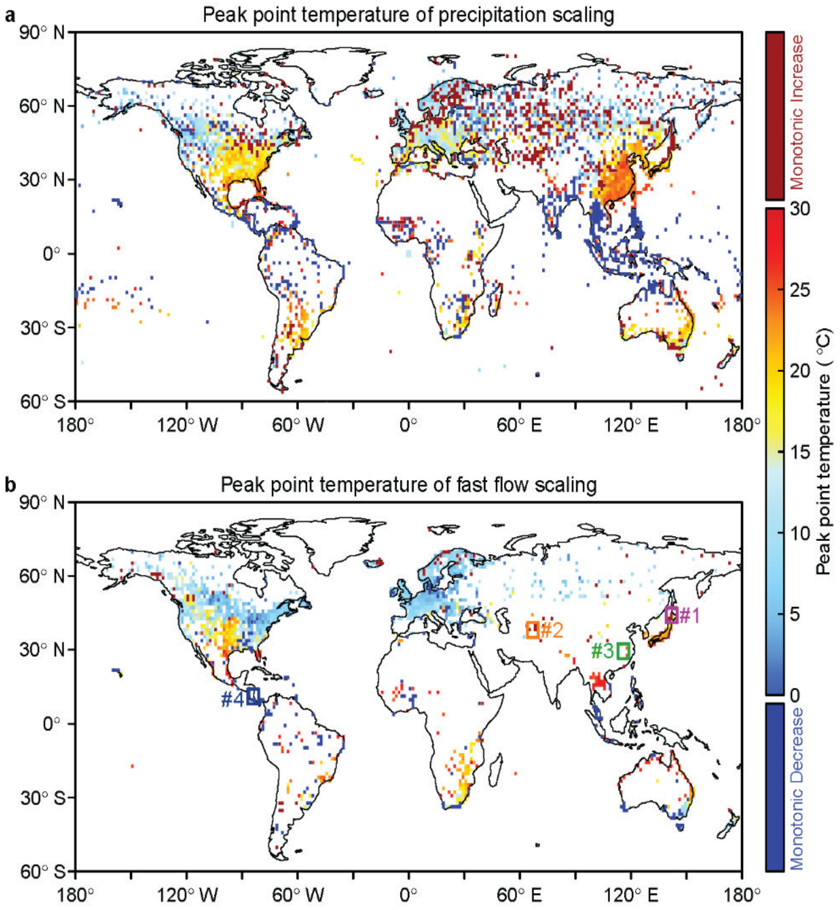


2 Hook structure of extreme precipitation and storm runoff

The underlying causes of this widely reported hook structure is not yet well-understood



Yin J, et al. Science China Earth Sciences (2023)



Yin J, et al. Nature Communications (2018)

2 Hook structure of extreme precipitation and storm runoff

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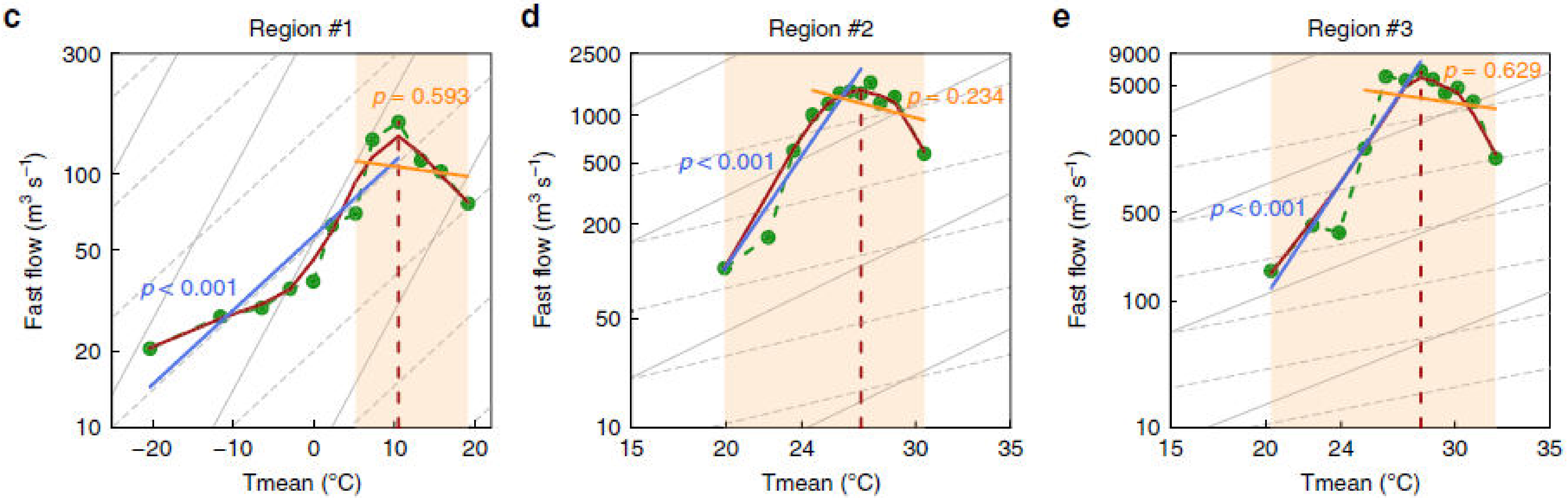

Figure: Temperature scaling of storm runoff over three typical catchments

Yin J, et al. Nature Communications (2018)

3 Understanding the Hook structure by atmospheric physics

Why can we observe a hook structure?

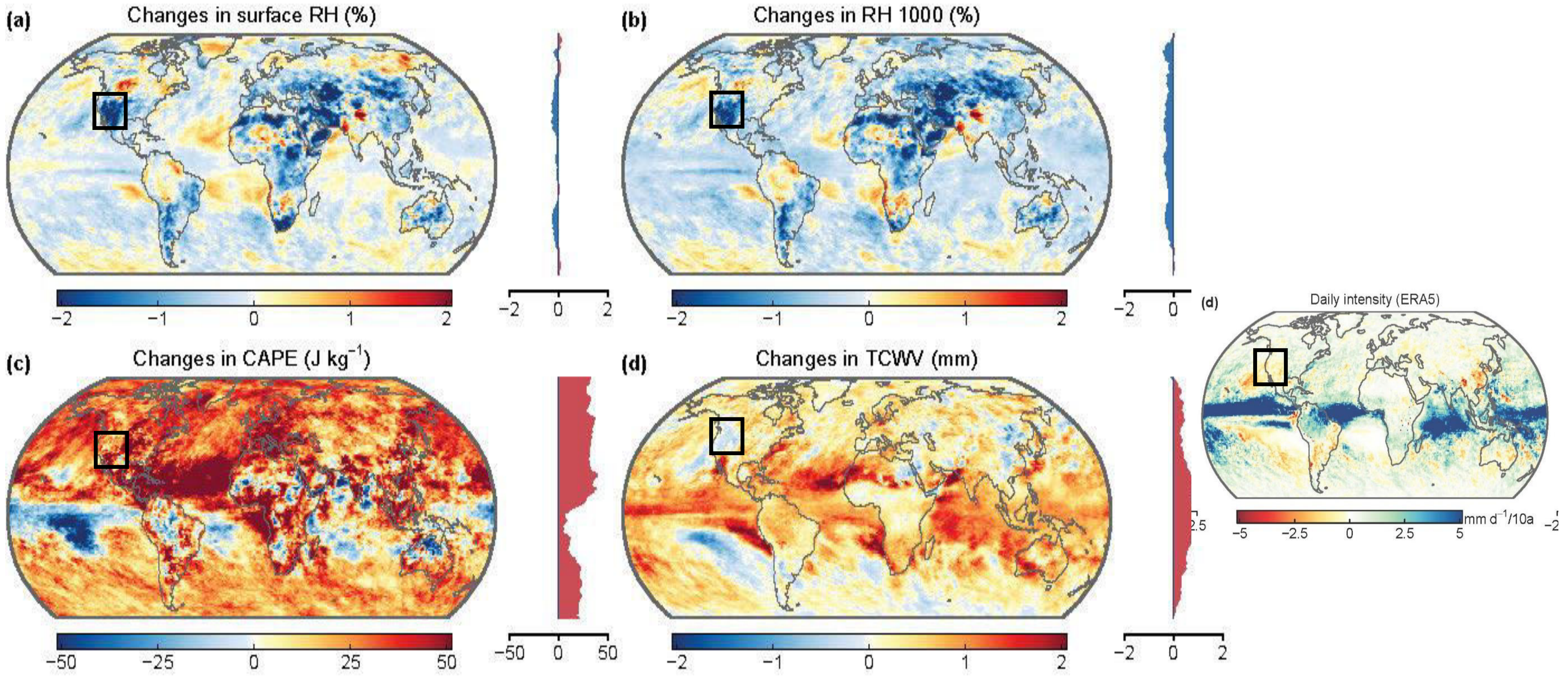

Figure: Trends in relative humidity, CAPE, and Total column water vapor (TCWV) during precipitation extremes

