Institute of Atmospheric Physics, Chinese Academy of Sciences

Projection of precipitation changes over global monsoon regions

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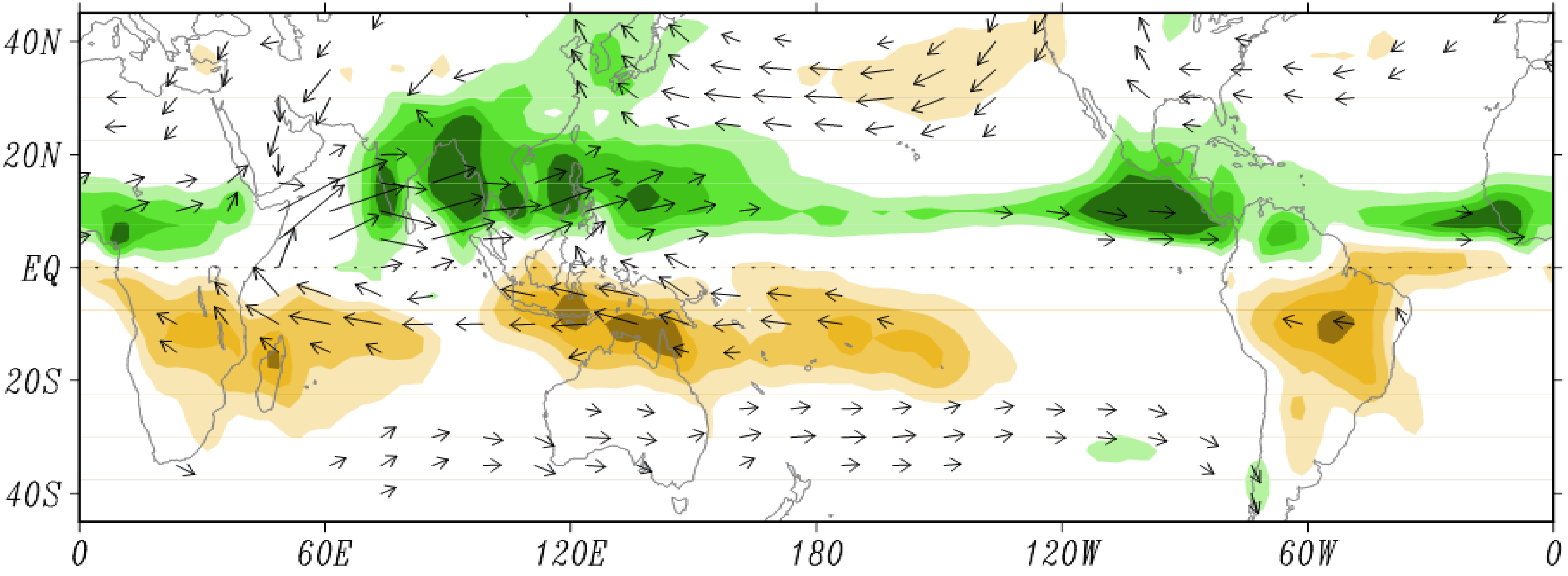
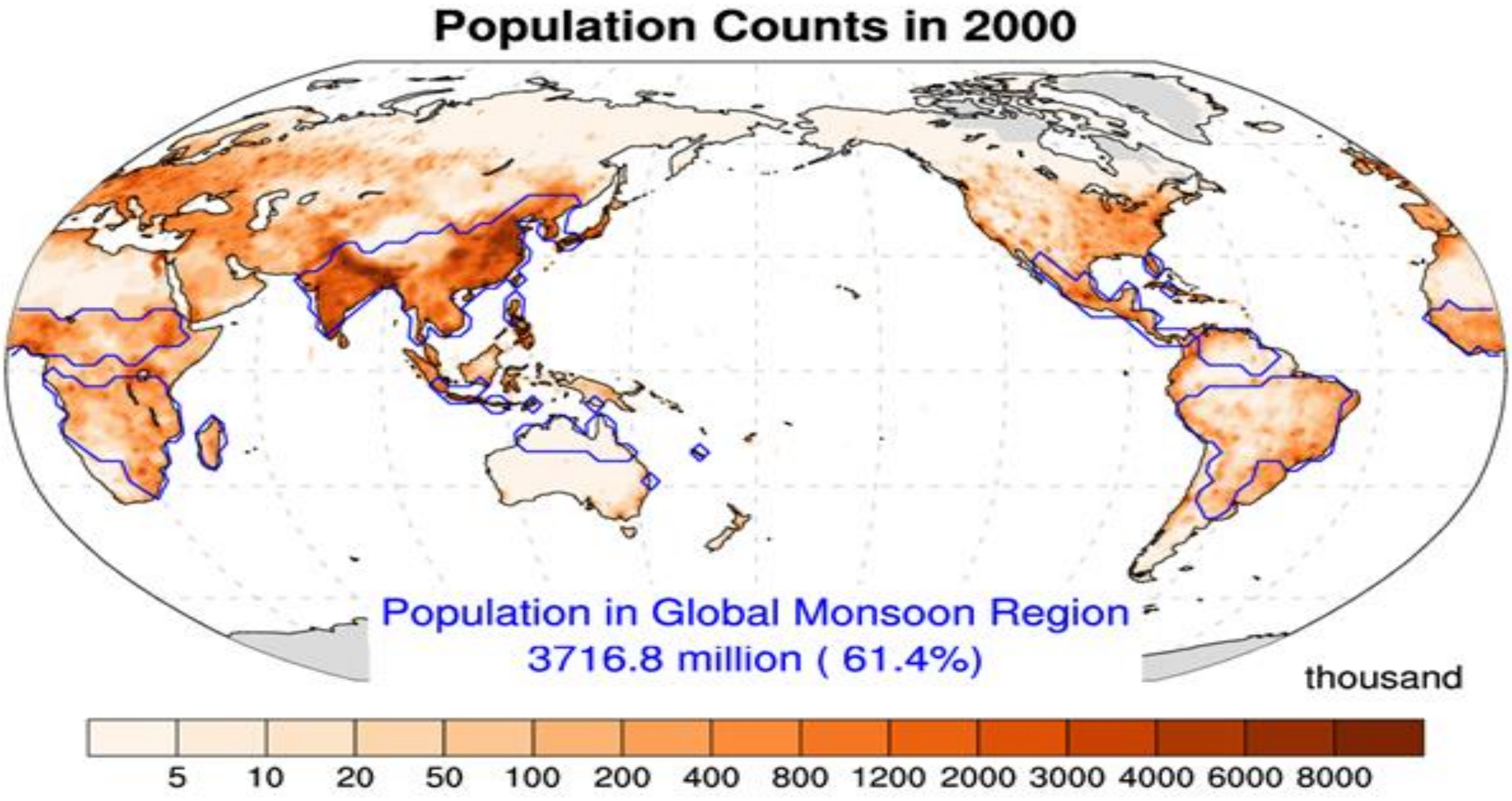
Global Flood Partnership Conference， 11-13 June, 2019, Guangzhou, China