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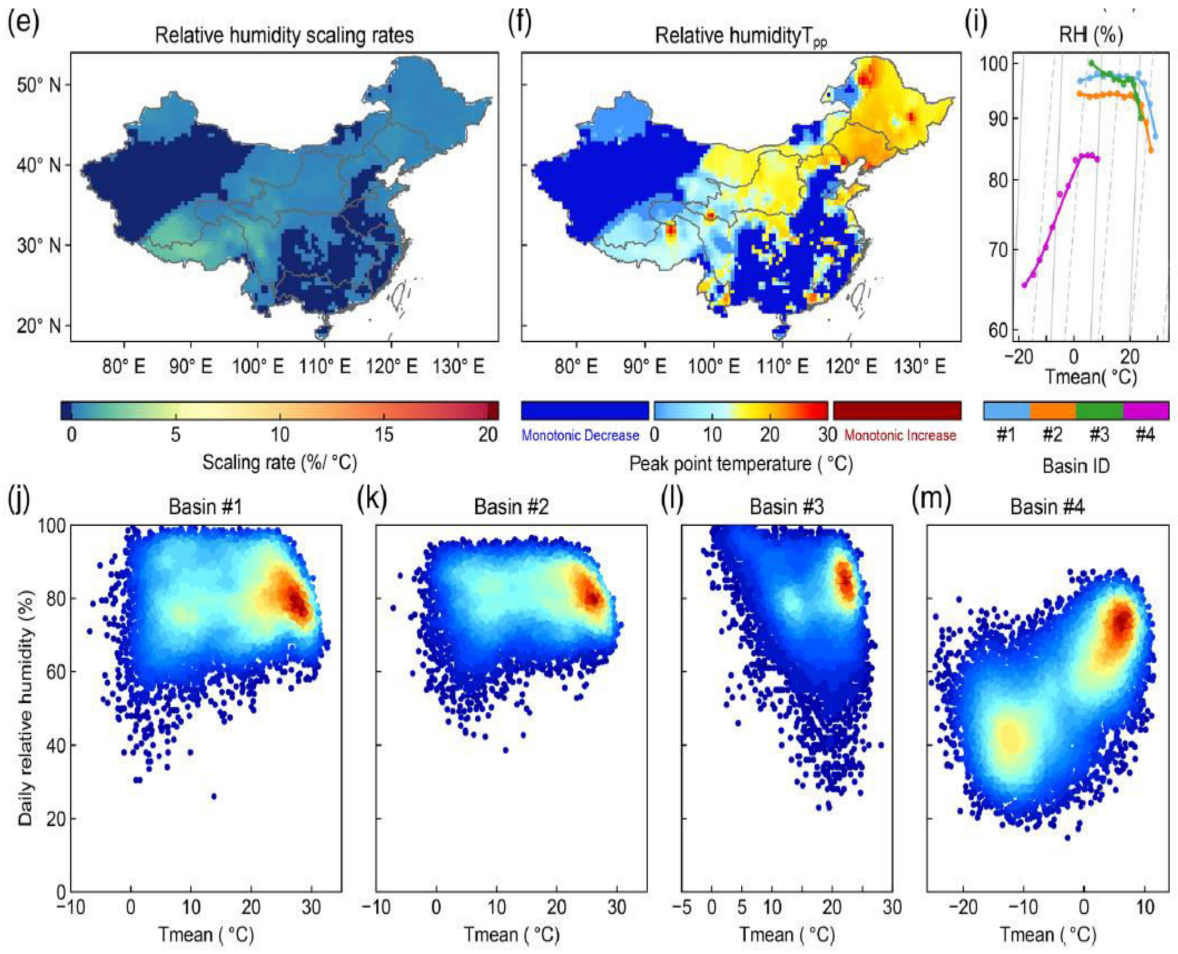


Figure: Scaling pattern between Relative humidity and temperatures

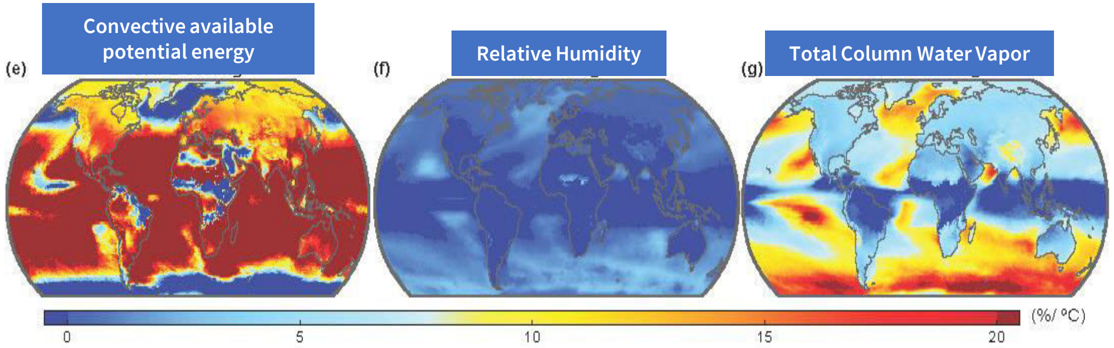


Figure: Temperature scaling of CAPE, RH and TCWV

- We find negative (sub C-C) scaling rates of *Relative Humidity* and *Total Column Water Vapor (TCWV)*, implying continental moisture limitations in hotter environments. Atmospheric dynamics might constrain extremes intensification.

Yin J, et al. Water Resources Research (2021)

3 Understanding the Hook structure by atmospheric physics

Why can we observe a hook structure?

Divergent sensitivities of P_e are reported

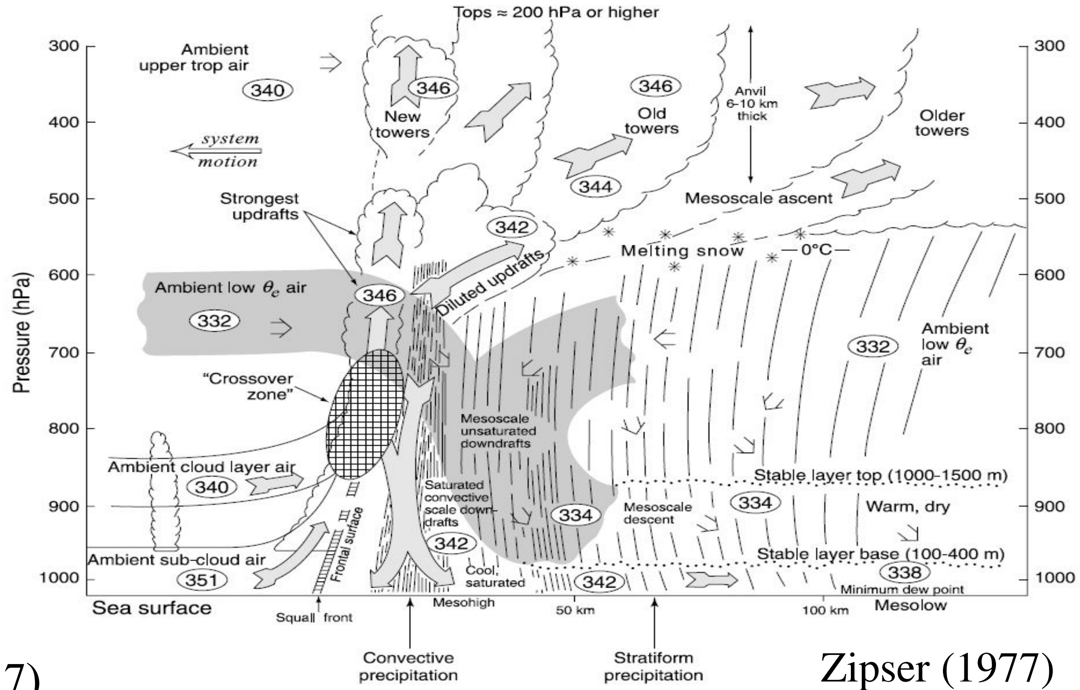
C-C scaling only tells part of the story

- **Local vertical motion**
- **Available atmospheric moisture**

$$P_e \sim -\left\{ \omega_e \left. \frac{dq_s}{dp} \right|_{\theta^*} \right\}$$

O'Gorman et al. (2012, 2017)

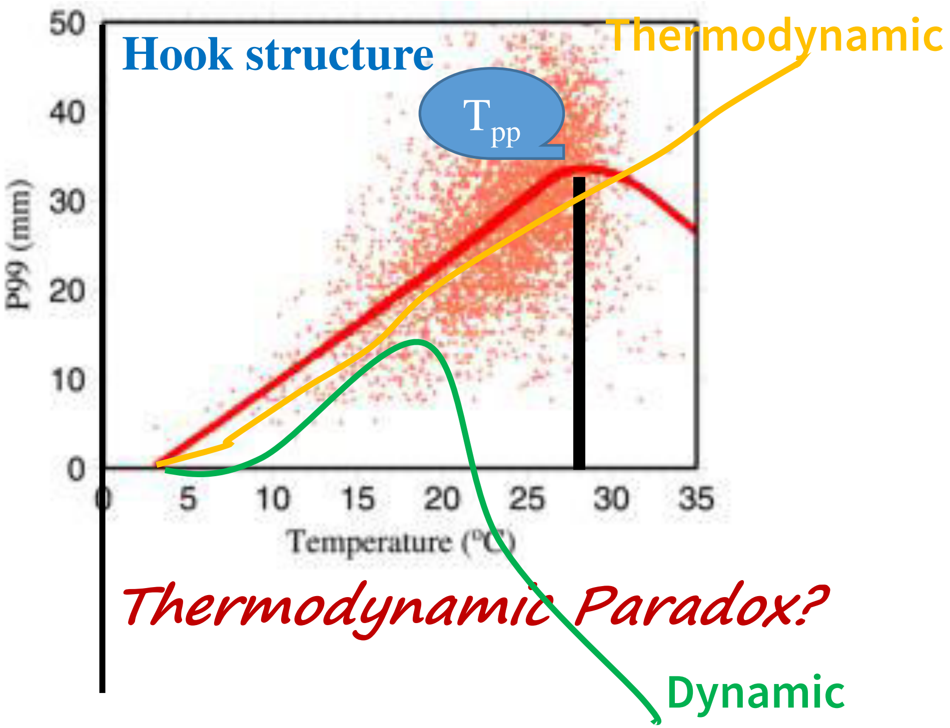
Precipitation involves complicated systems and coupled processes. How these physical processes impact Extreme precipitation sensitivity (*EPS*)?