Monsoon impacts a large part of the world



Global monsoon domain



Two-thirds of the world population are affected by monsoon

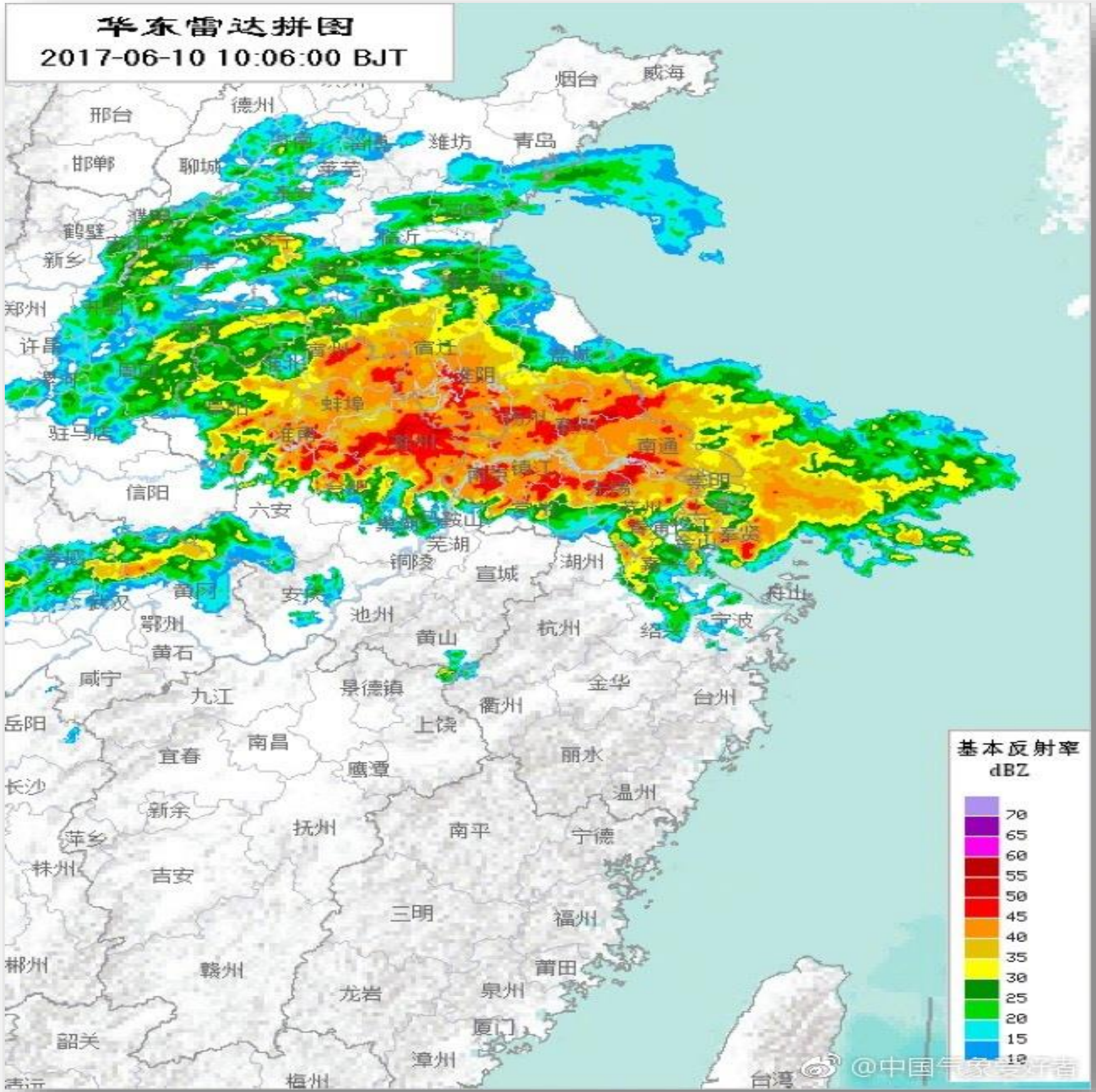
Indian Flood: 2014.09.1

http://i.dailymail.co.uk/i/pix/2014/09/1

Japan: 2018, 6.28-7.9

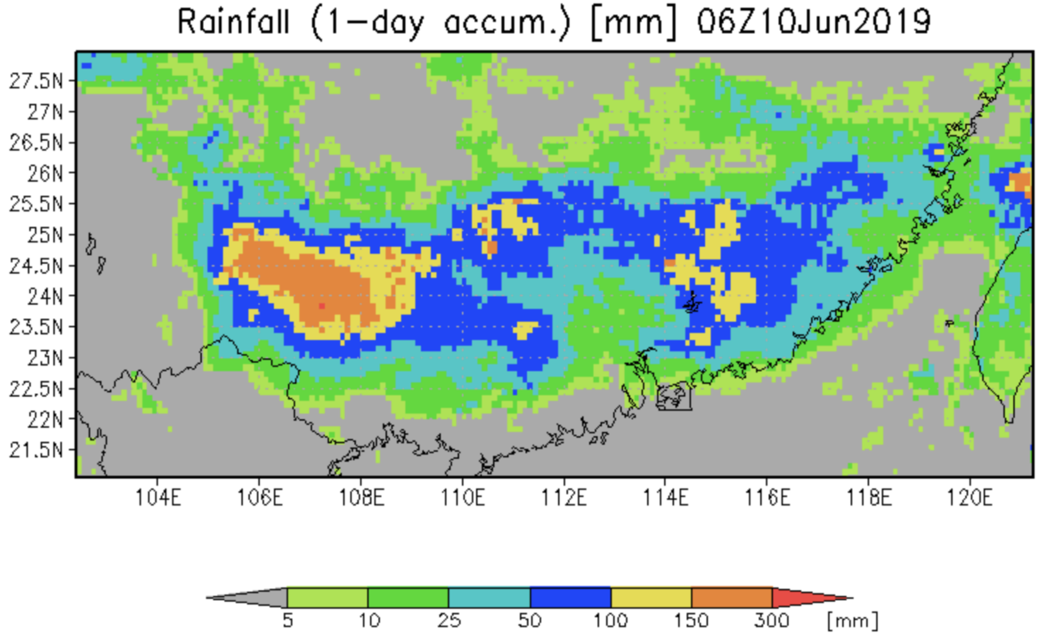
https://bousailog.com

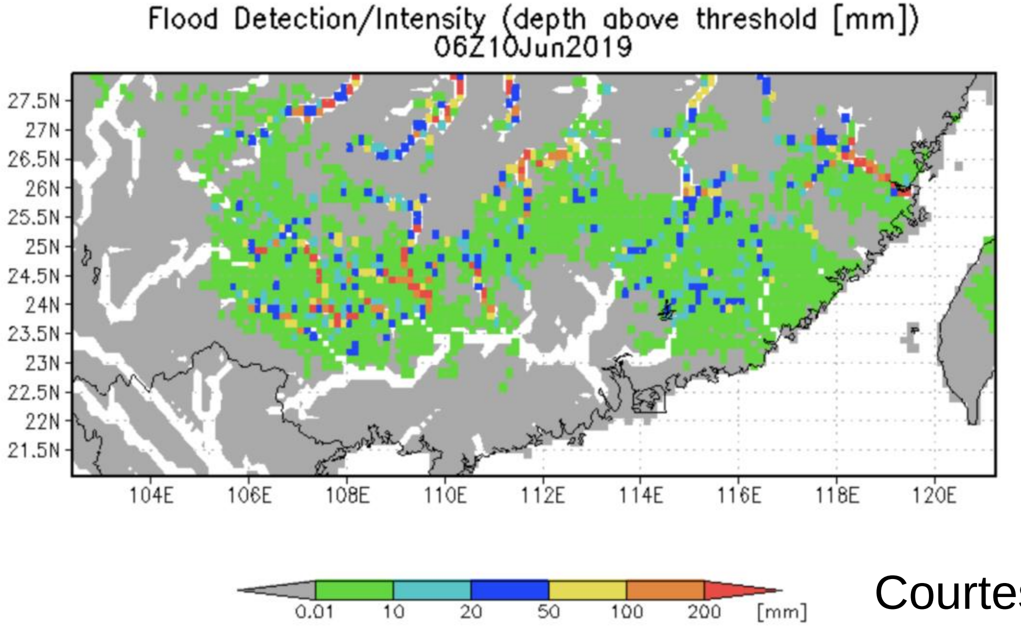
Nanjing, China: 2017, 6.10

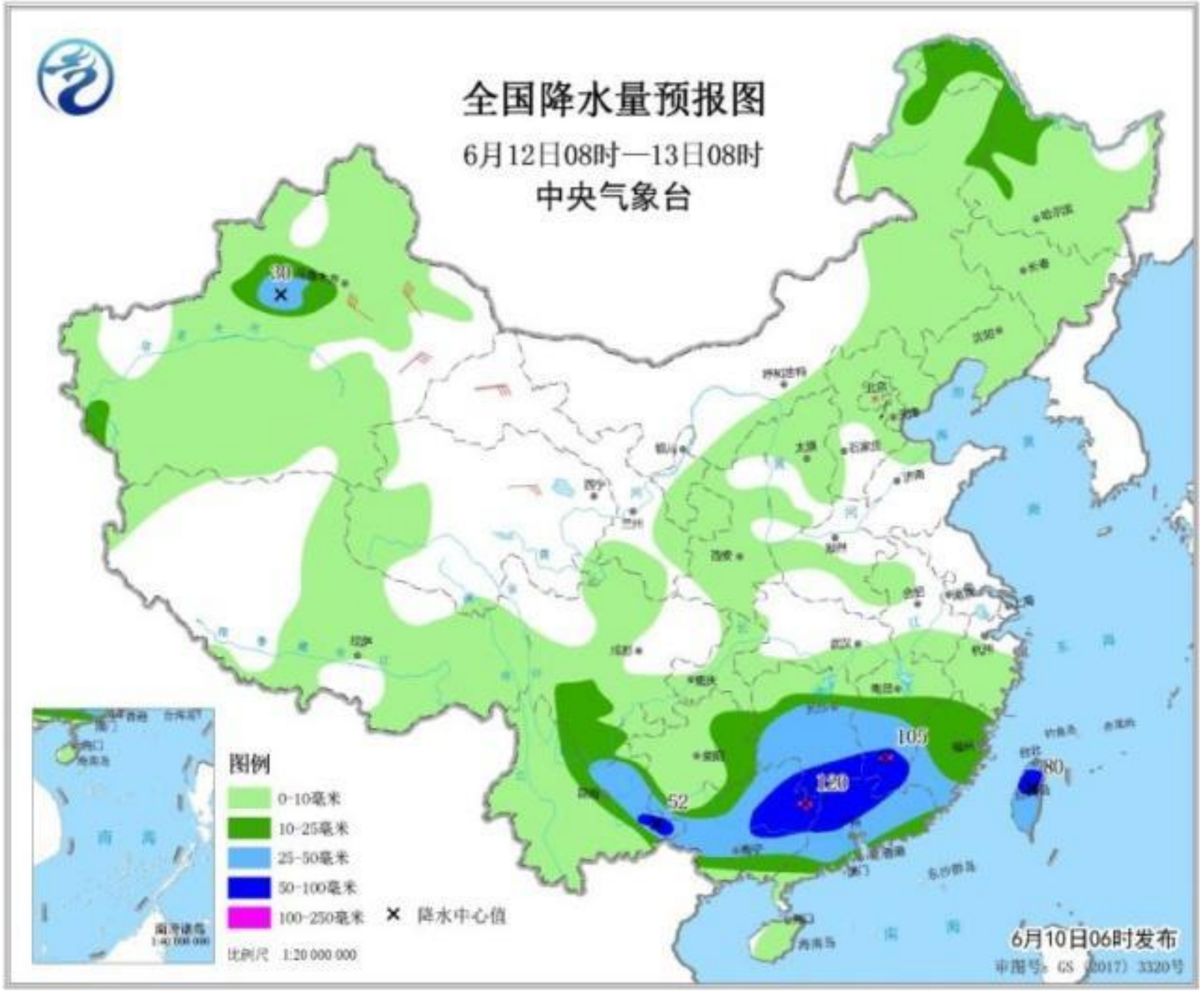


Guangzhou, June 10

June 10-11, 2019, S. China

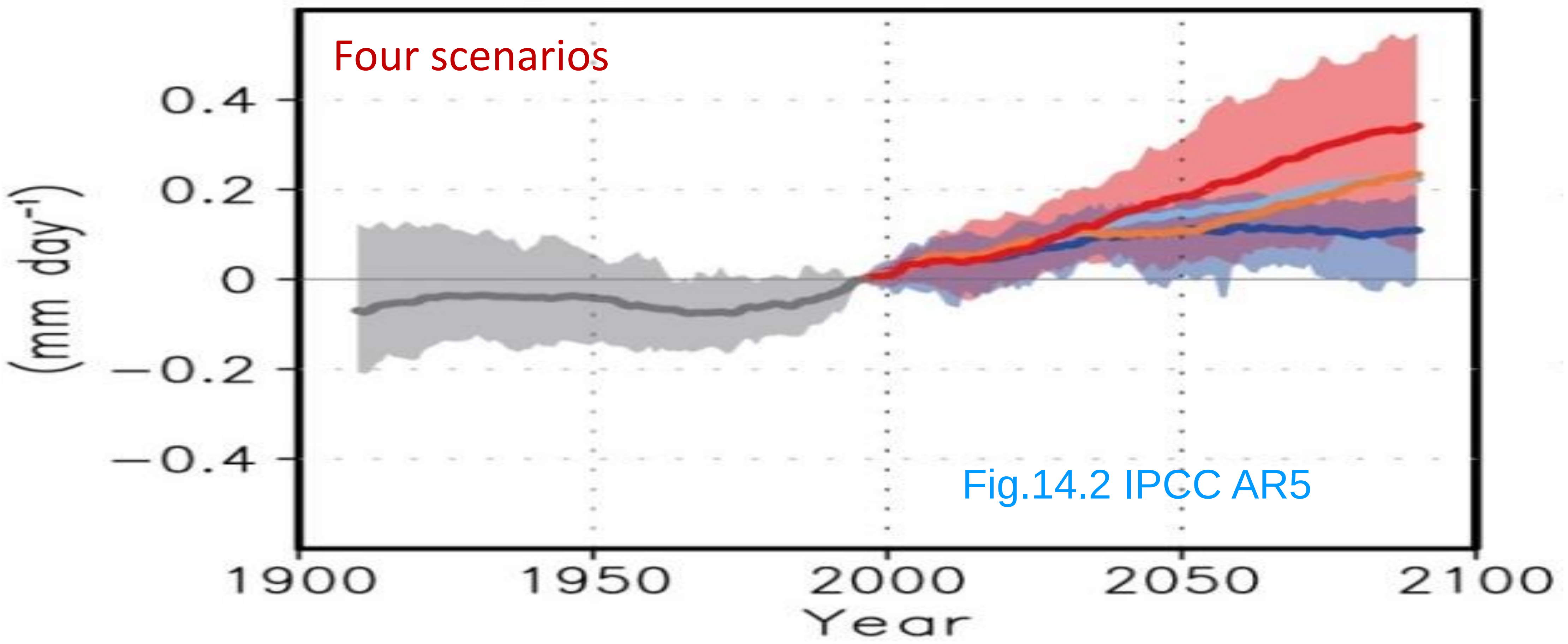






Courtesy: Huan Wu

Global monsoon precipitation projection in IPCC AR5



Kitoh, A., et al. 2013: Monsoons in a changing world: a regional perspective in a global context. *J. Geophys. Res. Atmos.*, 118, doi:10.1002/jgrd.50258

Projection of precipitation changes

- ◆Response of annual mean water cycle to global warming
- ◆Response of annual cycle of water cycle to global warming
- ◆Exposure to extreme precipitation

Model	Institute/Country	Resolution
ACCESS1.0	CSIRO–BOM/Australia	145 × 192, L38
ACCESS1.3	CSIRO–BOM/Australia	145 × 192, L38
BCC_CSM1.1	BCC–China Meteorological Administration (CMA)/China	64 × 128, L26
BCC_CSM1.1(m)	BCC–CMA/China	160 × 320, L26
BNU-ESM	Beijing Normal University/China	64 × 128, L26
CanESM2	CCCma/Canada	64 × 128, L35
CCSM4	NSF–DOE–NCAR/USA	192 × 288, L27
CESM1(BGC)	NSF–DOE–NCAR/USA	192 × 288, L27
CESM1(CAM5)	NSF–DOE–NCAR/USA	192 × 288, L27
CNRM-CM5	Centre National de Recherches Météorologiques – CERFACS/France	128 × 256, L31
CSIRO Mk3.6.0	CSIRO–QCCCE/Australia	96 × 192, L18
GFDL CM3	NOAA–GFDL/USA	90 × 144, L48
GFDL ESM2G	NOAA–GFDL/USA	90 × 144, L24
GFDL ESM2M	NOAA–GFDL/USA	90 × 144, L24
GISS-E2-H	NASA–GISS/USA	89 × 144, L40
GISS-E2/R	NASA–GISS/USA	89 × 144, L40
INM-CM4	Institute of Numerical Mathematics/Russia	120 × 180, L21
IPSL-CM5A-LR	IPSL/France	96 × 96, L39
IPSL-CM5A-MR	IPSL/France	143 × 144, L39
IPSL-CM5B-LR	IPSL/France	96 × 96, L39
MIROC5	MIROC/Japan	128 × 256, L40
MIROC-ESM	MIROC/Japan	64 × 128, L80
MIROC-ESM-CHEM	MIROC/Japan	64 × 128, L80
MRI-CGCM3	Meteorological Research Institute/Japan	160 × 320, L48
NorESM1-M	Norwegian Climate Centre (NCC)–Norwegian Meteorological Institute (NMI)/Norway	96 × 144, L26
NorESM1-ME	NCC–NMI/Norway	96 × 144, L26

- 27 CMIP5 models

  Historical

  RCP4.5

  RCP8.5

- Water cycle components

  P, E, q, V, Runoff,

  Soil moisture

- Extreme index

  RX5day

cmip Coupled Model Intercomparison Project

Definition of water cycle

Atmospheric water cycle

$$P - E = -\frac{\partial PW}{\partial t} - <\nabla \cdot \mathbf{V}q>$$

P: precipitation

E: evaporation

PW: precipitable water

V: wind vector

q: specific humidity

$-<\nabla \cdot \mathbf{V}q>$: total moisture convergence

Surface water cycle

$$\frac{\partial S}{\partial t} = P - E - R$$

S: subsurface water storage

R: total runoff

(Trenberth and Fasullo, 2013)

Analysis method

- **Response of the water cycle to global warming**
  - dX/dT (X: water cycle component)
  - regression coefficient between the smoothed water cycle components and global mean surface air temperature change
- **Moisture budget analysis**

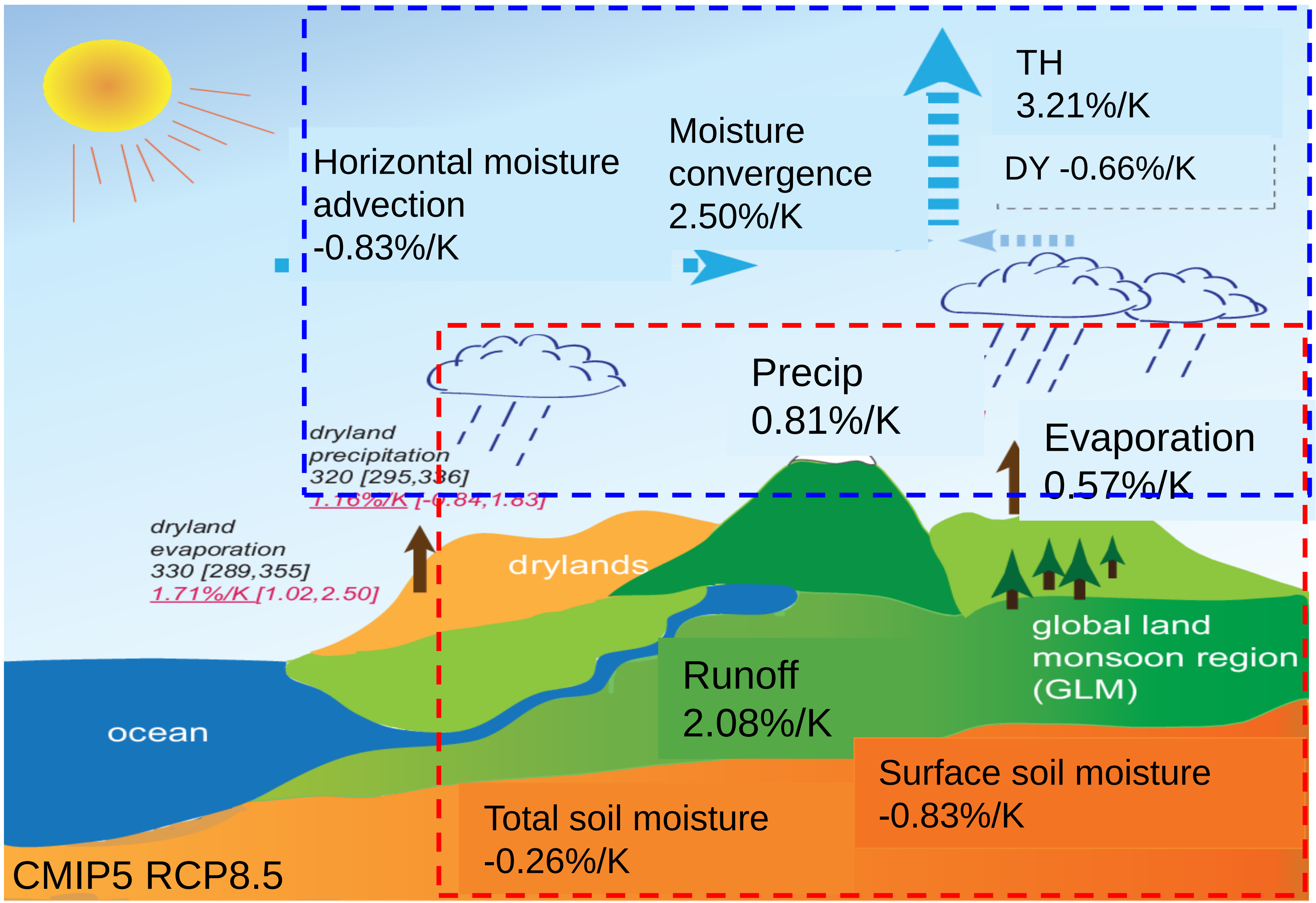
$$\Delta P = \Delta E - \Delta < V \cdot \nabla q > - \Delta < \omega \partial_p q >$$

Horizontal moisture advection

Vertical moisture advection

(Seager et al. 2010; Chou and Lan, 2013)

Response of annual mean water cycle to global warming



- Intensification of annual mean water cycle (P, E, P-E, R)
- Dominated by thermodynamic term of moisture convergence

Atmospheric water cycle

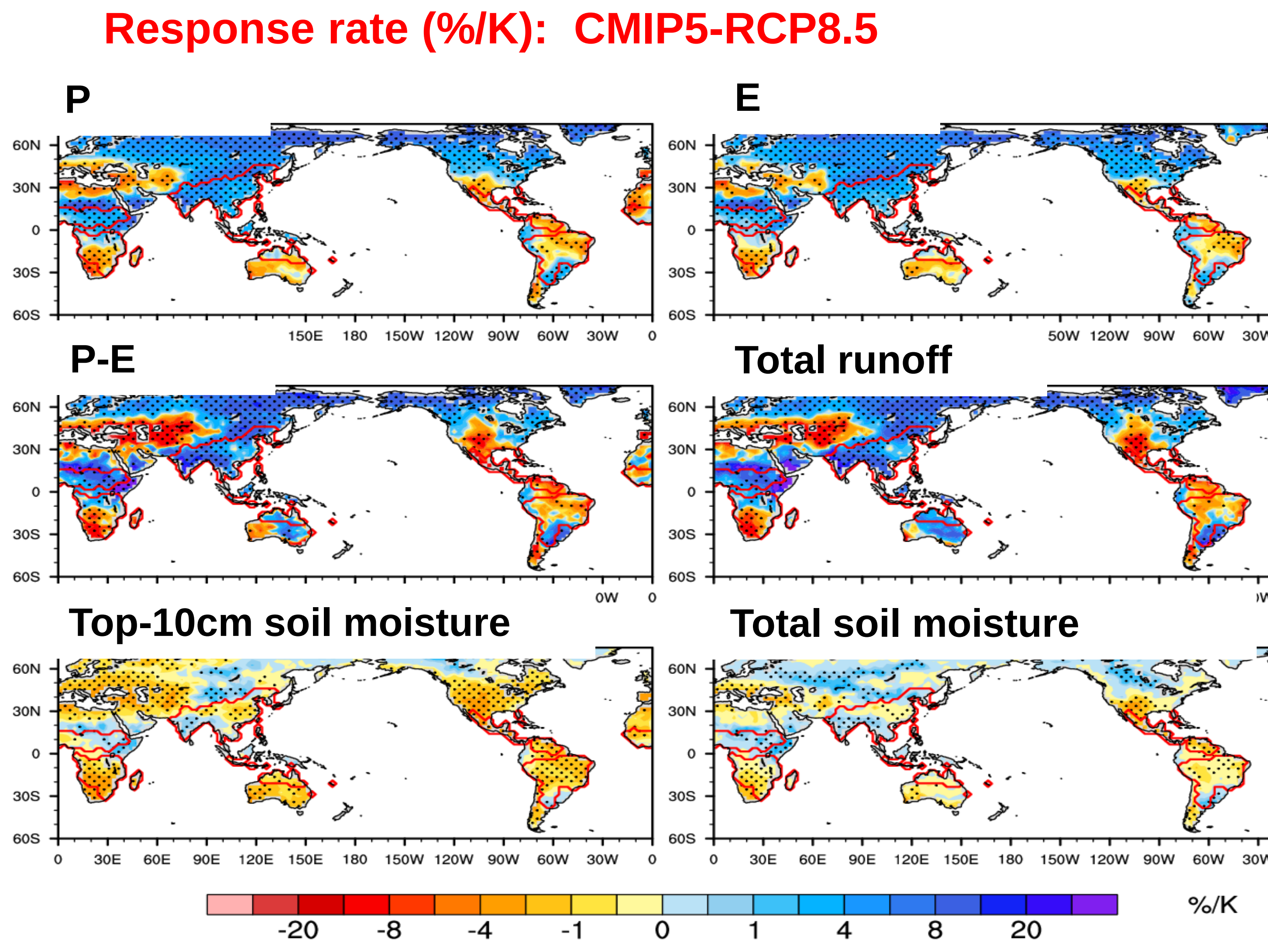
$$P - E = -\frac{\partial PW}{\partial t} - < \nabla \cdot \mathbf{V}q >$$