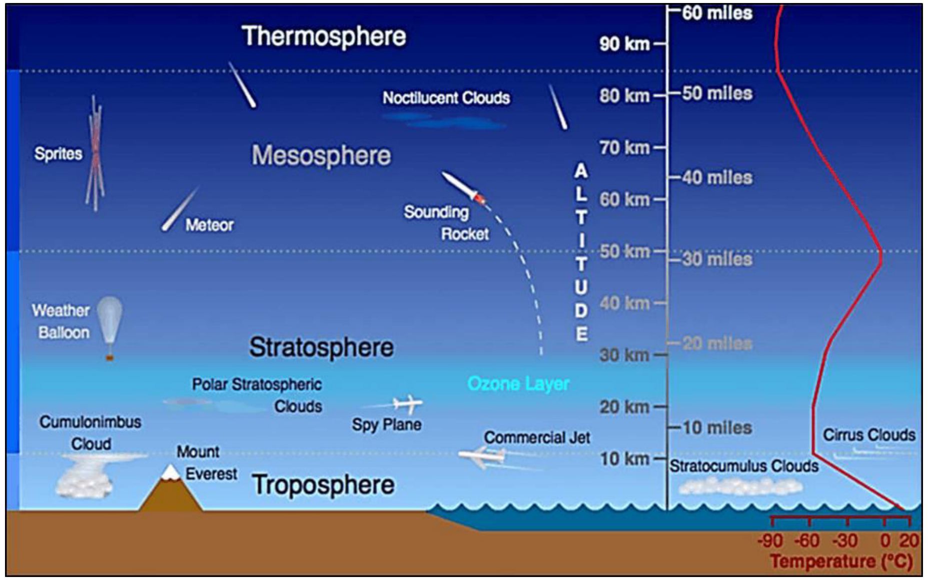
Zipser (1977)

- The physical-based diagnose model is used to quantify the thermodynamic and dynamic contributions of EPS, which is based on ***energy budged balance*** during precipitation processes.

3 Understanding the Hook structure by atmospheric physics



We focus on moisture transport in Troposphere



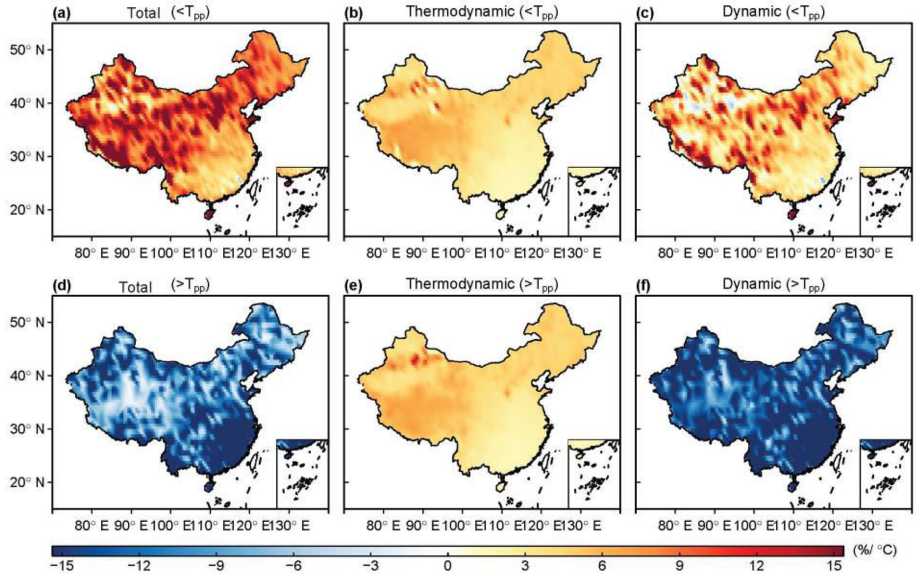
ERA5 data pressure levels (1-1000hPa)

Physics-diagnosed model

$$\frac{\delta P_e}{P_e} \approx \frac{\delta\{\omega(\partial q_{sat}/\partial p)\}}{\{\omega(\partial q_{sat}/\partial p)\}}$$

$$\frac{\delta P_e}{P_e} \approx \frac{\{\omega\delta(\partial q_{sat}/\partial p)\}}{\{\omega(\partial q_{sat}/\partial p)\}} + \frac{\{\delta(\omega)(\partial q_{sat}/\partial p)\}}{\{\omega(\partial q_{sat}/\partial p)\}}$$

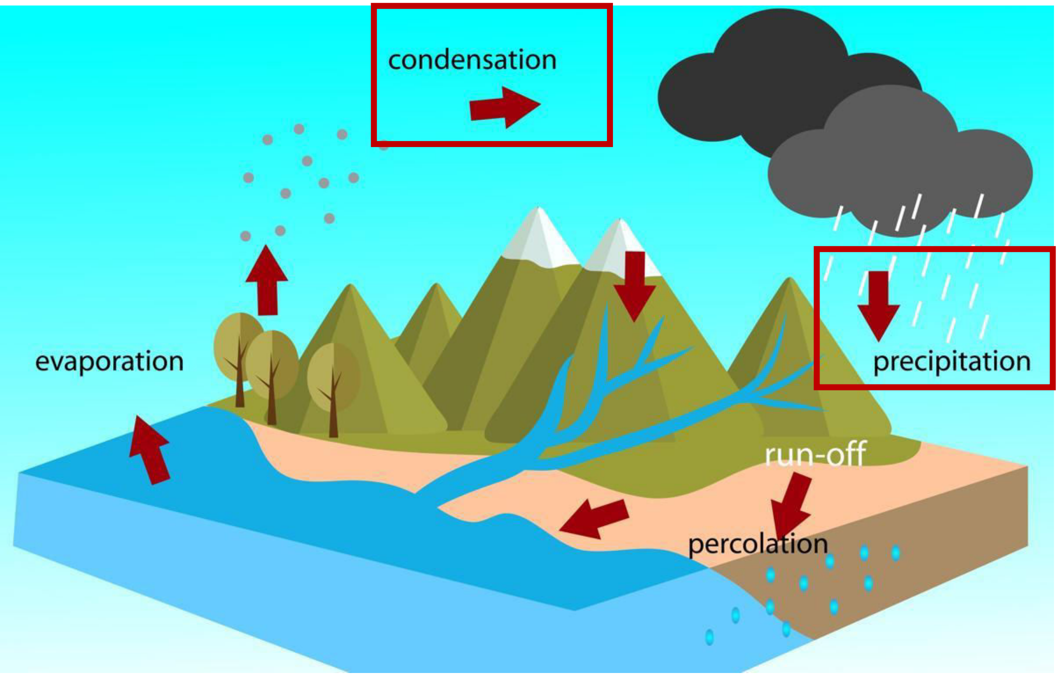
Thermodynamic *Dynamic*



Yin J, et al. Chinese Science Bulletin (2021)

3 Understanding the Hook structure by atmospheric physics

Thermodynamic contributes to precipitation intensification, while atmospheric dynamics decline precipitation in hotter environment



Atmospheric dynamics ⟺ Atmospheric thermodynamics

Physical-diagnostic model

$$\frac{\delta P_e}{P_e} \approx \underbrace{\frac{\{\omega\delta(\partial q_{sat}/\partial p)\}}{\{\omega(\partial q_{sat}/\partial p)\}}}_{\textit{Thermodynamic}} + \underbrace{\frac{\{\delta(\omega)(\partial q_{sat}/\partial p)\}}{\{\omega(\partial q_{sat}/\partial p)\}}}_{\textit{Dynamic}}$$

Do all the thermodynamic components always intensify precipitation extremes?

3 Understanding the Hook structure by atmospheric physics

Do all the thermodynamic components always intensify precipitation extremes?Can we know more details?

$$P_e \sim -\left\{ \omega_e \left. \frac{dq_s}{dp} \right|_{\theta^*} \right\}$$

By further decomposing moist-adiabatic derivative of saturation specific humidity

CMIP6

WCRP World Climate Research Programme

ERA-5

ECMWF

$$P_{the} \sim -\left\{ \omega_{avg} \left. \frac{dq_s}{dp} \right|_{\theta^*} \right\} = -\left\{ \omega_{avg} \left(\frac{\partial q_s}{\partial p} + \frac{\partial q_s}{\partial T} \cdot \left. \frac{dT}{dp} \right|_{\theta^*} \right) \right\} = -\left\{ \omega_{avg} \frac{\partial q_s}{\partial p} \right\} - \left\{ \omega_{avg} \frac{\partial q_s}{\partial T} \cdot \left. \frac{dT}{dp} \right|_{\theta^*} \right\}$$

Pressure component

$$pPR = -\left\{ \omega_{avg} \frac{\partial q_s}{\partial p} \right\}$$

Temperature component

$$pT = -\left\{ \omega_{avg} \frac{\partial q_s}{\partial T} \cdot \left(\left. \frac{dT}{dp} \right|_{\theta^*} \right)_{avg} \right\}$$

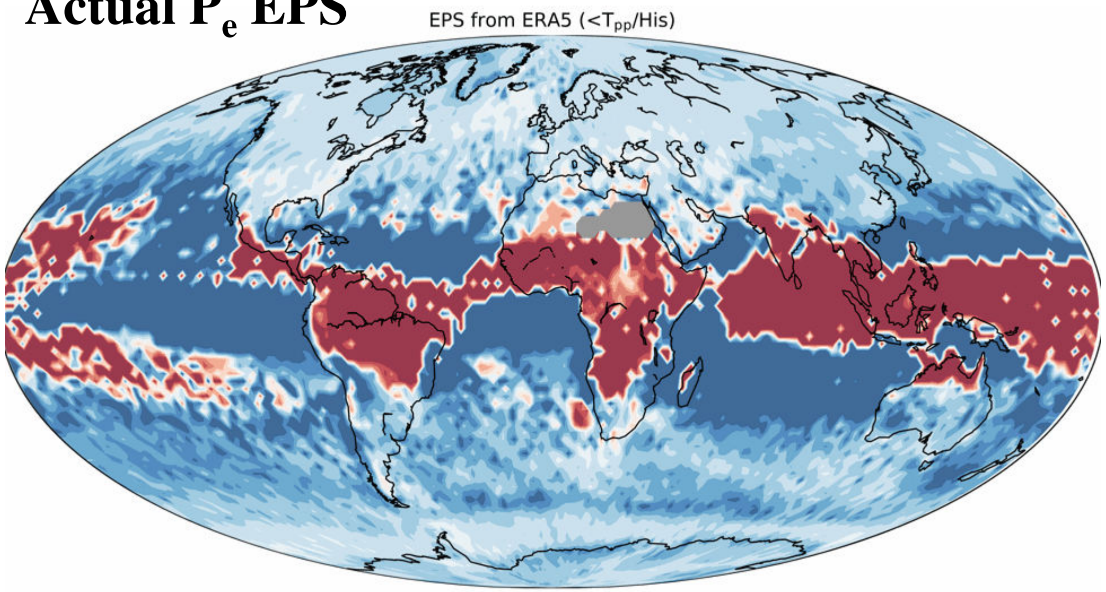
Lapse Rate component

$$pLR = -\left\{ \omega_{avg} \frac{\partial q_s}{\partial T} \cdot \left. \frac{dT}{dp} \right|_{\theta^*} \right\} - \left(-\left\{ \omega_{avg} \frac{\partial q_s}{\partial T} \cdot \left(\left. \frac{dT}{dp} \right|_{\theta^*} \right)_{avg} \right\} \right)$$

Gu, Yin, Nature Communications (2023)*

3 Understanding the Hook structure by atmospheric physics

Does the thermodynamic always intensify precipitation extremes? Can we know more details?



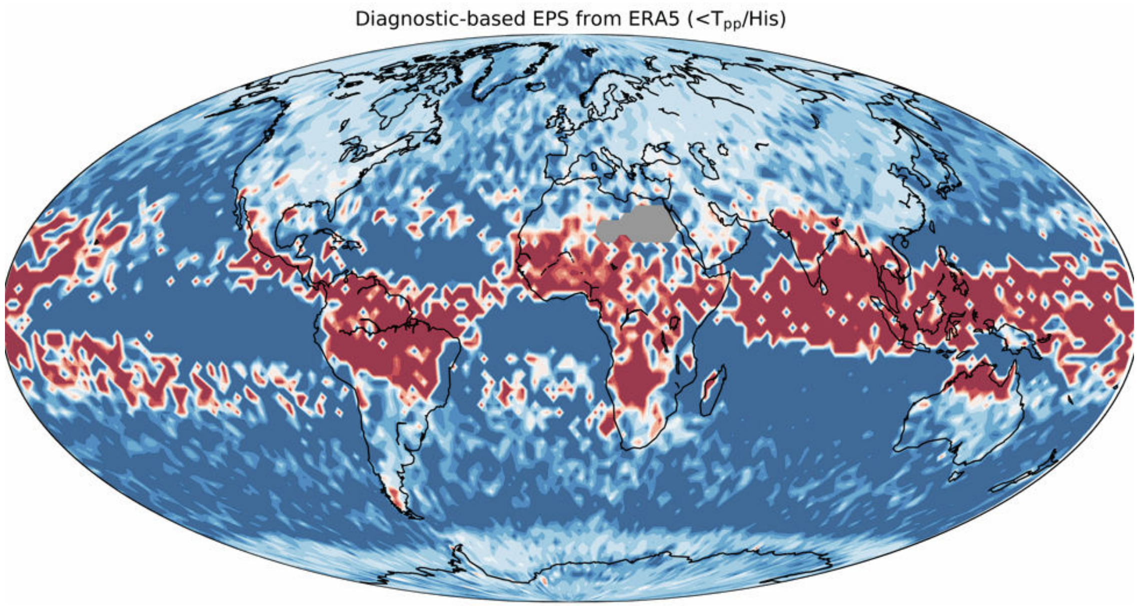


Figure: Evaluation of simulation performance of physically diagnostic model

*Gu, **Yin*, Nature Communications** (2023)*

3 Understanding the Hook structure by atmospheric physics

The thermodynamic components do not always contribute to precipitation intensification due to changes in temperature laps rate

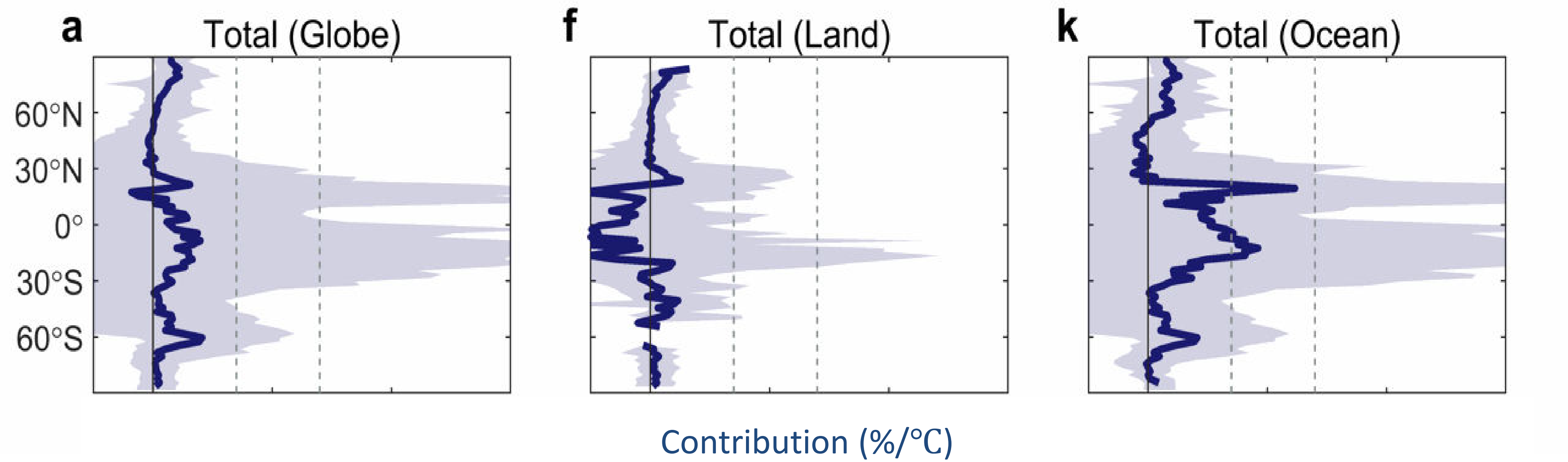


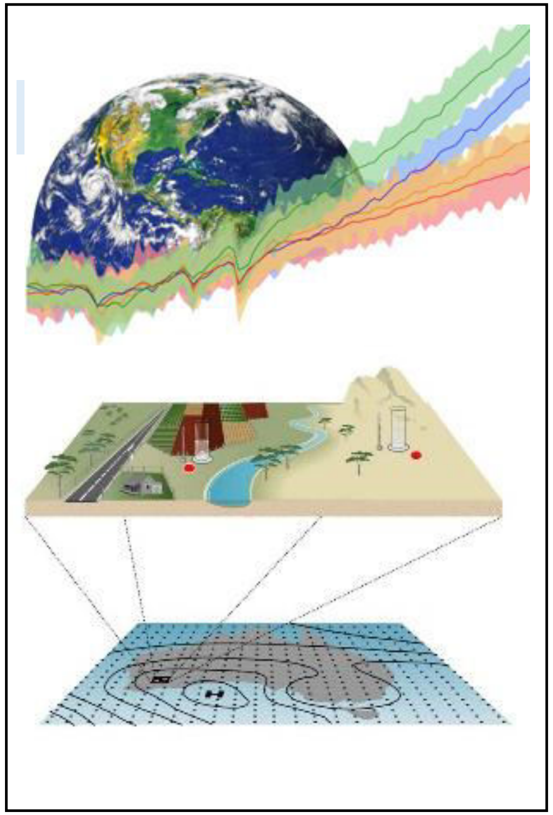
Figure: Zonal EPS anomalies between the reference and future periods

*Gu, **Yin***, et al. Nature Communications (2023)*

4 A potential upper bound for future extremes?

Does the hook structure imply a potential upper bound for future extremes?