Surface water cycle

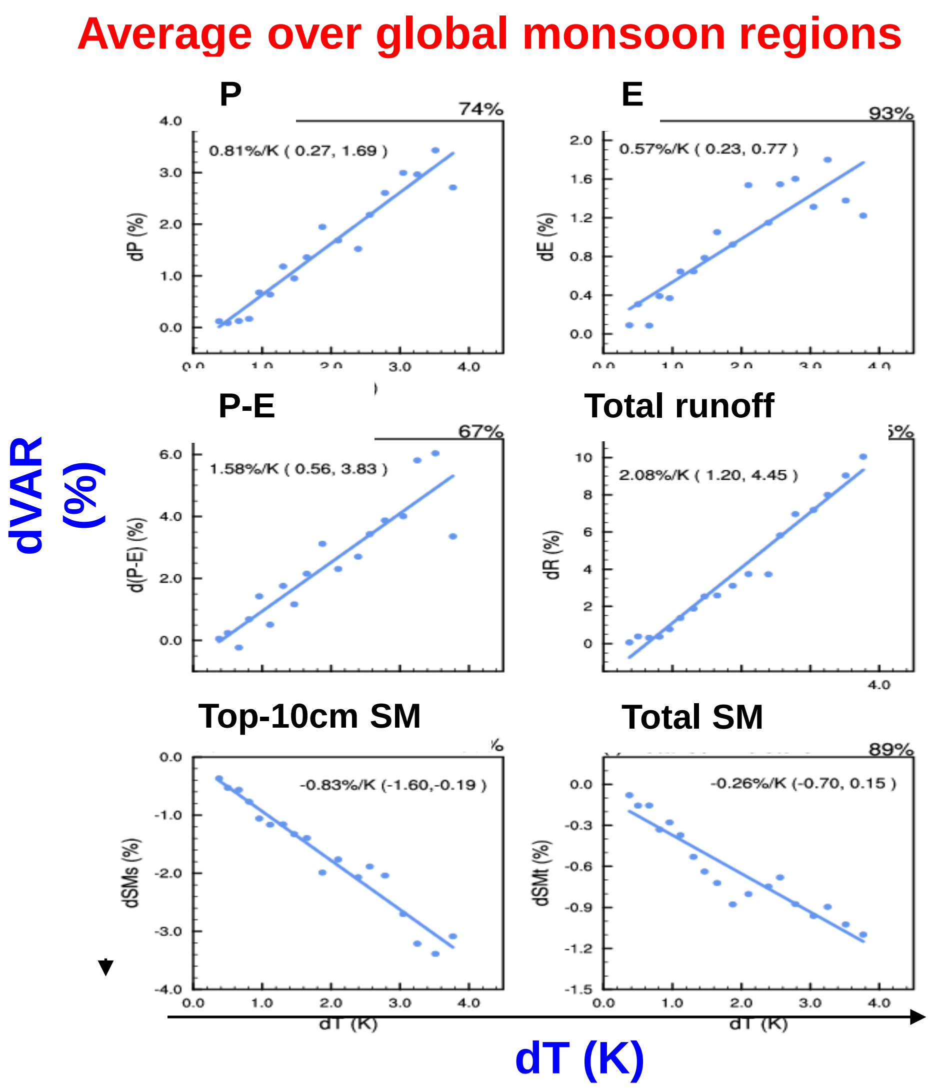
$$\frac{\partial S}{\partial t} = P - E - R$$

Zhang W. , T. Zhou*, L. Zhang et al. 2019: Future intensification of the water cycle with an enhanced annual cycle over global land monsoon regions. *Journal of Climate*, in press, doi: 10.1175/JCLI-D-18-0628.1.

Response of annual mean water cycle to global warming



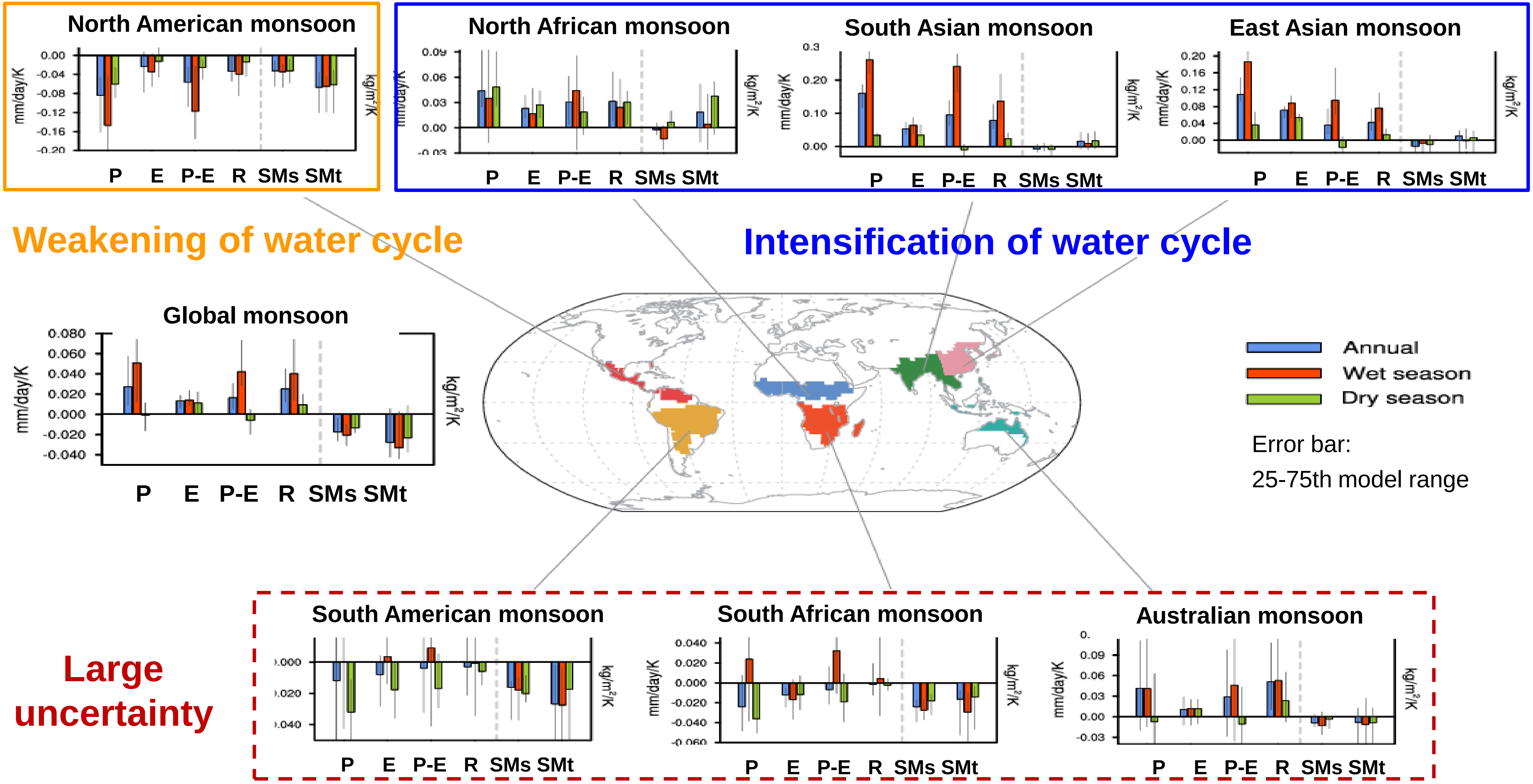
Shading: multimodel median; dots: ≥2/3 models agree in sign



Linear fit: multimodel median

Zhang W. , T. Zhou*, L. Zhang et al. 2019: Future intensification of the water cycle with an enhanced annual cycle over global land monsoon regions. *Journal of Climate*, in press, doi: 10.1175/JCLI-D-18-0628.1.

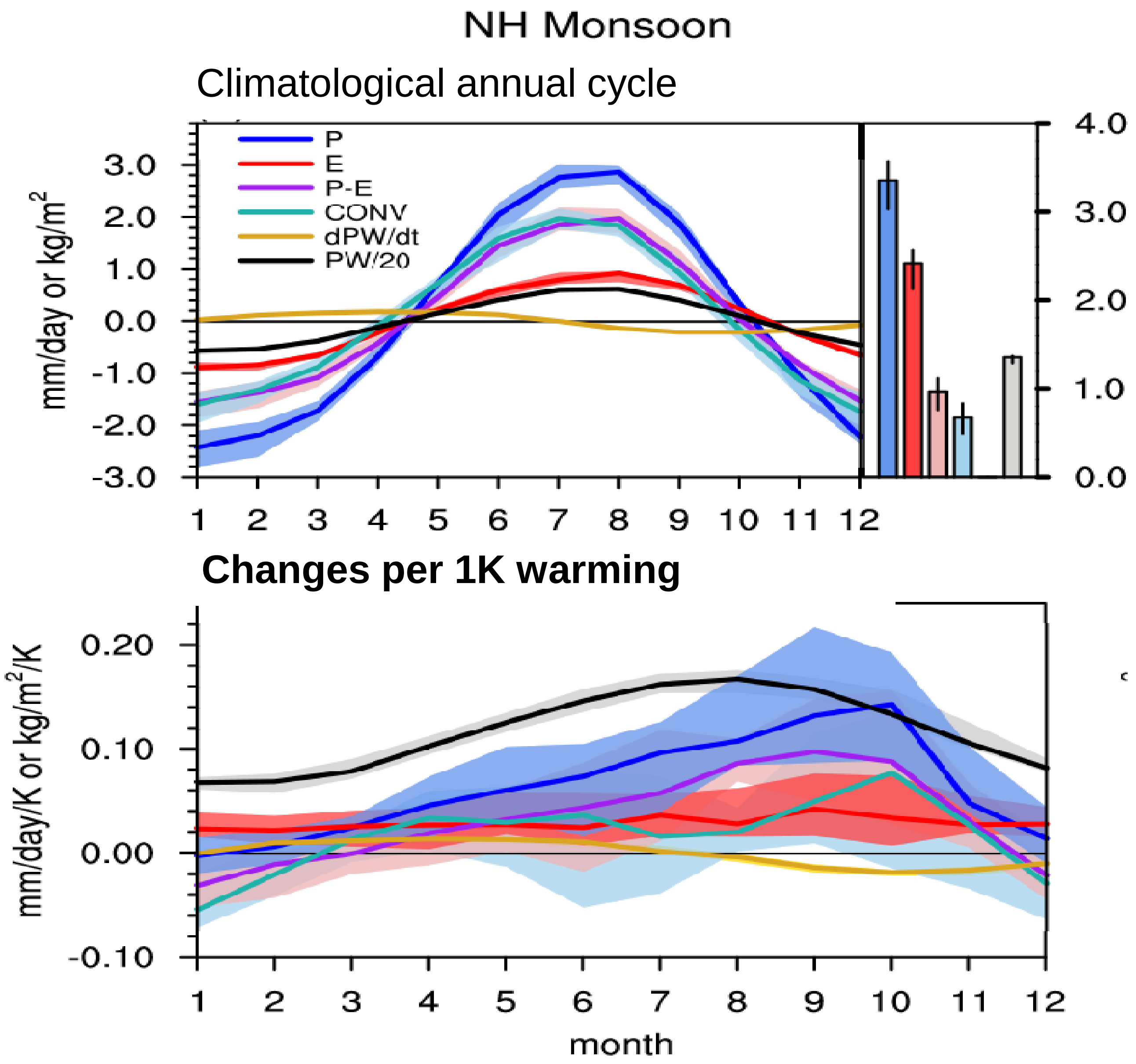
Response in monsoon sub-regions



Projection of precipitation changes

- ◆Response of annual mean water cycle to global warming
- ◆Response of annual cycle of water cycle to global warming
- ◆Exposure to extreme precipitation

Changes in seasonality of atmospheric water cycle



◆ Increase in seasonality:

- P, P-E, moisture convergence, precipitable water

◆ Phase delay in annual cycle:

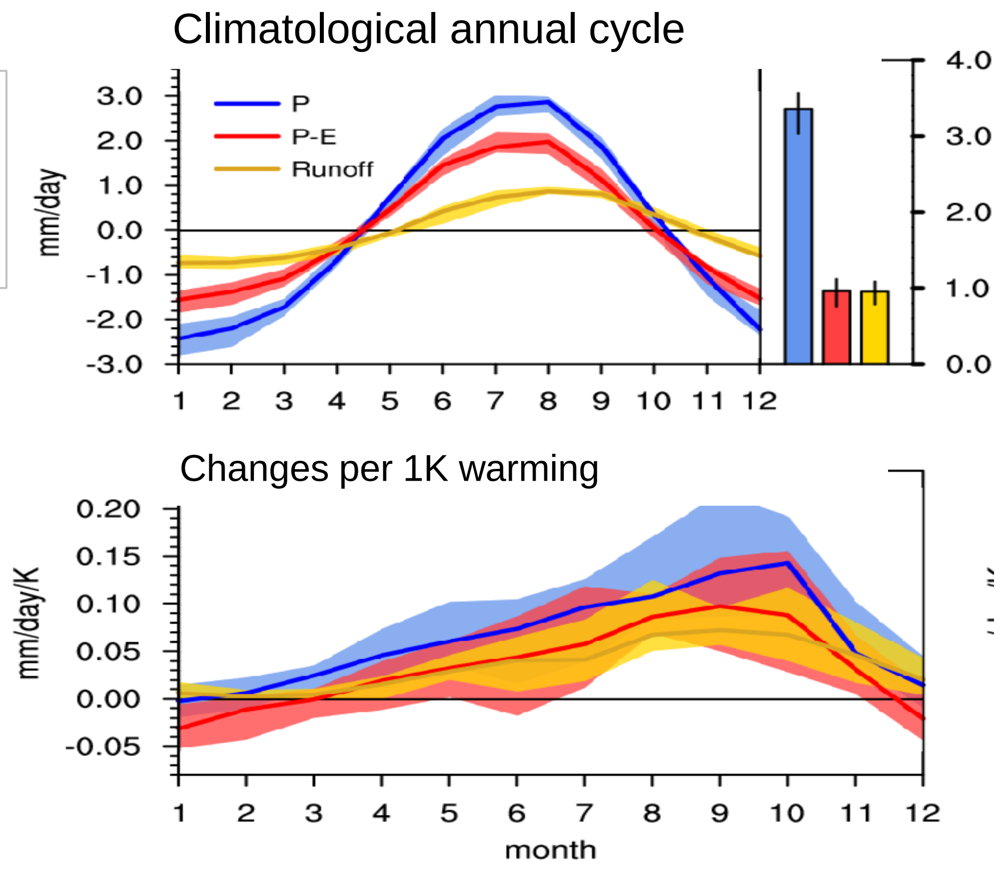
- greatest increases toward end of monsoon season
- delayed retreat in NH monsoon and delayed onset in SH monsoon

Zhang W. , T. Zhou*, L. Zhang et al. 2019: Future intensification of the water cycle with an enhanced annual cycle over global land monsoon regions. *Journal of Climate*, in press, doi: 10.1175/JCLI-D-18-0628.1.