Climate-hydrological model chain



31 multi-model ensemble

WCRP CMIP5 World Climate Research Programme

Quantile mapping correction

11 multi-member ensemble

WCRP CMIP6 World Climate Research Programme

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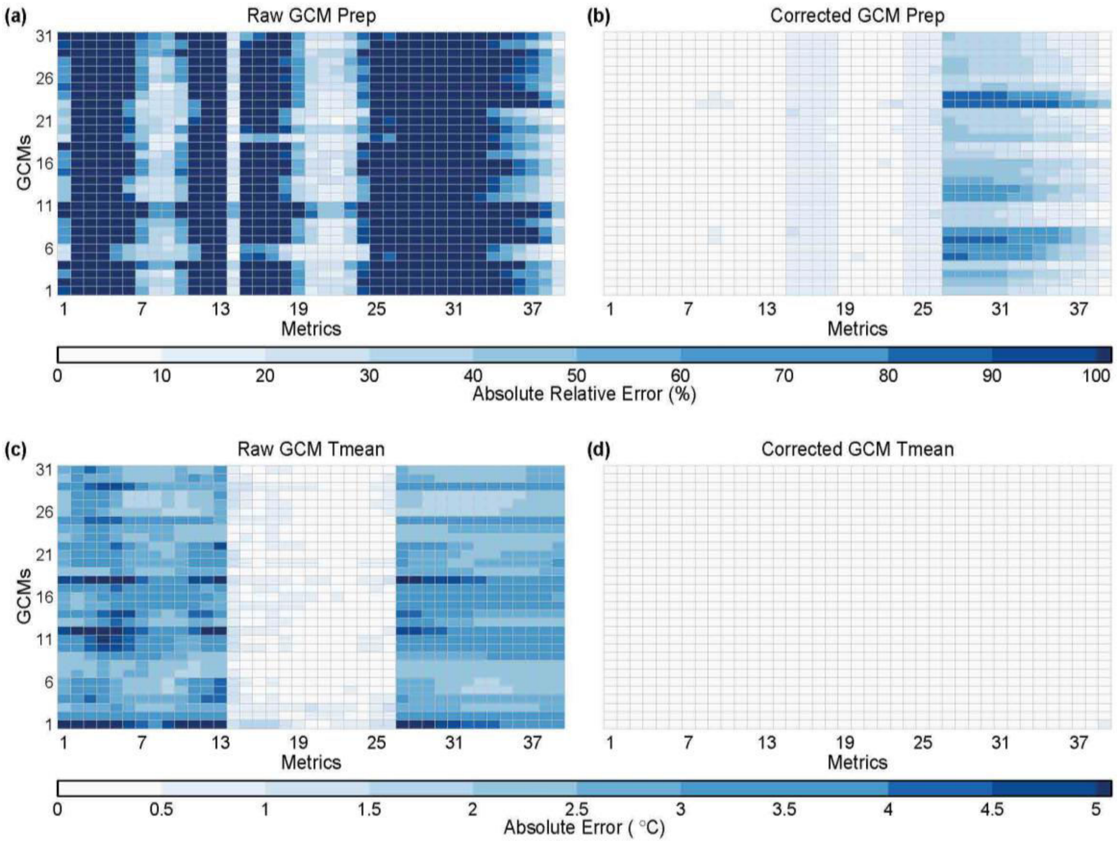
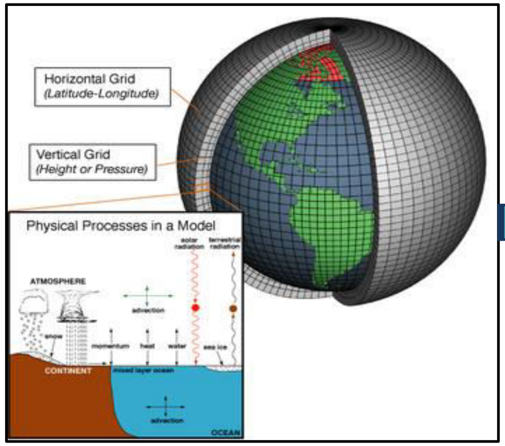


Figure: Bias correction performance of climate outputs

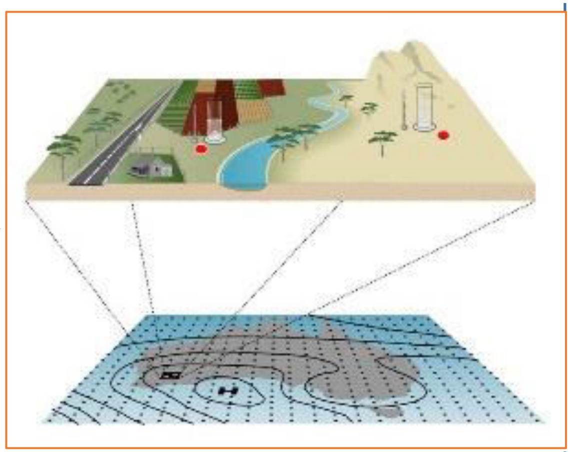
4 A potential upper bound for future extremes?

We propose a hybrid HM-LSTM model

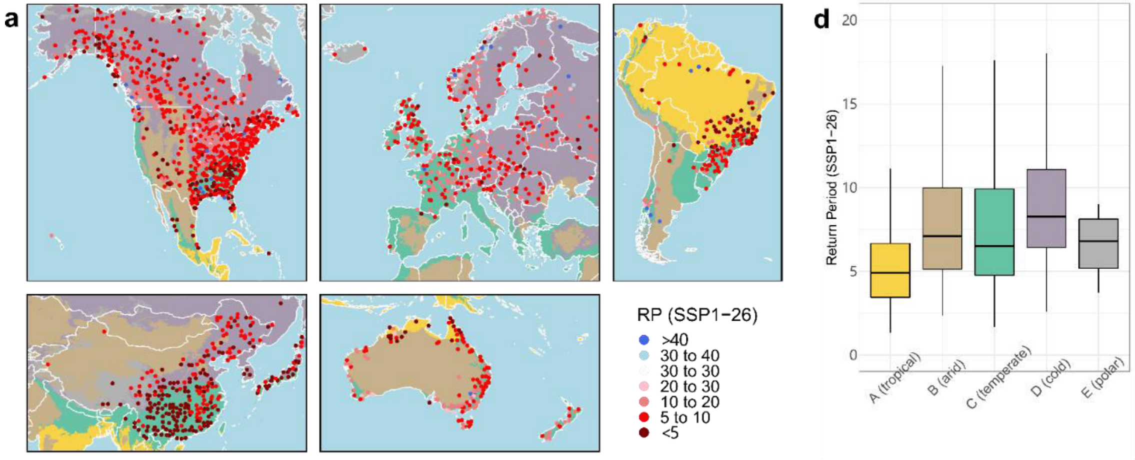
Yin J, et al. Nature Sustainability (2023)*



Global climate model outputs



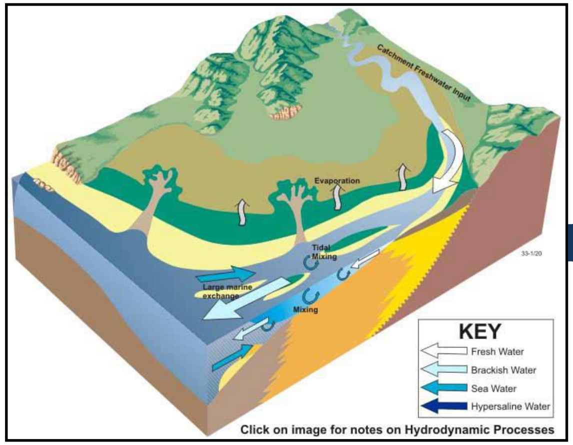
Downscaling methods



Climate variables

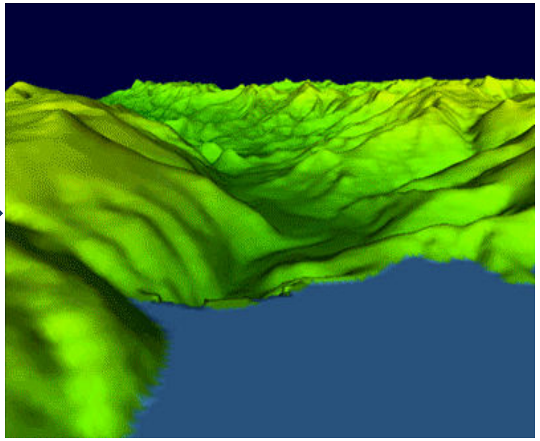
RF algorithms

Sensitivity Analysis



Hydrological model (HM)