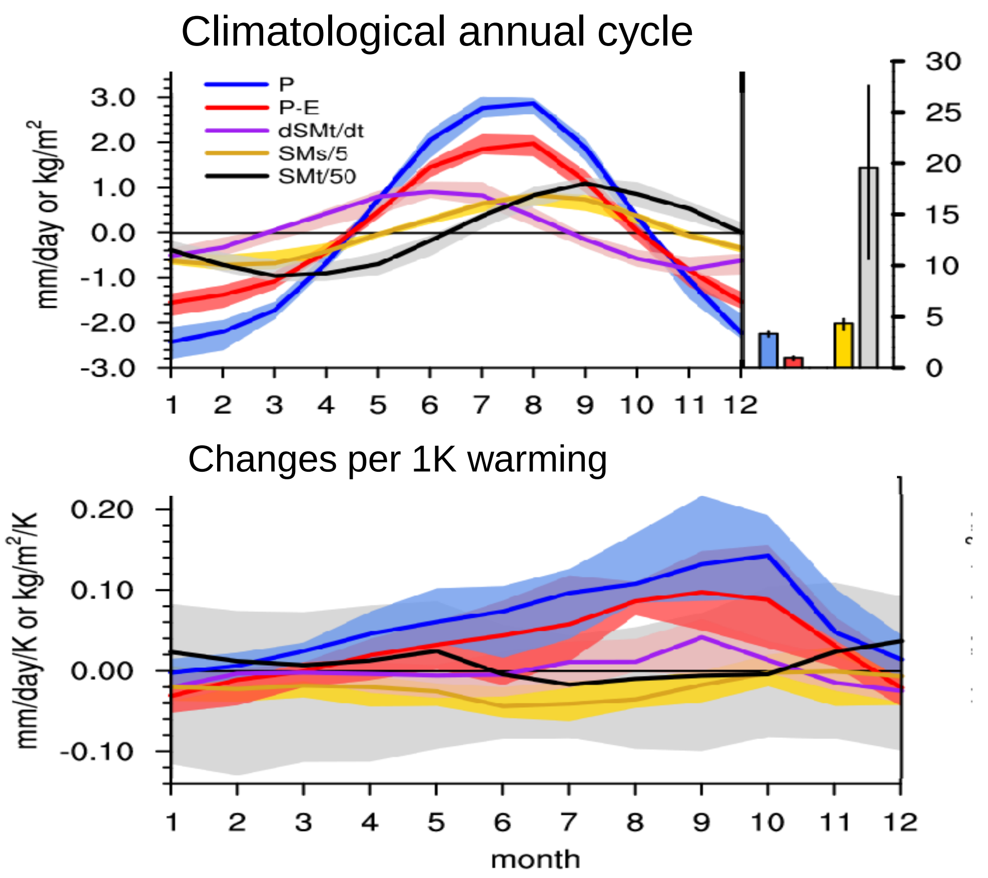
Changes in seasonality of surface water cycle

P
P-E
Runoff

Runoff: NH monsoon



Soil moisture: NH monsoon



P
P-E
dSM/dt
SMs
SMt

- Increased seasonality in R
- greatest increases toward end of monsoon season
- Flood risks

- Surface soil moisture decrease steadily throughout the year
- Drought risks

Mechanisms for enhanced annual cycle

Moisture budget analysis

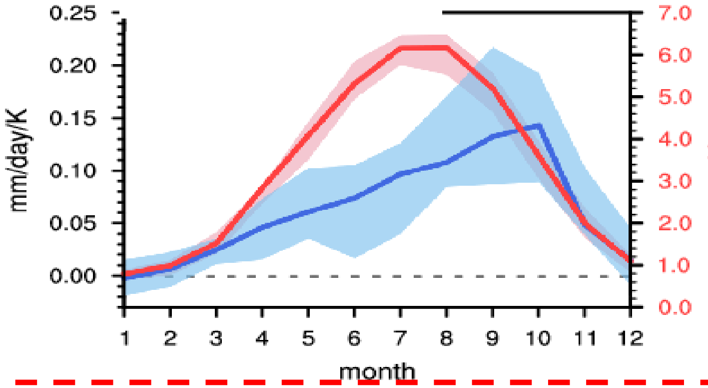
$$\Delta P = -\ \Delta\!< \mathrm{V} \cdot \nabla q > - \Delta\!< \omega \partial_p q > + \Delta E$$

Red: climatology

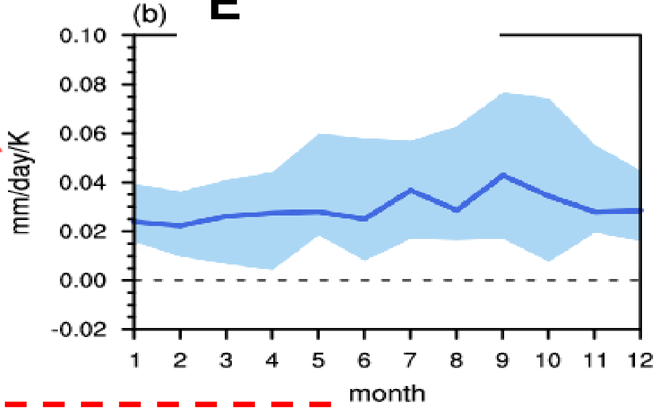
Blue: change

(mm/day/K)

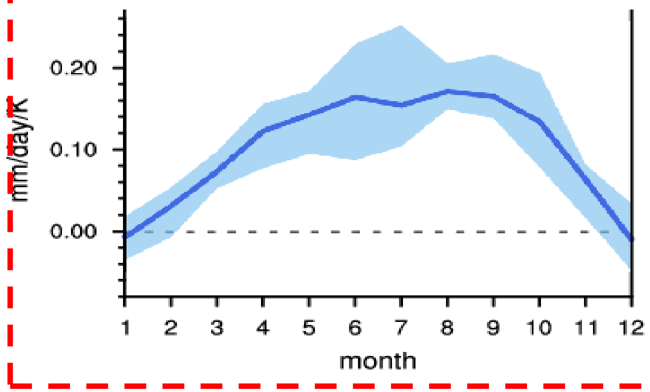
P



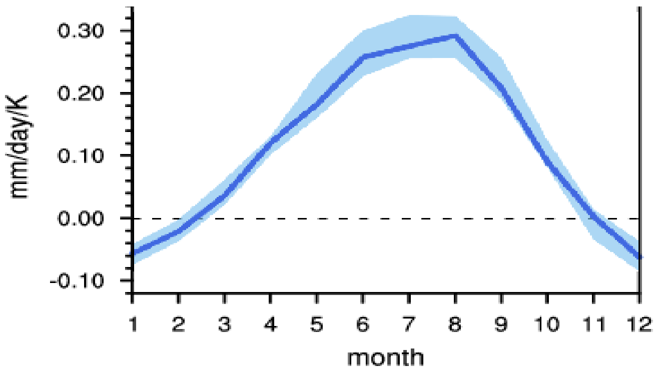
E



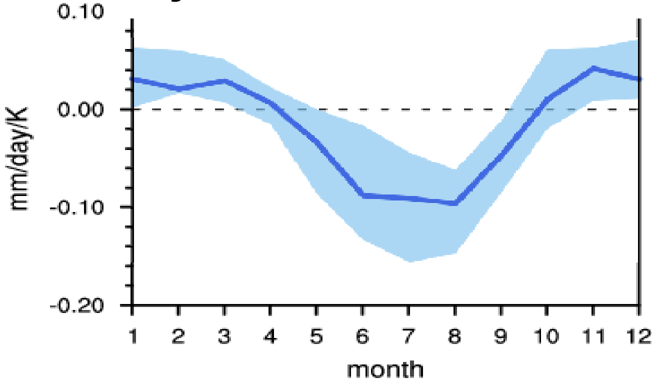
Moisture convergence



Thermodynamics

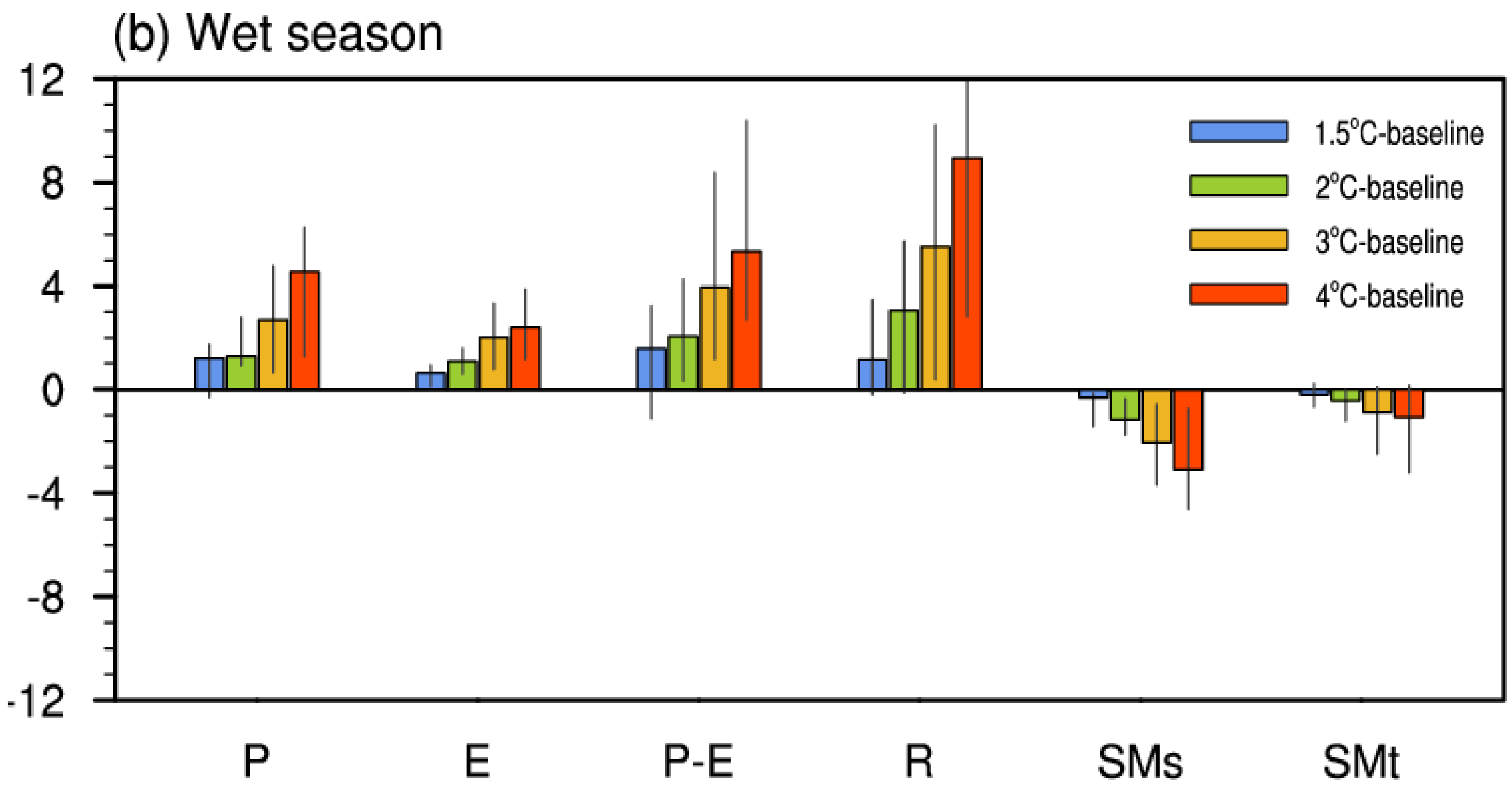


Dynamics



- **Enhanced annual cycle of P is dominated by thermodynamic component of moisture convergence**

Changes in water cycle components over the GLM region at 1.5° C, 2° C, 3° C and 4° C warming levels



Limiting global warming to 1.5° C, the low warming target set by the Paris Agreement, could robustly reduce additional hydrological risks from increased seasonality as compared to higher warming thresholds.

Zhang W. , T. Zhou*, L. Zhang et al. 2019: Future intensification of the water cycle with an enhanced annual cycle over global land monsoon regions. *Journal of Climate*, in press, doi: 10.1175/JCLI-D-18-0628.1.

Interim Summary 1

◆ Changes in annual mean water cycle

- Robust intensification in P, E, P-E and total runoff; decreases in surface and total soil moisture

- Regional characteristics: the North African, South and East Asian monsoon regions would experience an intensified water cycle, while North American monsoon region would experience a weakened water cycle

◆ Changes in annual cycle of water cycle

- Enhanced annual cycle in P, P-E and total runoff; dominated by thermodynamic contribution of moisture convergence

- Phase delay

◆ Implication for increases in flood risks in monsoon season

Zhang W. , T. Zhou*, L. Zhang et al. 2019: Future intensification of the water cycle with an enhanced annual cycle over global land monsoon regions. *Journal of Climate*, in press, doi: 10.1175/JCLI-D-18-0628.1.

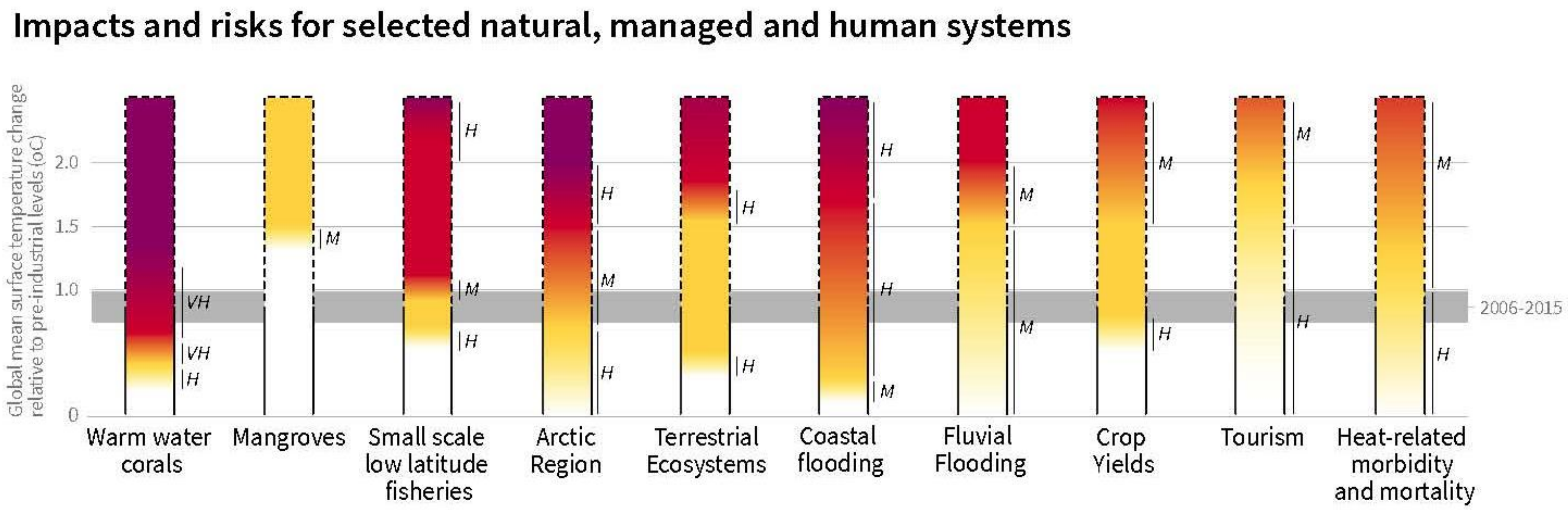
Projection of precipitation changes

- ◆Response of annual mean water cycle to global warming
- ◆Response of annual cycle of water cycle to global warming
- ◆Exposure to extreme precipitation

The Goal of Paris Climate Agreement

"Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C, recognizing that this would significantly reduce the risks and impacts of climate change".