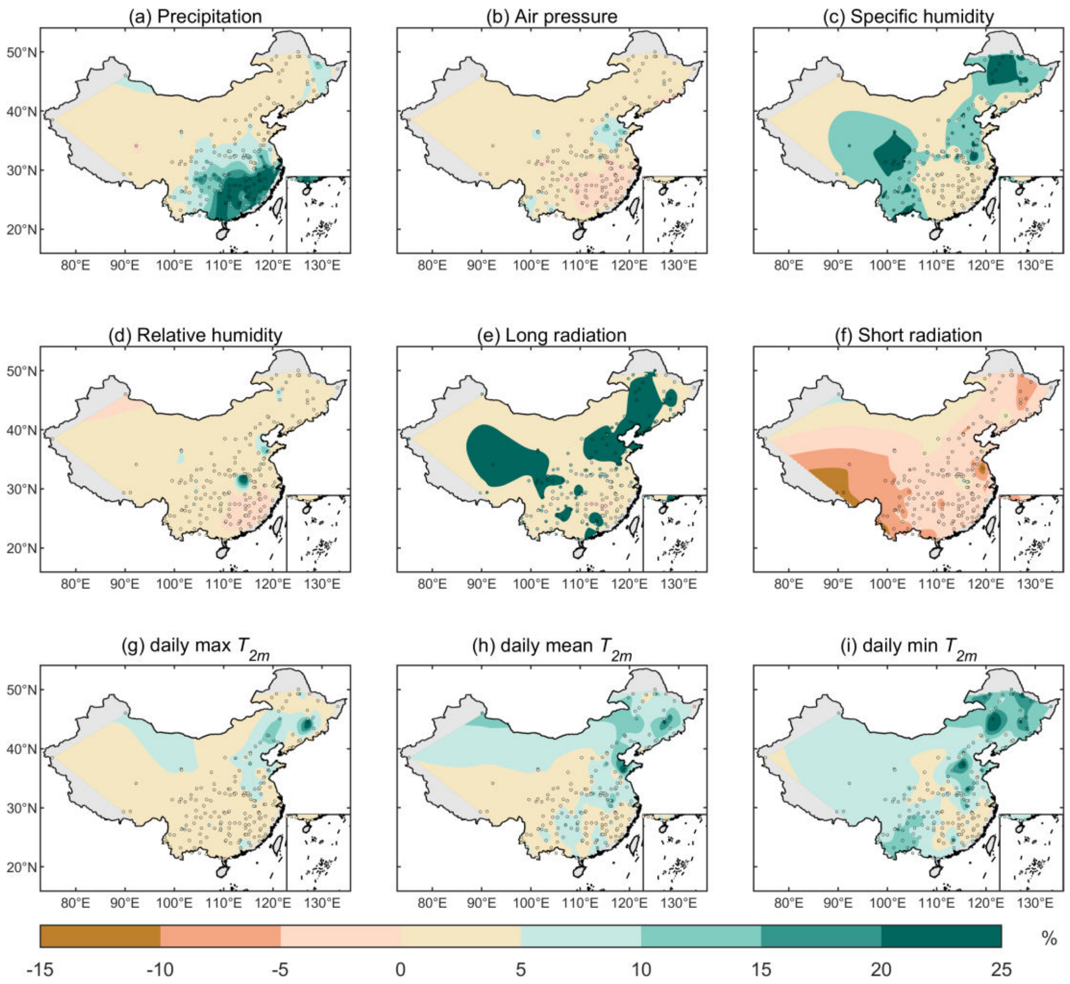
Runoff simulations /projections



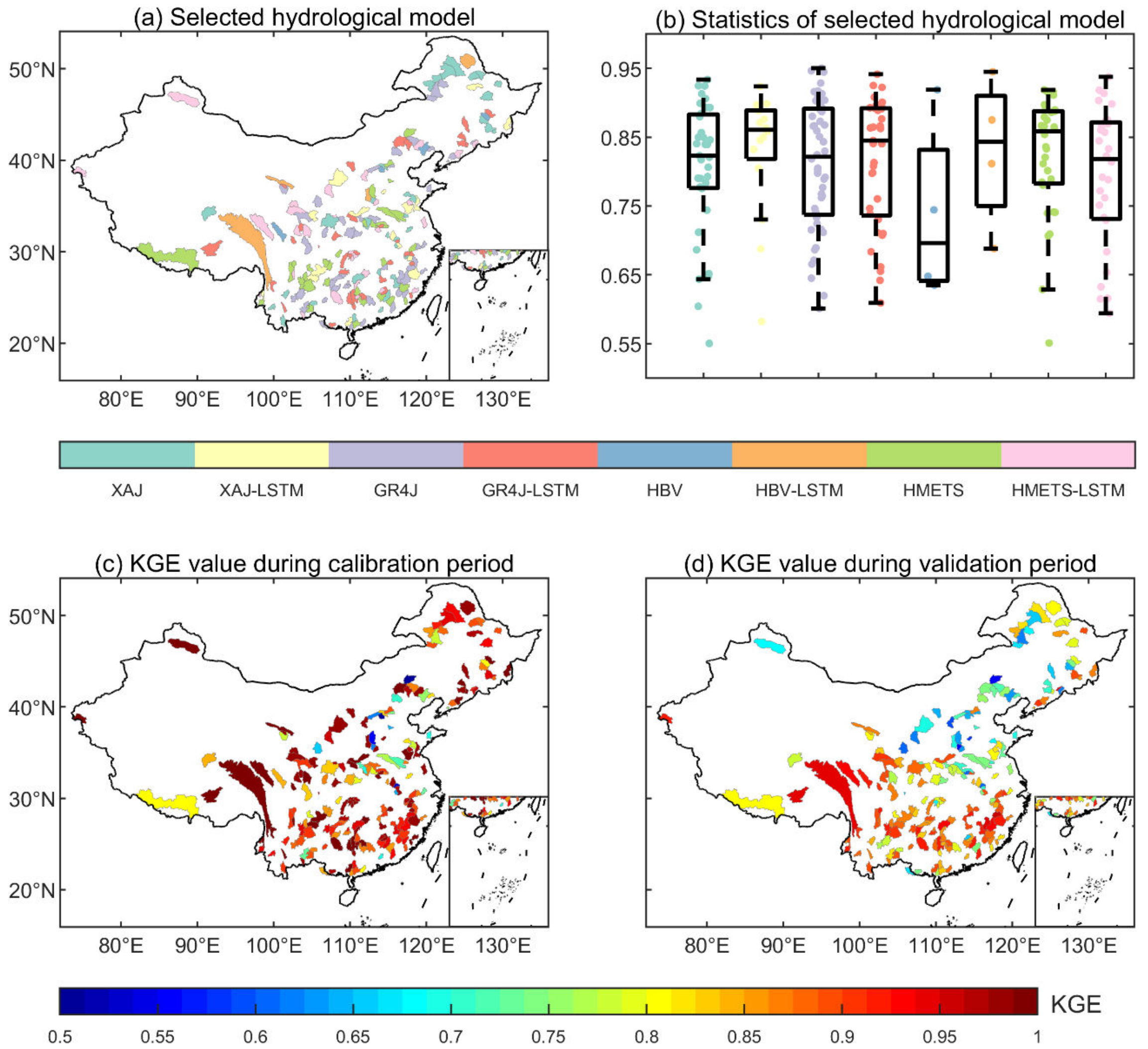
Flood assessment

4 A potential upper bound for future extremes?

Sensitivity of climate variables to runoff



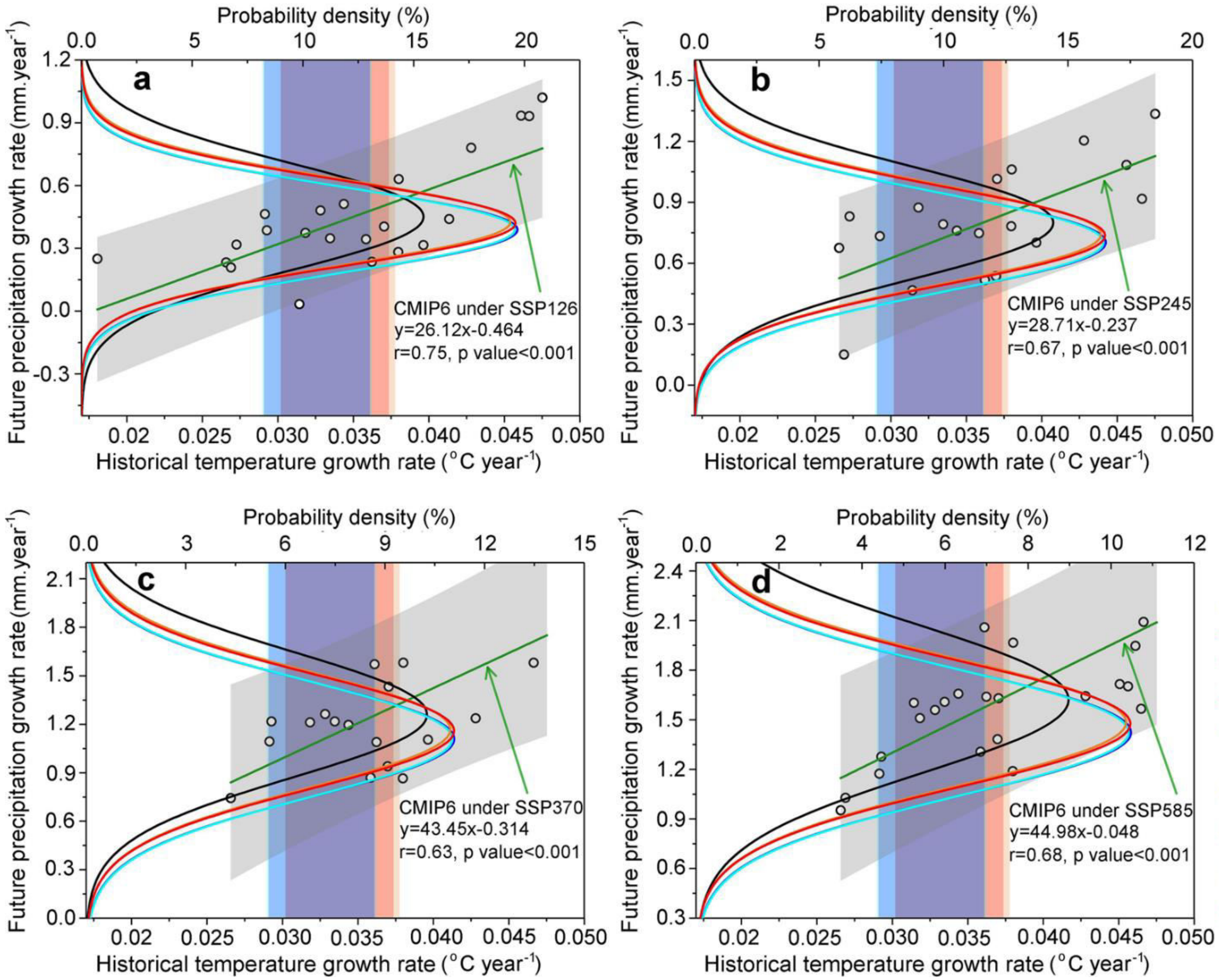
Kang S, ***Yin J*, et al., 2023 Earth's Future***

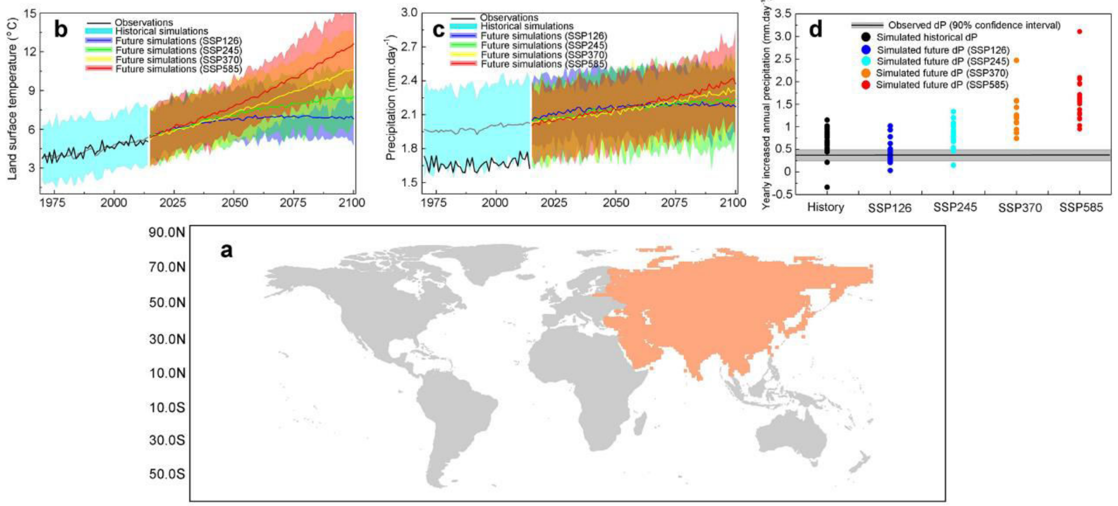


Performance of machine Learning-constrained runoff Simulations

4 A potential upper bound for future extremes?

Future projection of precipitation, evaporation and snow cover by Emergent Constraint





PDF before EC

emergent constraint and bias correction methods). We use the least-squares linear regression method to build the emergent constraint relationship (See Eq. (1))[25]. The prediction error of the regression (σ_y) is calculated by Eq. (2).

$$y_i = ax_i + b \tag{1}$$

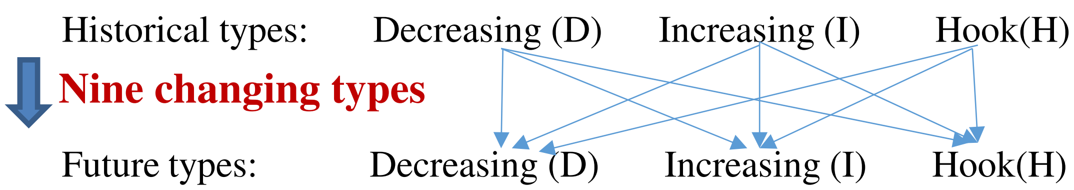
where y_i is the value given by x_i; a and b are the slope and intercept values, respectively;

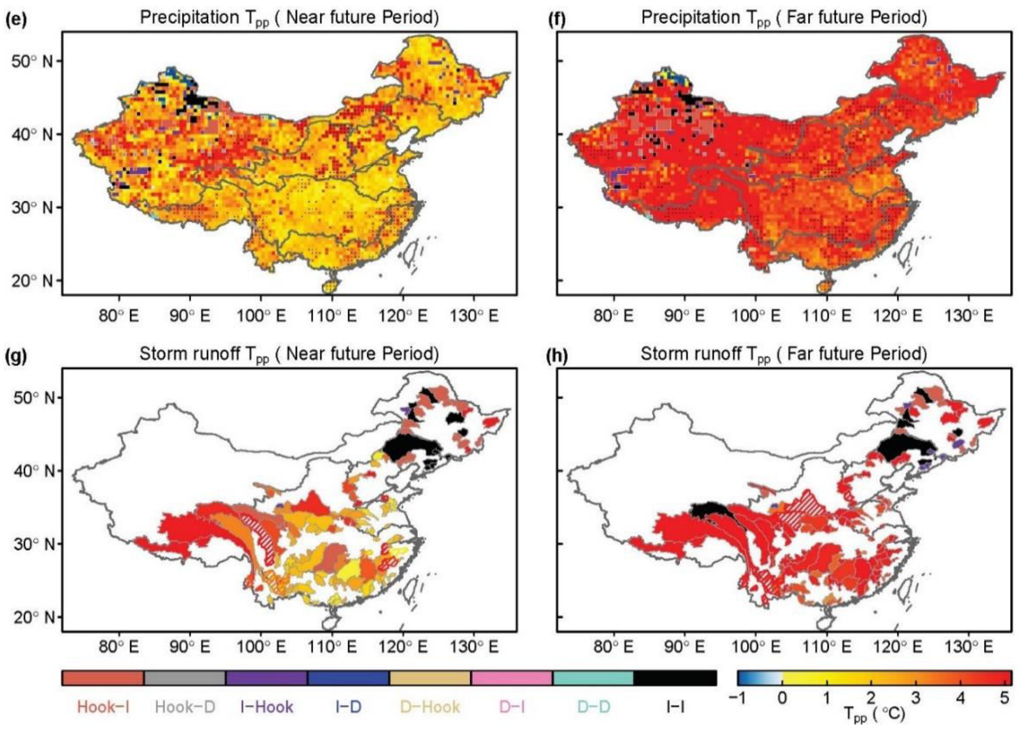
$$\sigma_y(x) = s\sqrt{1 + \frac{1}{N} + \frac{(x - \bar{x})^2}{N \cdot \sigma_x^2}} \tag{2}$$

Cai, Yue, Slater, ***Yin et al. Nature Communications (2022)***

4 A potential upper bound for future extremes?

Does the hook structure imply a potential upper bound for future extremes?





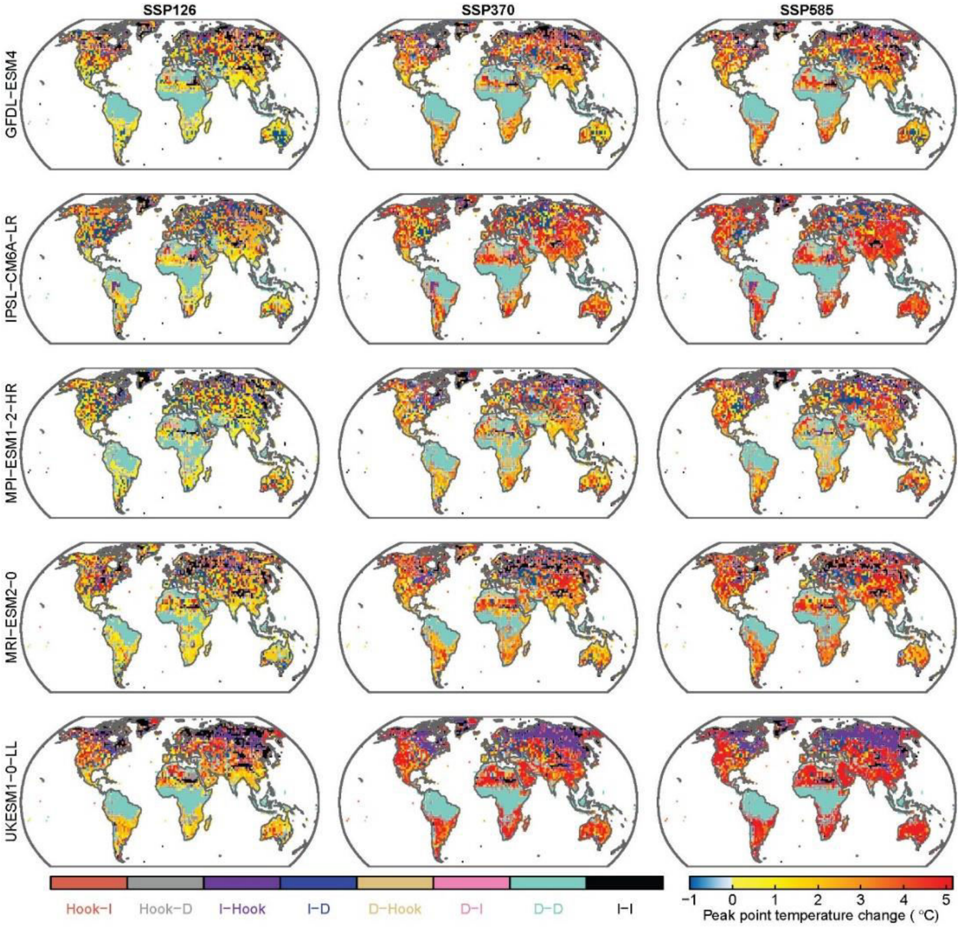


Figure: The GCM ensemble mean change of scaling structures and T_{pp} relative to historical period