IPCC AR6 Special Report on the impacts of global warming of 1.5°C

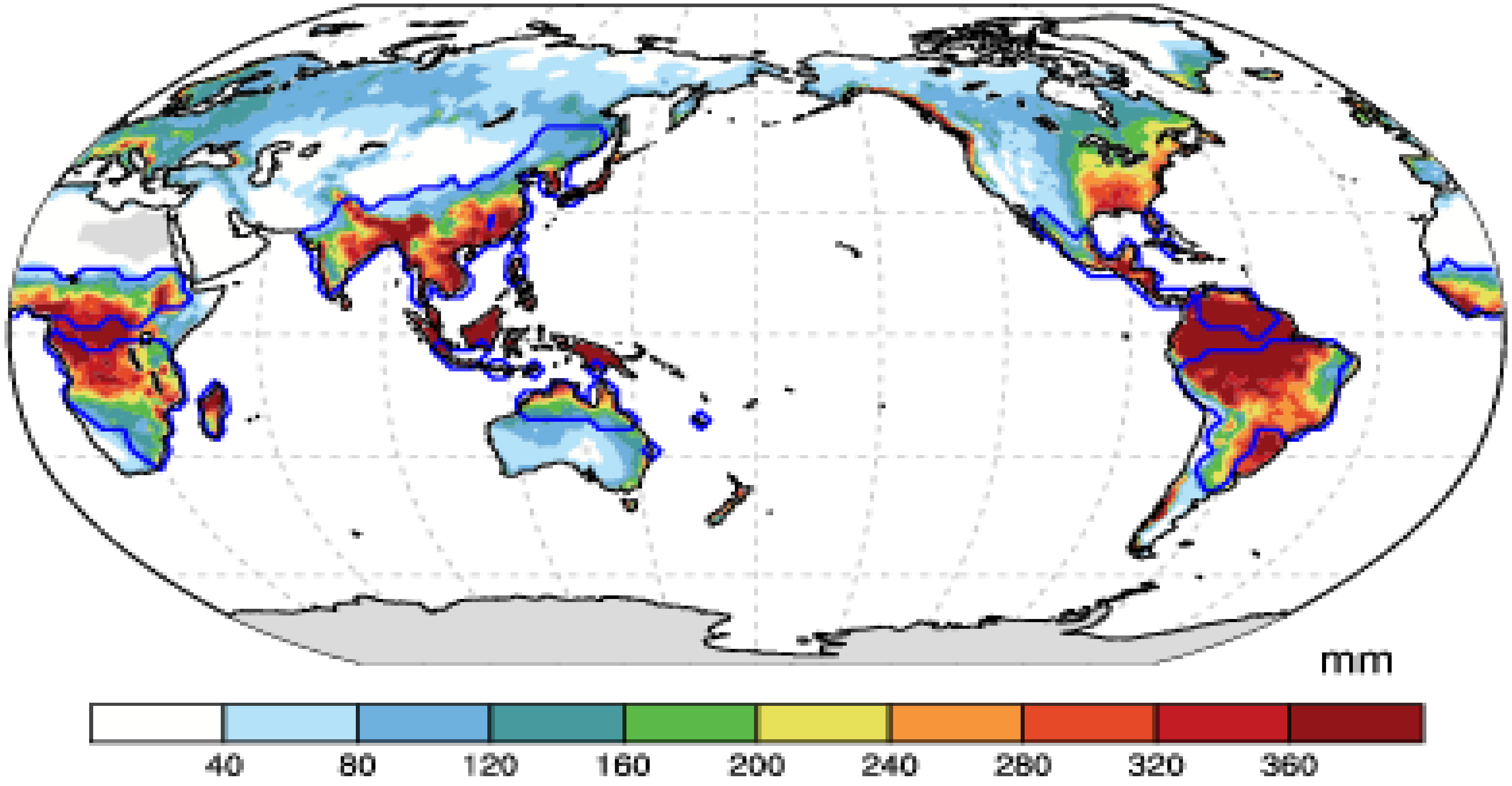


Impacts and risks in monsoon regions?

(IPCC 2018)

Accumulated extreme precipitation in observation

R95ptot



Large contributions of extreme precipitation in monsoon domain

Accumulated precipitation on very wet days with daily precipitation exceeding the 95th percentile on wet days (R95ptot) for GPCC in 1998-2011

Any reduced exposure to extreme precipitation in 0.5C less warming?

◆ **Daily precipitation data:**

- 27 CMIP5 models: historical + RCP4.5/RCP8.5

We compare the worlds under 1.5° C and 2° C warming in CMIP5 models

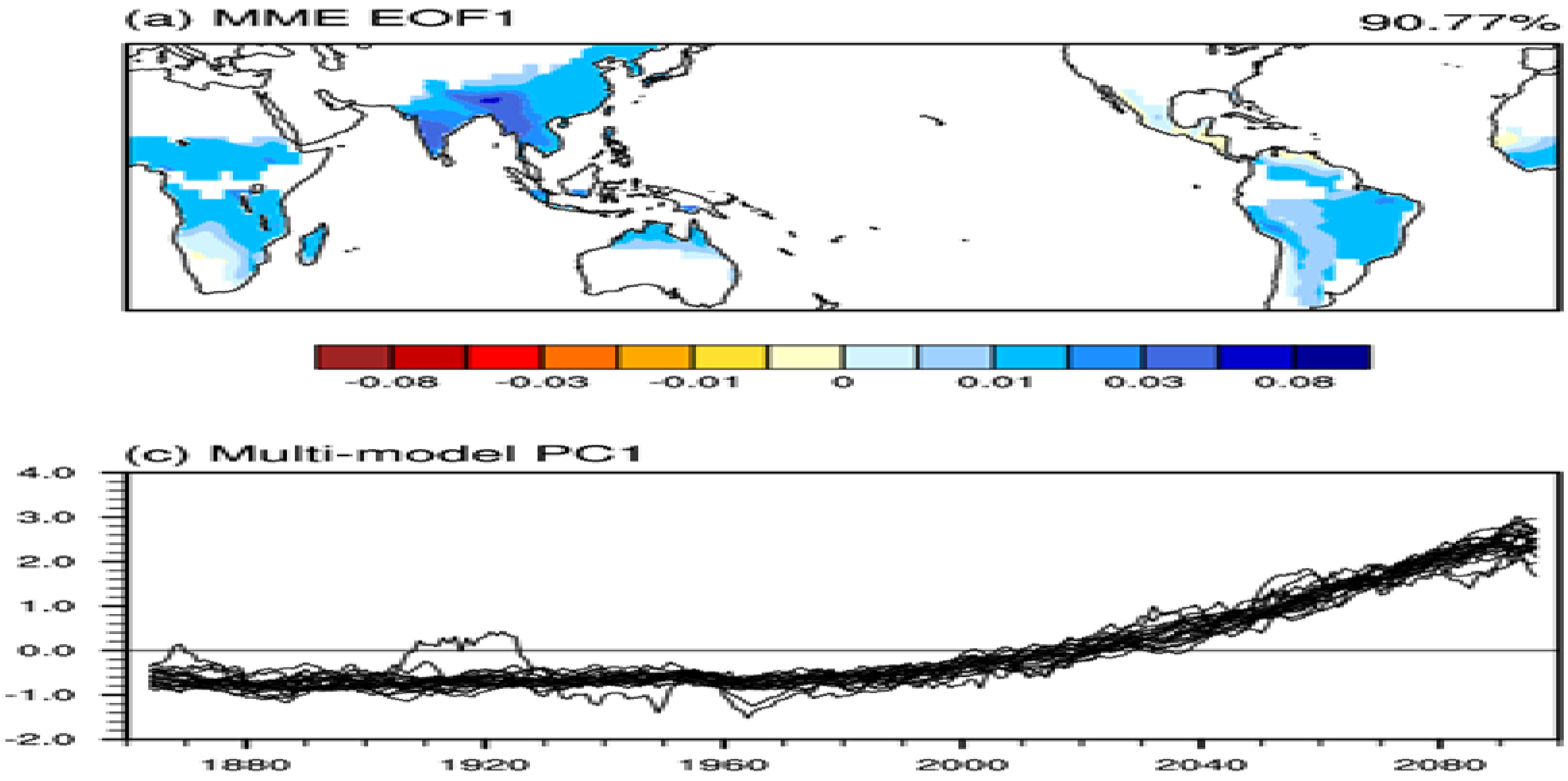
◆ **Population:**

- Gridded Population in 2000 (NASA Socioeconomic Data and Applications Center)
- Projected 21st century population under Shared Socioeconomic Pathways (SSPs)

◆ **Extreme Precipitation index: RX5day**

Zhang W., T. Zhou*, L. Zou, L. Zhang, X. Chen, 2018: Reduced exposure to extreme precipitation by 0.5° C less warming for global land monsoon regions . ***Nature Communication*** 9, Article number: 3153 (2018). doi: 10.1038/s41467-018-05633-3

The leading EOF of RX5day in CMIP5 RCP8.5 Projection

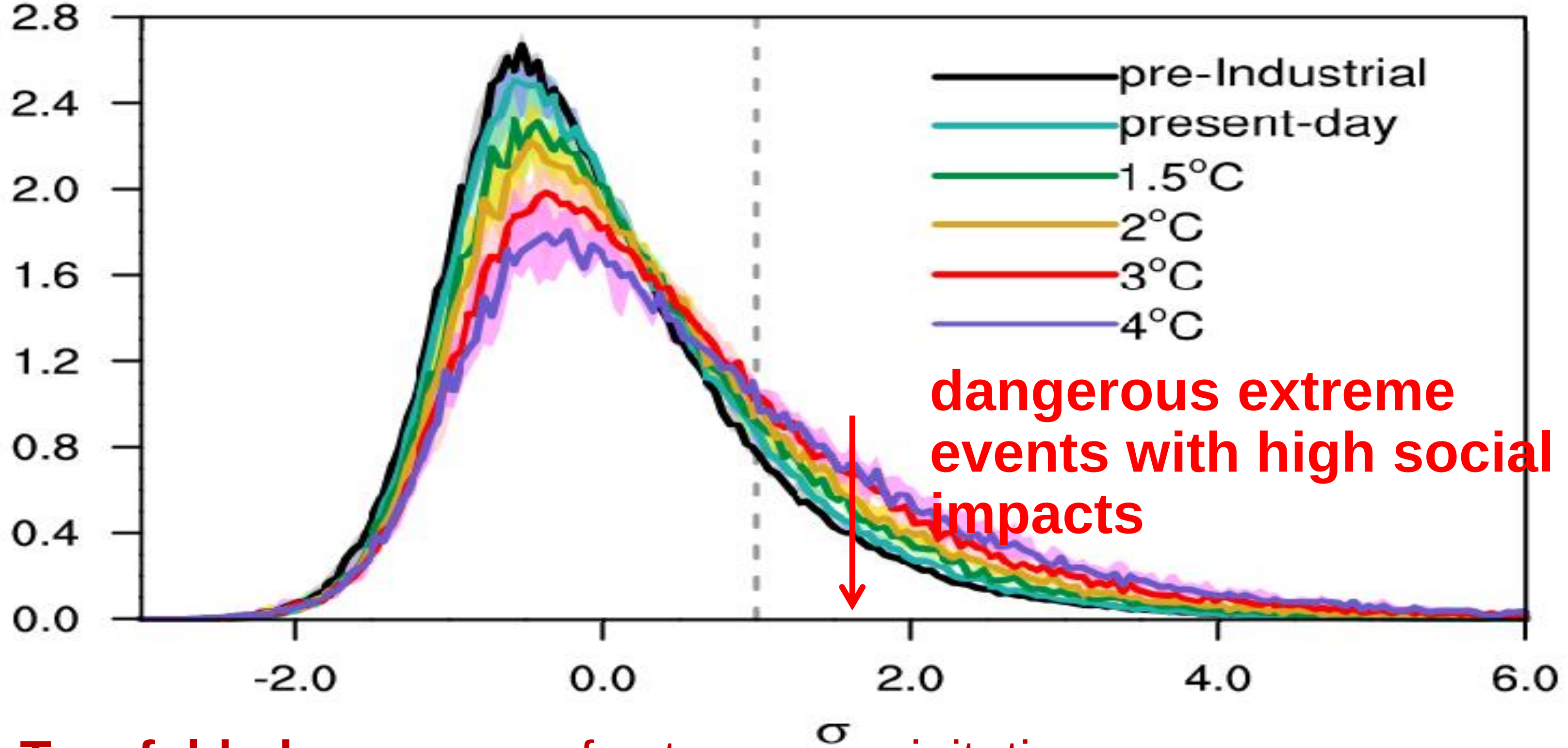


Increasing trend is evident in global monsoon domains except for N. American monsoon

Zhang W., T. Zhou*, L. Zou, L. Zhang, X. Chen, 2018: Reduced exposure to extreme precipitation by 0.5° C less warming for global land monsoon regions . ***Nature Communication*** 9, Article number: 3153 (2018). doi: 10.1038/s41467-018-05633-3

Response of extreme precipitation to warming in CMIP5 Models

PDF of Rx5day over global land monsoon region



Once-in-10/20-year events derived from Generalized Extreme Value (GEV) distribution

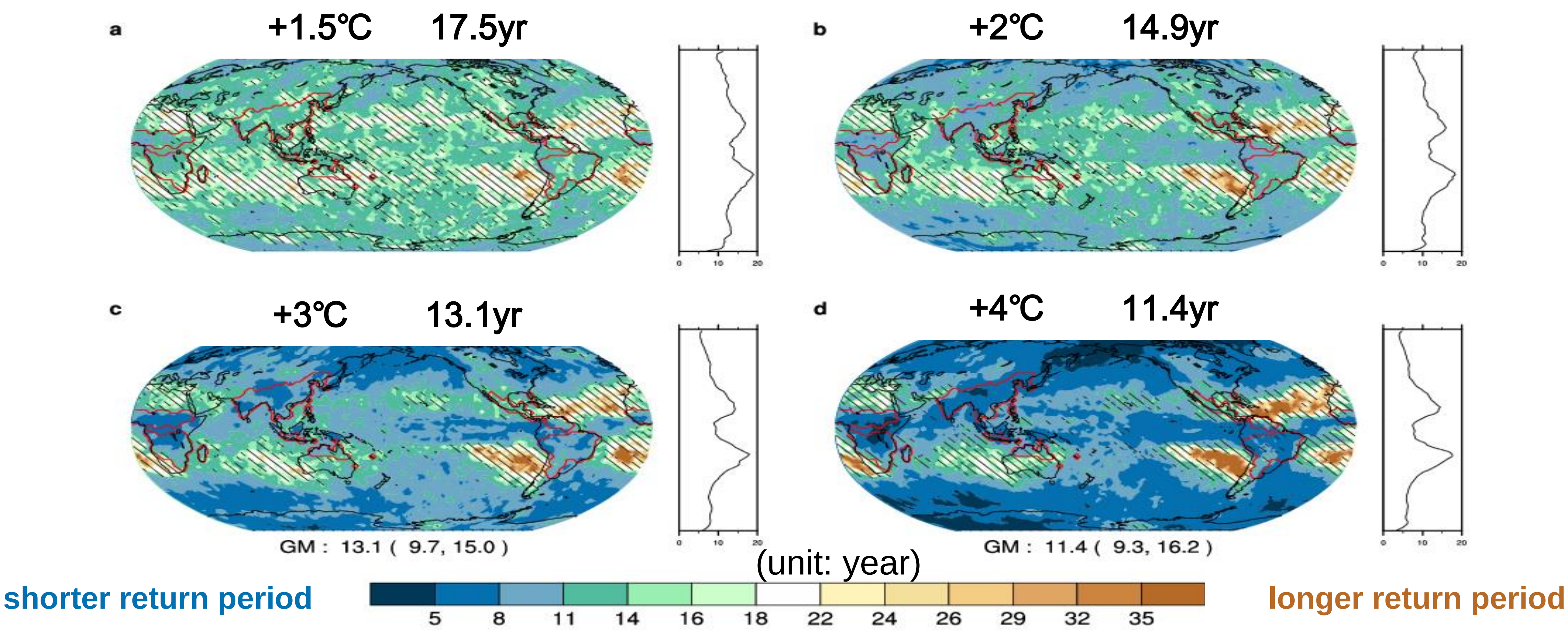
Two-folded response of extreme precipitation

- Increase in mean state (shift of the distribution)
- Increase in variability (widening of the distribution)

Zhang W., T. Zhou*, L. Zou, L. Zhang, X. Chen, 2018: Reduced exposure to extreme precipitation by 0.5° C less warming for global land monsoon regions . ***Nature Communication*** 9, Article number: 3153 (2018). doi: 10.1038/s41467-018-05633-3

Changes in return periods under warming conditions

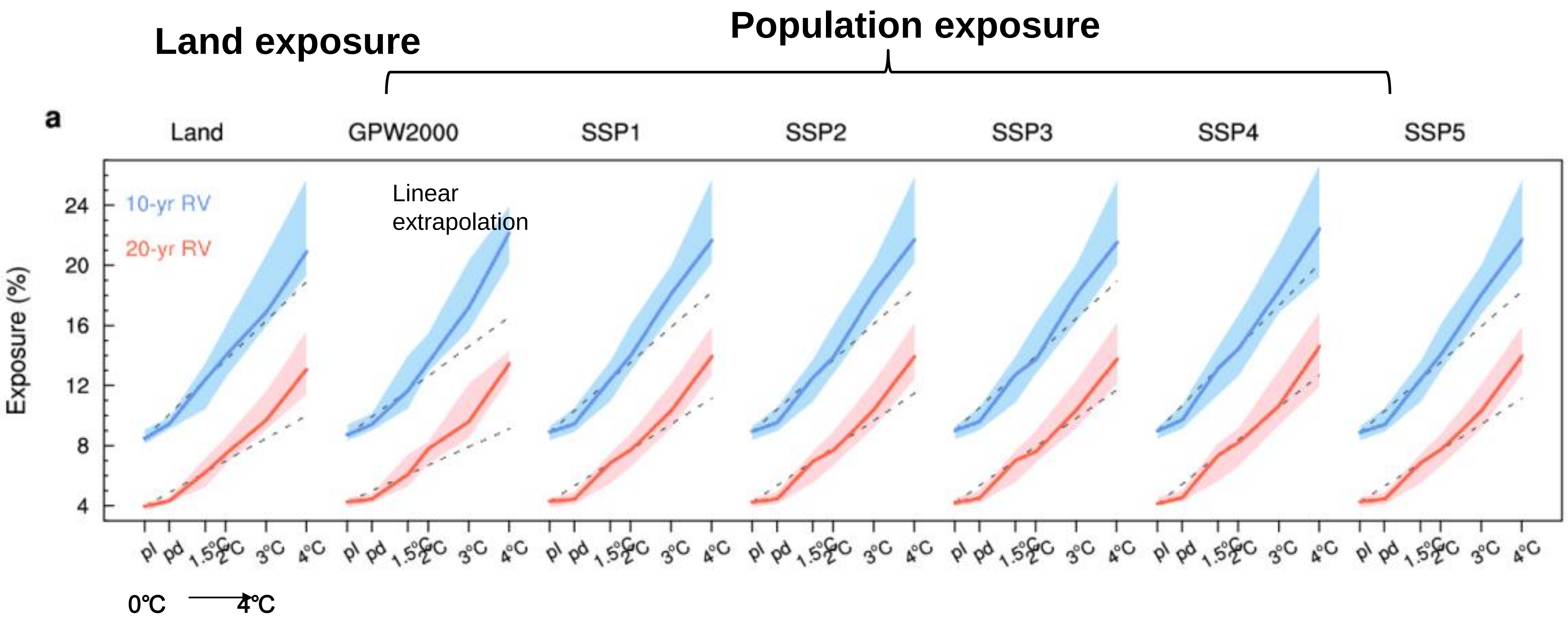
Return periods of historical (1950-2005) once-in-20-year Rx5day events



Shorter return periods for dangerous extremes are expected under further warming conditions.

Zhang W., T. Zhou*, L. Zou, L. Zhang, X. Chen, 2018: Reduced exposure to extreme precipitation by 0.5° C less warming for global land monsoon regions . ***Nature Communication*** 9, Article number: 3153 (2018). doi: 10.1038/s41467-018-05633-3

Increases in exposure with global warming levels



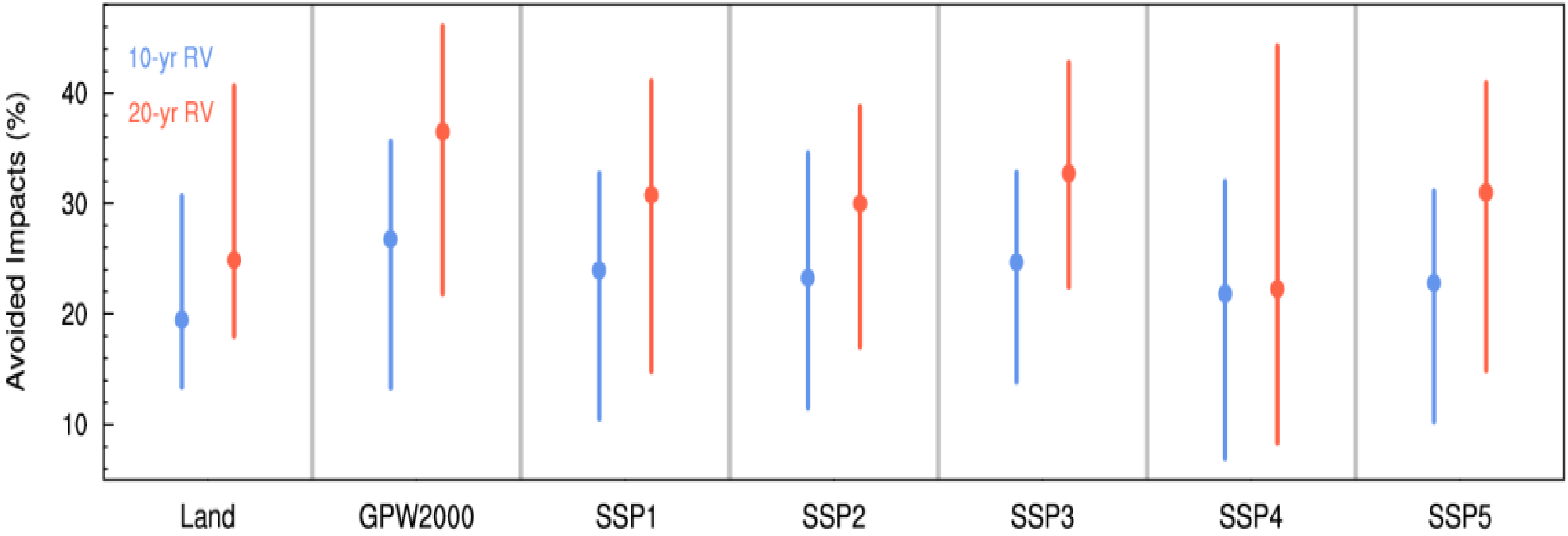
- **Consistent increases in exposure to dangerous extremes with warming**
- **Nonlinear increases for warming higher than 2℃**

once-in-10-year events

once-in-20-year events

Zhang W., T. Zhou*, L. Zou, L. Zhang, X. Chen, 2018: Reduced exposure to extreme precipitation by 0.5° C less warming for global land monsoon regions . ***Nature Communication*** 9, Article number: 3153 (2018). doi: 10.1038/s41467-018-05633-3

1.5℃ vs. 2℃: avoided impacts for global land monsoon region

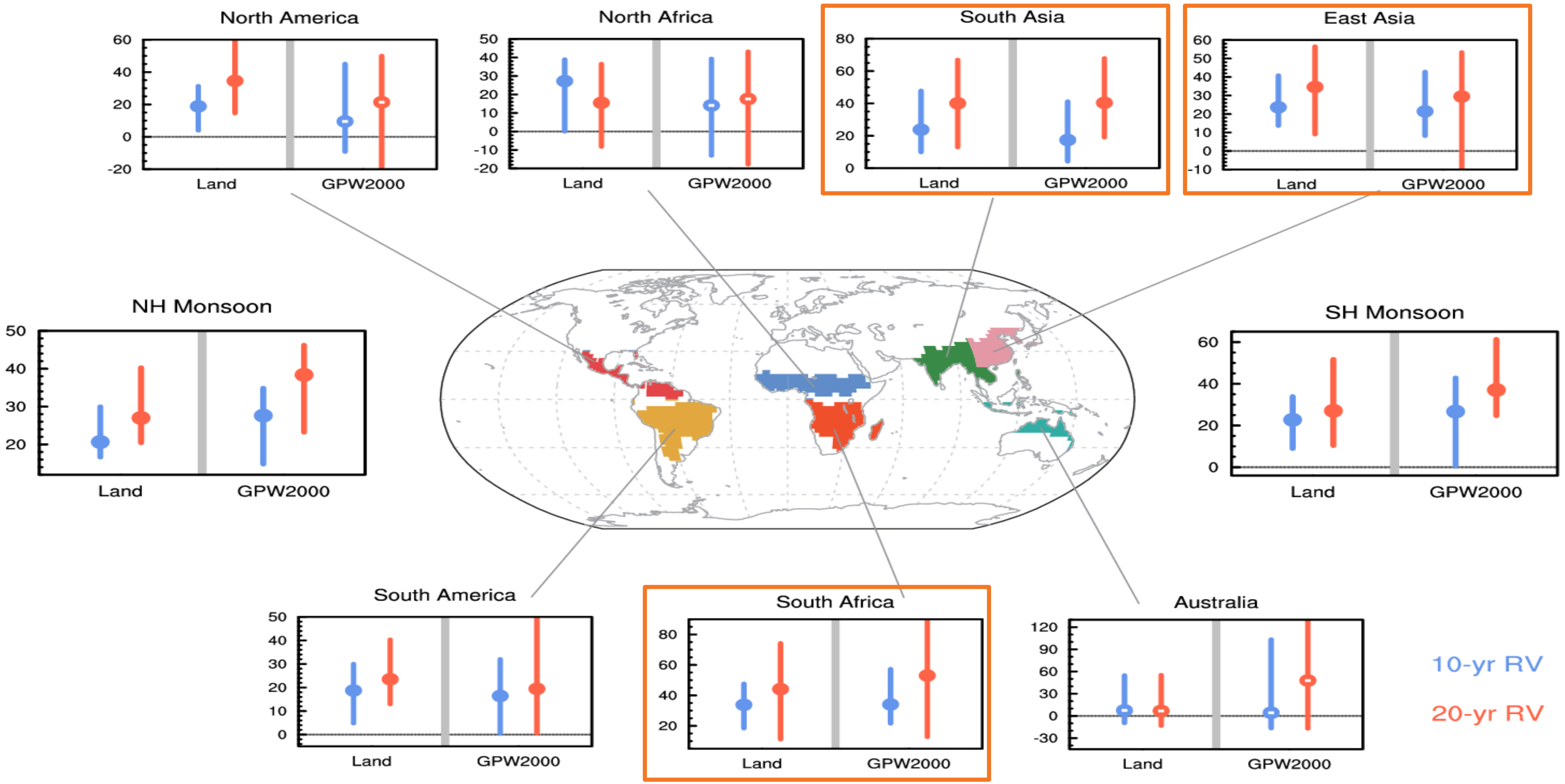


$$Avoided\ \ Impact = \frac{EXP_{2°C} - EXP_{1.5°C}}{EXP_{present-day}} \times 100\%$$

- **Avoided exposure: ~20-40%**
- **More remarkable avoided impacts for more intense extremes**

Zhang W., T. Zhou*, L. Zou, L. Zhang, X. Chen, 2018: Reduced exposure to extreme precipitation by 0.5° C less warming for global land monsoon regions . ***Nature Communication*** 9, Article number: 3153 (2018). doi: 10.1038/s41467-018-05633-3

Avoided impacts: regional hotspots



- **South African, South Asian, and East Asian monsoon regions would benefit most from the 0.5° C less warming.**

Interim Summary 2

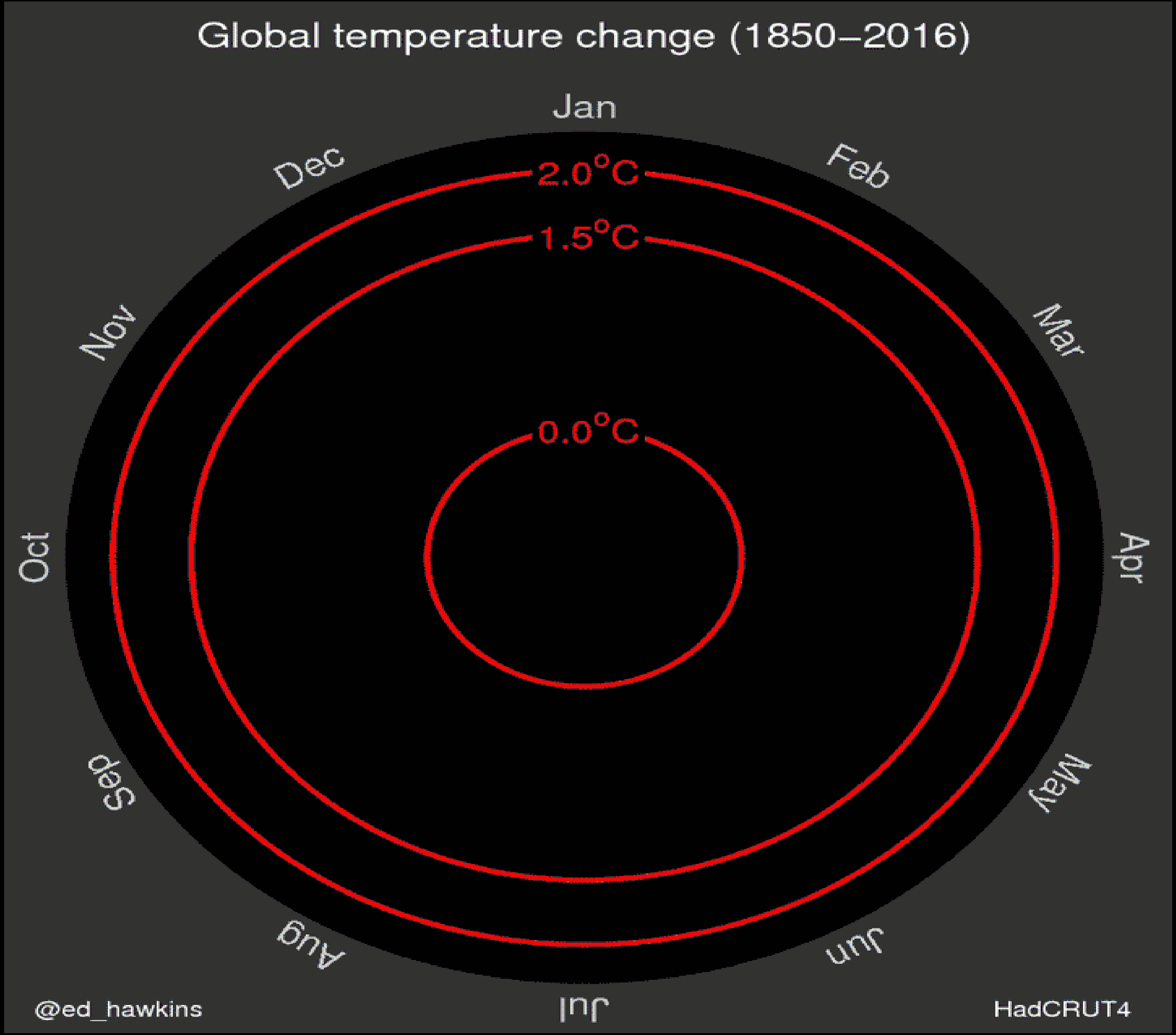
1. Both the mean state and variability of extreme precipitation would increase with warming, corresponding to the rightward shift and widening of the PDF, respectively.
2. Shorter return periods for dangerous extremes are expected under warming conditions, leading to increases in both areal and population exposures to dangerous extremes.
3. The 0.5° C less warming would reduce areal and population exposures to dangerous extreme precipitation (once-in-10/20-year) events by ~20-40%, for the global land monsoon region.
4. South African, South Asian, and East Asian monsoon regions would benefit most from the 1.5° C low warming target, in terms of reduced exposure to dangerous extremes.

We highlight the benefits of the 1.5° C low warming target in terms of lower exposure to dangerous precipitation extremes for the populous monsoon regions.

Zhang W., T. Zhou*, L. Zou, L. Zhang, X. Chen, 2018: Reduced exposure to extreme precipitation by 0.5° C less warming for global land monsoon regions . ***Nature Communication*** 9, Article number: 3153 (2018). doi: 10.1038/s41467-018-05633-3

Taking home messages

Continued efforts to limit warming to 1.5°C would bring considerable benefits in terms of minimizing exposures to enhanced water cycle, and precipitation extremes in global land monsoon domain.