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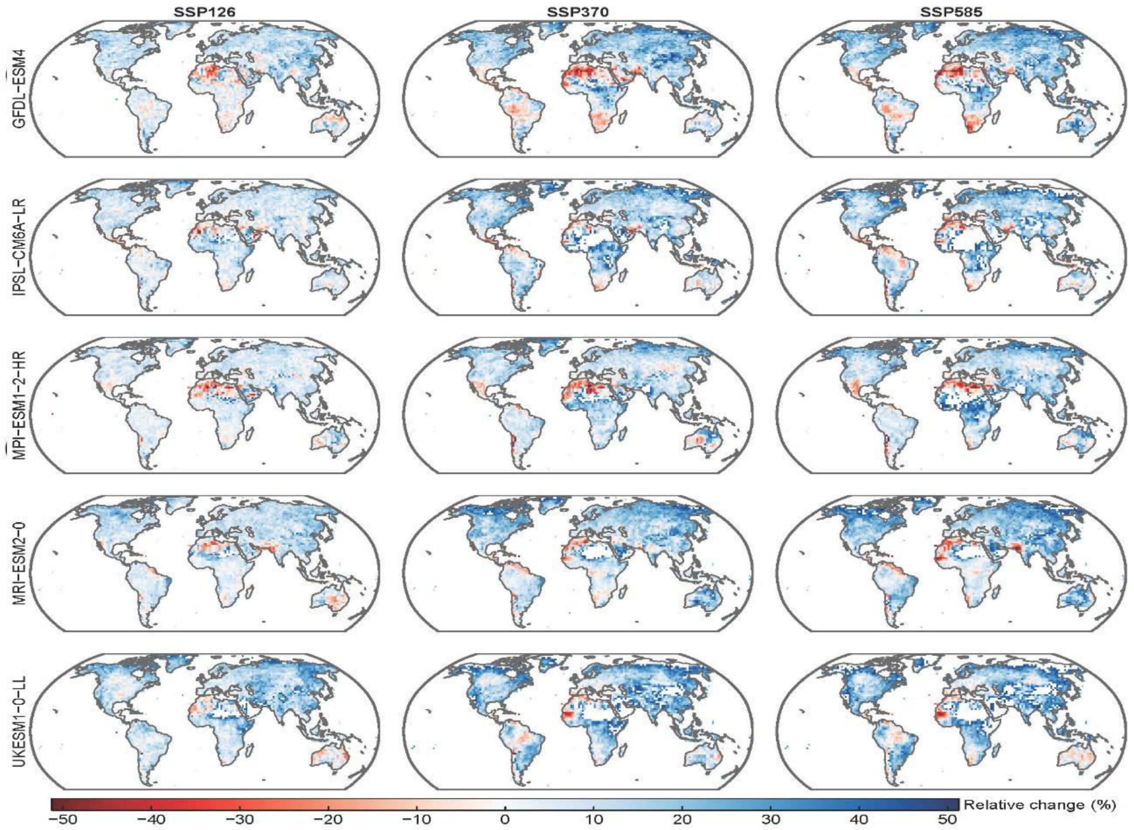
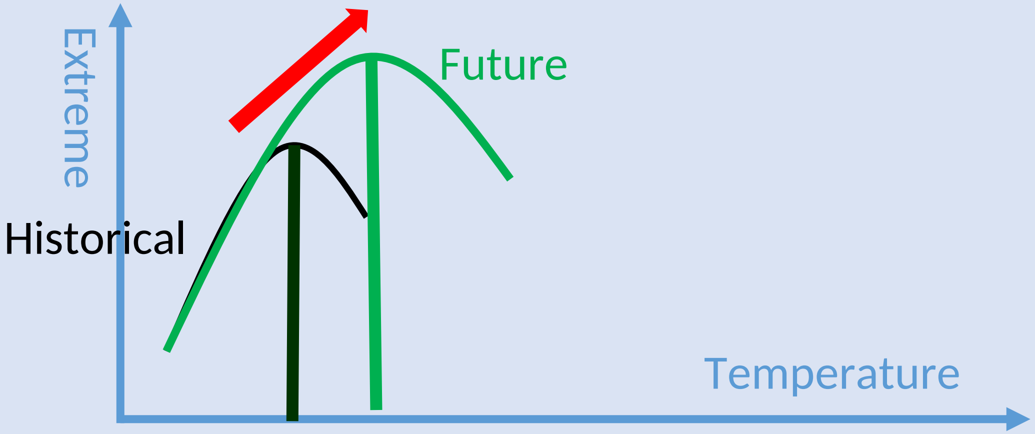


Figure: Relative changes of precipitation extremes in future climates

The hook structure is not stable under climate warming!

Along with an increasing T_{pp}, the hook structure shows an upward shift, resulting in a significant intensification of hydrological extremes in the future.



More than 80% of continental areas retain a hook structure during historical and future periods, while Peak point temperature (T_{pp}) progressively increases with atmospheric warming.

4 A potential upper bound for future extremes?

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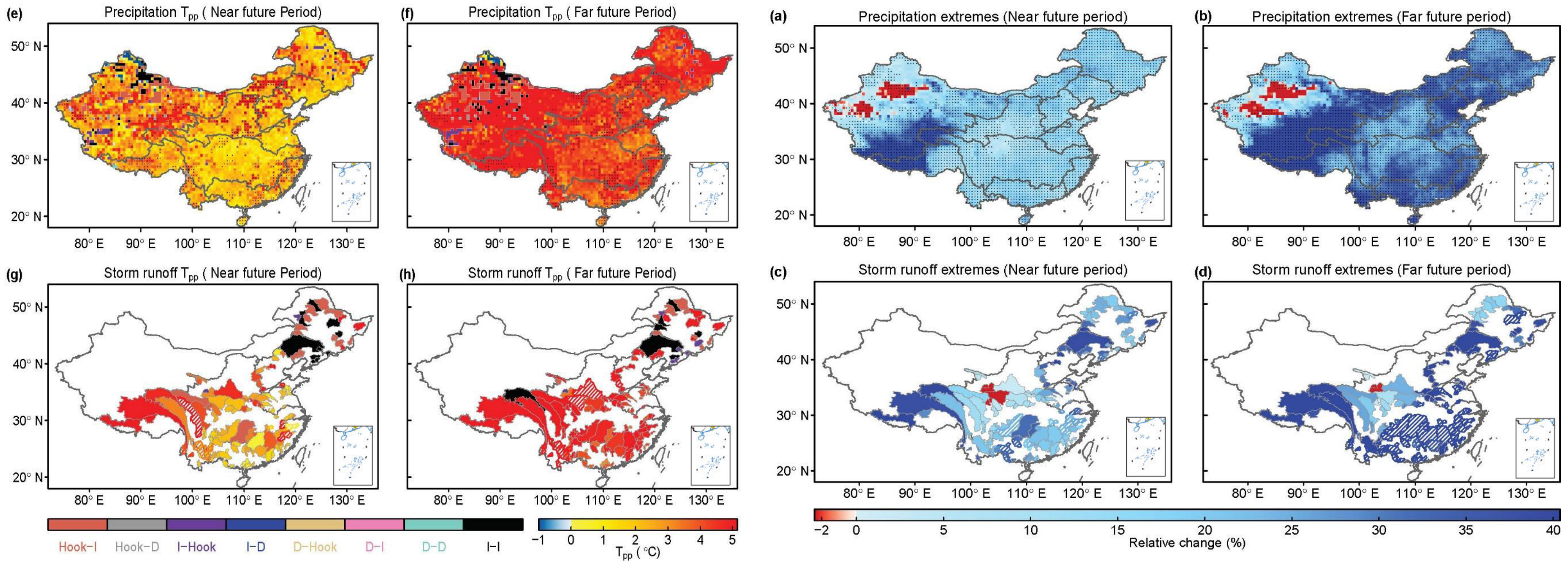
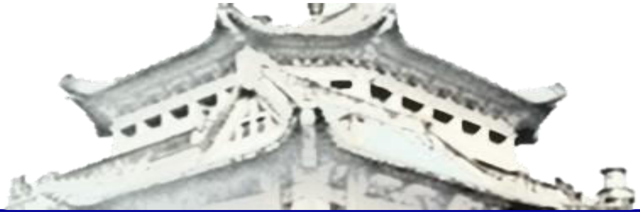


T_{pp} shifts toward warmer temperatures, resulting in 10%–30% increases in storm runoff extremes.

Yin J, et al., WRR (2021 Editors' Choice Awards)

Conclusions

- Precipitation and storm runoff extremes show a hook structure with temperature rising.
- Atmospheric thermodynamic intensifies precipitation extremes, while atmospheric dynamics decline precipitation in hotter environment.
- The thermodynamic components do not always contribute to precipitation intensification due to changes in temperature laps rate.
- The hook structure does not imply potential bound for future extreme intensification.



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Thank you!

Research interests:

Atmospheric dynamics; Climate change;
Ecohydrology; Machine learning;
Hydrological extremes; Remote sensing

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In collaboration with Prof. Pierre Gentine, Prof. Louise Slater and Prof. Shenglian Guo