Global temperature change (1850–2016)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
2.0°C
1.5°C
0.0°C
@ed_hawkins
HadCRUT4

We need climate action for mitigation

As the 'Katowice Climate Package' is adopted, **Michał Kurtyka**,COP24 President, takes a giant leap for climate action

SCI
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nature climate change

LETTERS

https://doi.org/10.1038/s41558-018-0145-6

Record-breaking climate extremes in Africa under stabilized 1.5 °C and 2 °C global warming scenarios

Shingirai Nangombe[1,2,3], Tianjun Zhou[1,2*], Wenxia Zhang[1,2], Bo Wu[1], Shuai Hu[1,2], Liwei Zou[1] and Donghuan Li[1,2]

- **Model data:** CESM low warming experiments monthly data
- **Extreme events:** historical record-breaking climate events examined are:

(1) Extremely hot 2015 over Africa

(2) Extremely hot DJF 2009/2010 in North Africa

(3) Extremely high February 2000 precipitation over southeast Africa

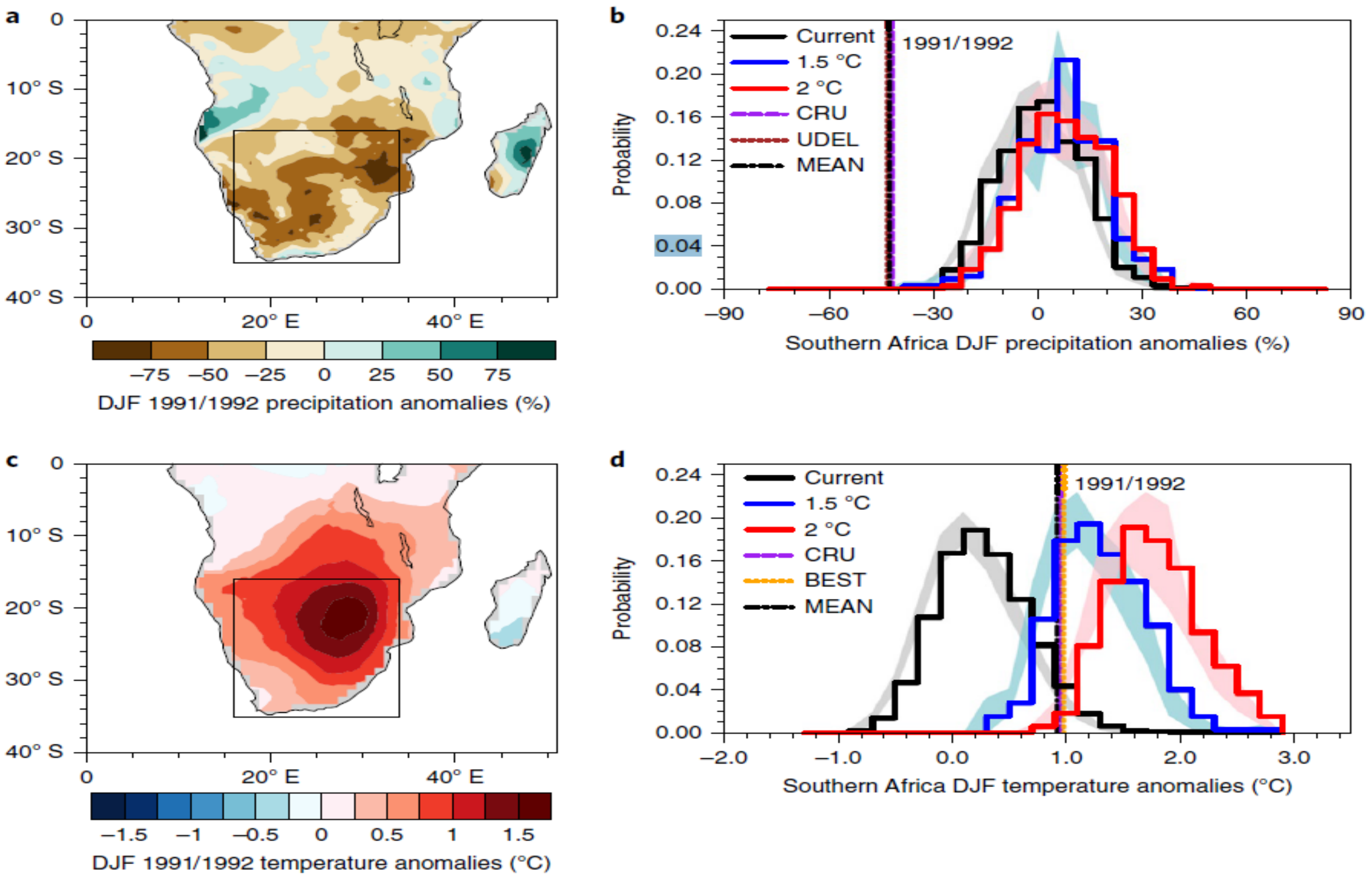
(4) Severe drought of 1991/92 over southern Africa

✓Baseline period of 1976 -2005 is referred to as the present day.

✓The pre-industrial period in this study is 1850-1920.

✓A period of 2071-2100 represents for the 1.5° C and 2° C warming period relative to pre-industrial levels.

1991/92 Southern Africa drought



- Ts and Pr used as proxies for drought
- **1991/92 DJF extreme low precipitation over southern Africa**
- projected to be rare in future scenarios
- Consistent with the multi-model projections in CMIP5 over same area

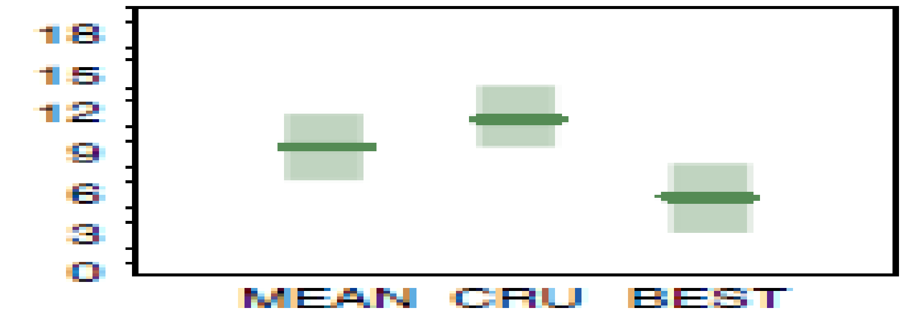
- **1991/92 DJF extreme high temperature over southern Africa**
- 1.5°C: 74% (70%-78%)
- 2°C: 98% (97%-100%)

Regardless of the insignificant precipitation change projected, excessive warming alone might increase the probability of similar droughts occurring in warmer worlds

Nangombe S., Tianjun Zhou*, Wenxia Zhang, Bo Wu, Shuai Hu, L. Zou & D. Li: Record-breaking climate extremes in Africa under stabilized 1.5C and 2C global warming scenarios. *Nature Climate Change* (2018) doi:10.1038/s41558-018-0145-6

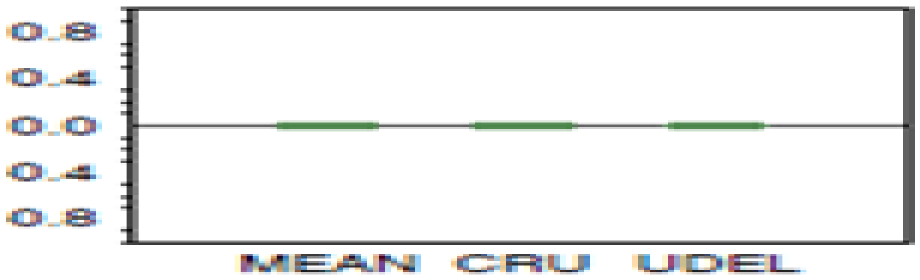
Avoided impacts of 0.5C less warming

2015 heat wave



1991/92 heat wave

1991/92 rainfall



- **Half-degree less warming will reduce the probability of heat event occurrences by:**

- 10% (7%-12%) for events similar to that of 2015 in Africa

- 25% (20%-29%) for high temperatures with magnitudes similar to that during 1991/1992 southern African drought

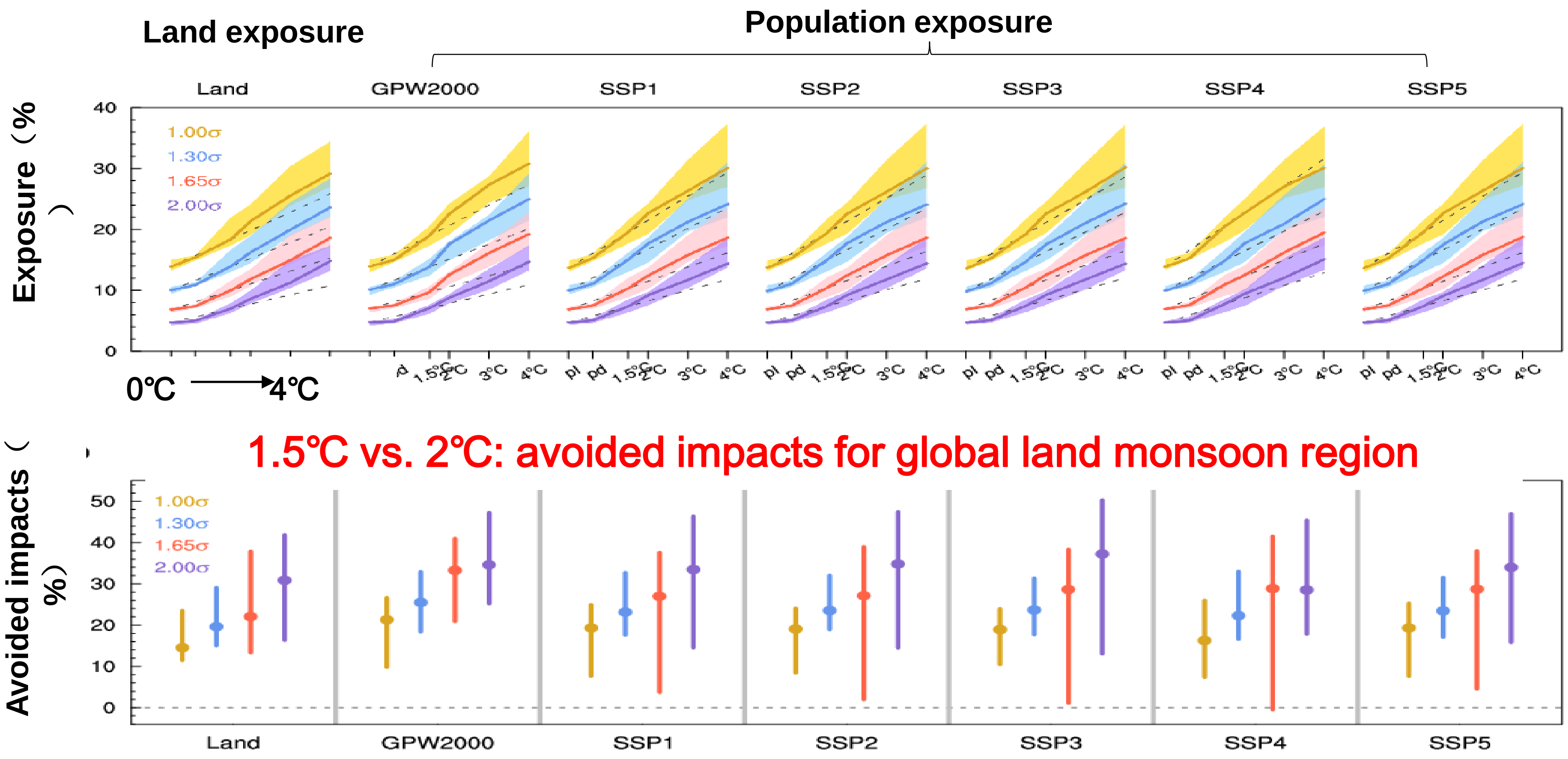
Nangombe S., Tianjun Zhou*, Wenxia Zhang, Bo Wu, Shuai Hu, L. Zou & D. Li: Record-breaking climate extremes in Africa under stabilized 1.5C and 2C global warming scenarios. *Nature Climate Change* (2018) doi:10.1038/s41558-018-0145-6

- Limiting warming to 1.5^{o}C instead of 2^{o}C is projected to reduce the probability of heat event occurrences by--25% (20%-29%) for high temperatures with magnitudes similar to that during 1991/1992 southern African drought. The precipitation change is not significant due to the limitation of models.

Nangombe S., Tianjun Zhou*, Wenxia Zhang, Bo Wu, Shuai Hu, L. Zou & D. Li: Record-breaking climate extremes in Africa under stabilized 1.5C and 2C global warming scenarios. *Nature Climate Change* (2018) doi:10.1038/s41558-018-0145-6

Robustness of the conclusion:

Do not rely on definitions of dangerous events



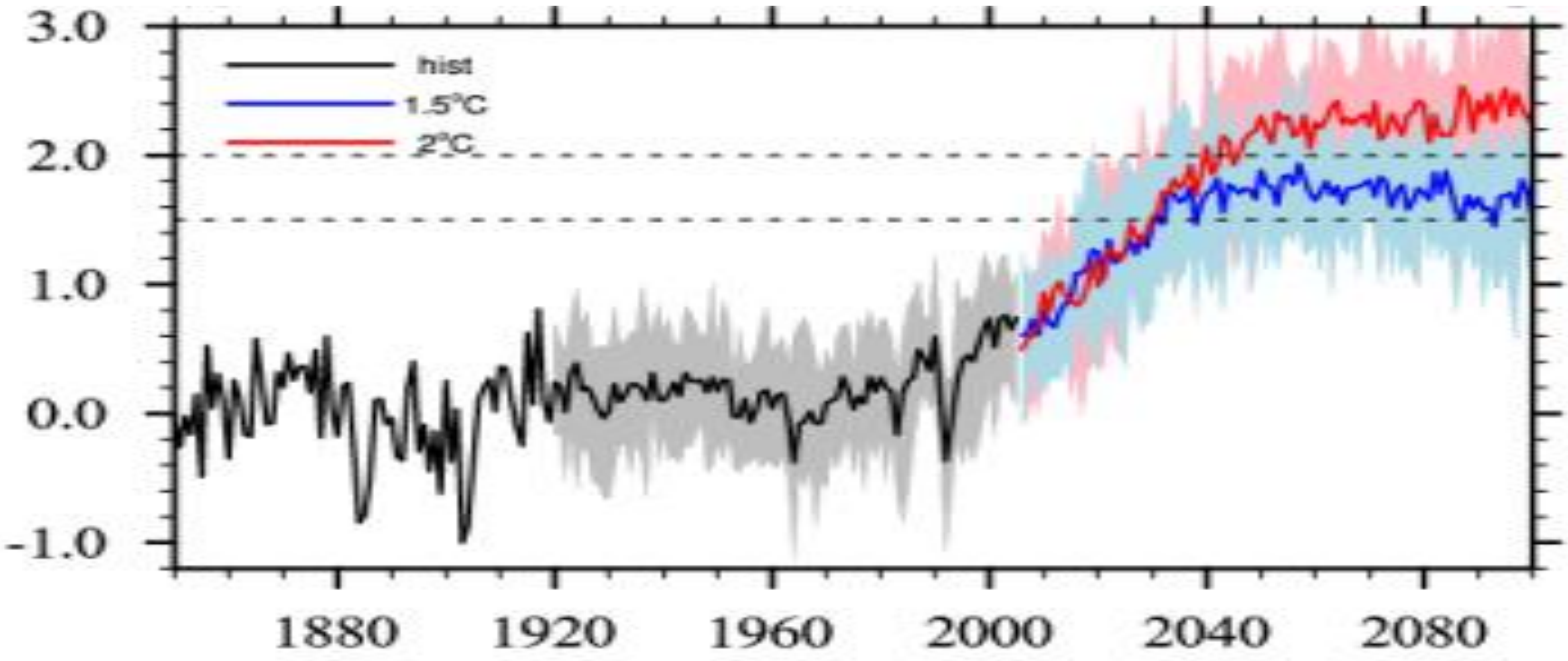
σ-exceedance matrix:

normalization with respect to 1950-2005

1.00 σ—once-in-6-yr
1.30 σ—once-in-10-yr
1.65 σ—once-in-20-yr
2.00 σ—once-in-44-yr

- Results based on the *σ-exceedance matrix* quantitatively support those based on the GEV R*eturn Values*, adding fidelity to the conclusion that the 0.5° C lower warming target benefits the populous monsoon regions.

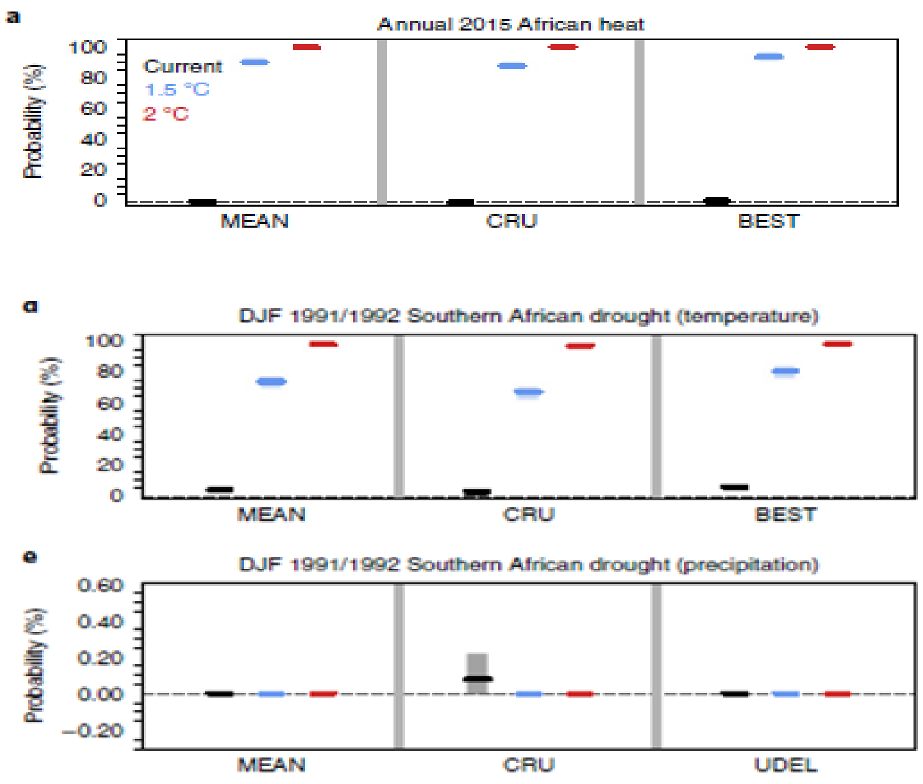
Changes of surface air temperature over East Asia



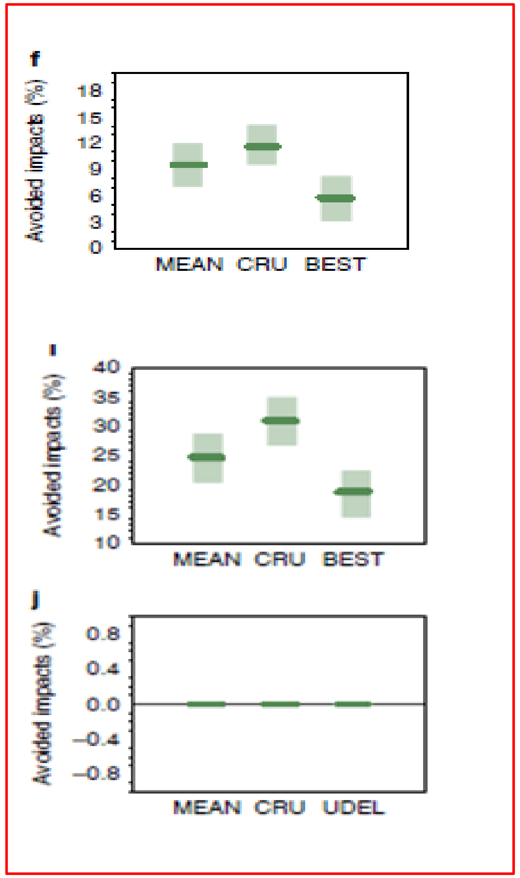
- Regional mean SAT over East Asia will increase **0.2° C larger than global mean** by the end of 21st century: 1.7° C at 1.5° C warming level; 2.3° C at 2° C warming level

Avoided impacts of 0.5C less warming

Probability



Avoided Impatcs



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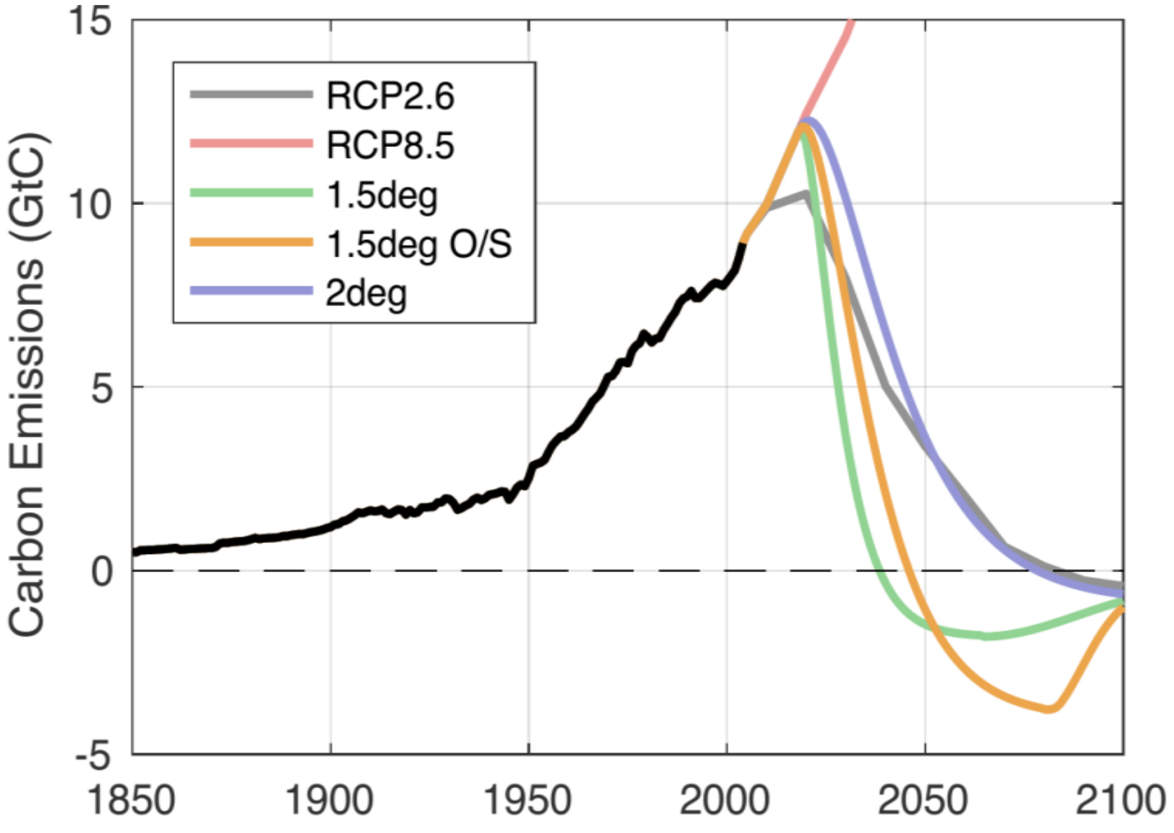
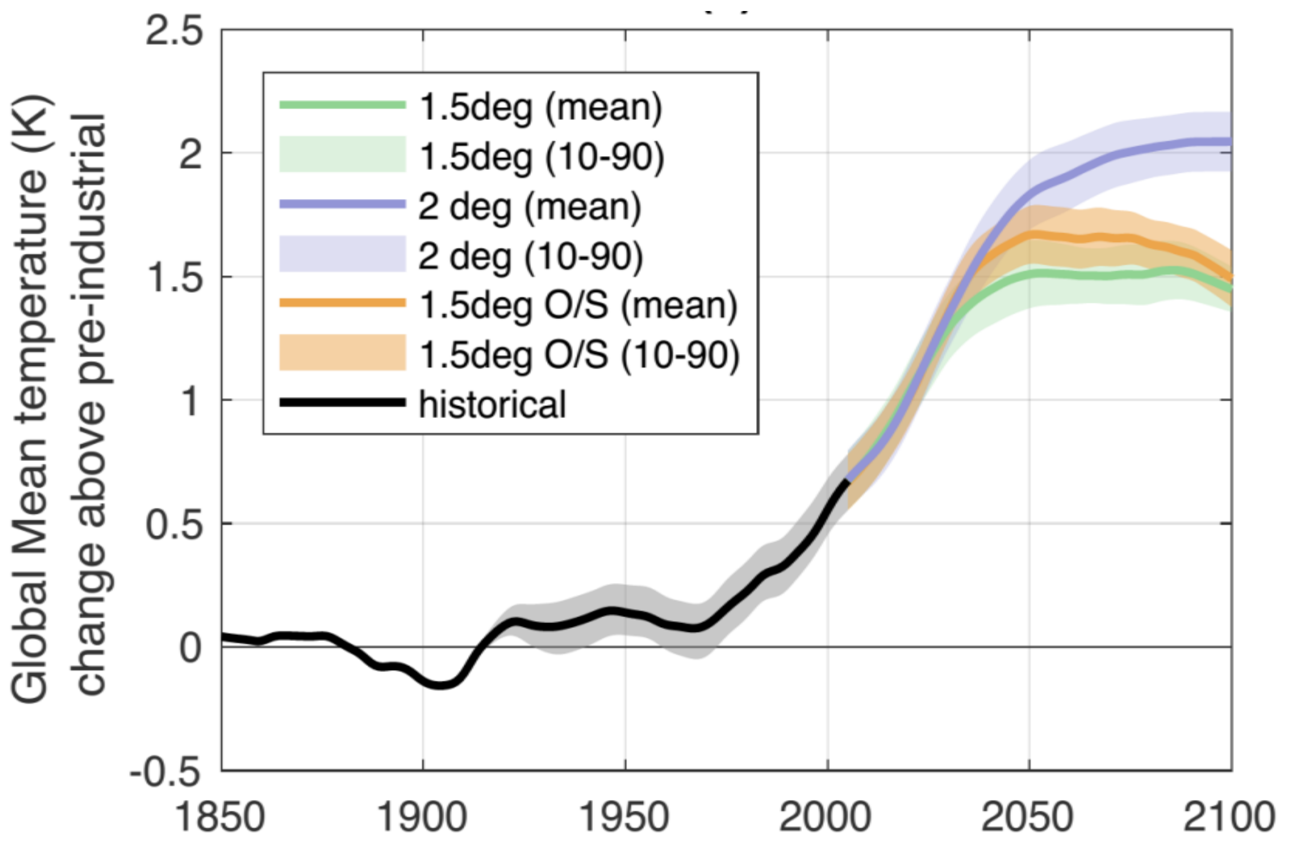
Nangombe Shingirai, Tianjun Zhou*, Wenxia Zhang, Bo Wu, Shuai Hu, Liwei Zou & Donghuan Li: Record-breaking climate extremes in Africa under stabilized 1.5C and 2C global warming scenarios. ***Nature Climate Change*** (2018) doi:10.1038/s41558-018-0145-6

CESM Low-warming experiments

Total carbon emissions trajectory



Annual global mean temperatures

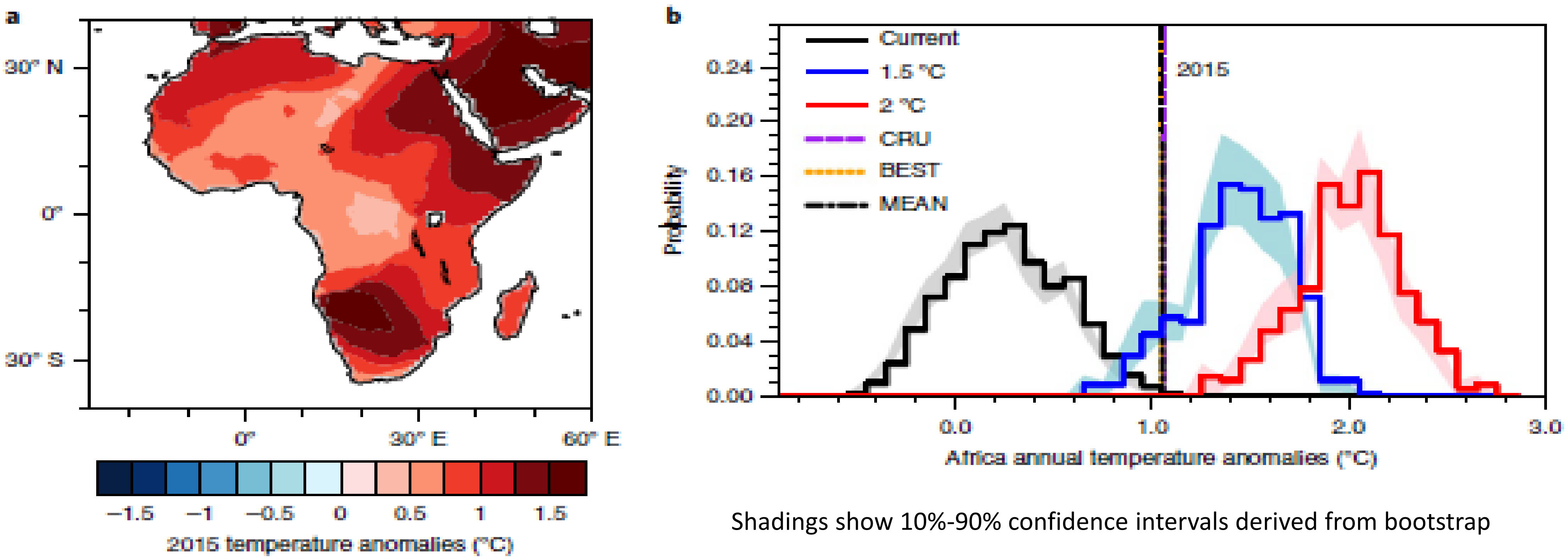


◆***1.5degNE:*** stabilizes in 2050 at 1.5 °C above pre-industrial levels

◆***2.0degNE:*** stabilizes at slightly over 2.1 °C, reaching 2.1 °C by 2090.

Sanderson et al. (2017)

Likelihood of extreme events over Africa



Shadings show 10%-90% confidence intervals derived from bootstrap

- **2015 extremely high temperature over Africa**

- 1.5°C: 91% (88%-93%)
- 2°C: 100% (100%-100%)

Nangombe S., Tianjun Zhou*, Wenxia Zhang, Bo Wu, Shuai Hu, L. Zou & D. Li: Record-breaking climate extremes in Africa under stabilized 1.5C and 2C global warming scenarios. *Nature Climate Change* (2018) doi:10.1038/s41558-018-0145-6

Extreme Precipitation

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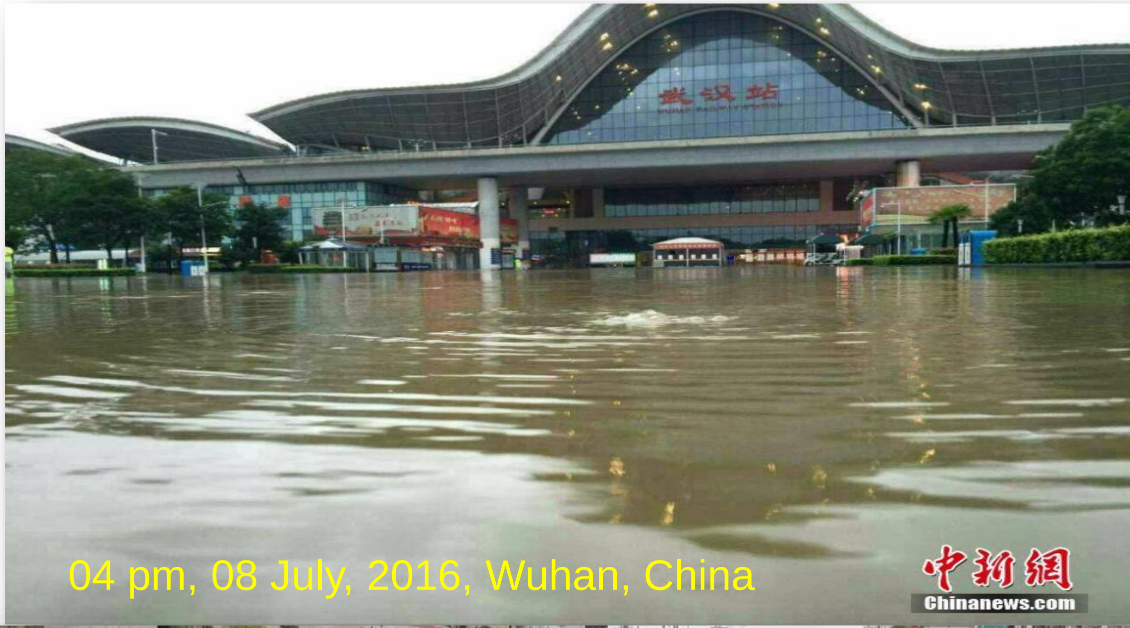
Reduced exposure to extreme precipitation from 0.5 °C less warming in global land monsoon regions

Wenxia Zhang[1,2], Tianjun Zhou[1,2], Liwei Zou[1], Lixia Zhang[1,3] & Xiaolong Chen[1]

The Paris Agreement set a goal to keep global warming well below 2 °C and pursue efforts to limit it to 1.5 °C. Understanding how 0.5 °C less warming reduces impacts and risks is key for climate policies. Here, we show that both areal and population exposures to dangerous extreme precipitation events (e.g., once in 10- and 20-year events) would increase consistently with warming in the populous global land monsoon regions based on Coupled Model Intercomparison Project Phase 5 multimodel projections. The 0.5 °C less warming would reduce areal and population exposures to once-in-20-year extreme precipitation events by 25% (18–41%) and 36% (22–46%), respectively. The avoided impacts are more remarkable for more intense extremes. Among the monsoon subregions, South Africa is the most impacted, followed by South Asia and East Asia. Our results improve the understanding of future vulnerability to, and risk of, climate extremes, which is paramount for mitigation and adaptation activities for the global monsoon region where nearly two-thirds of the world's population lives.



04 pm, 08 July, 2016, Wuhan, China

2018年7月8日，日本冈山县仓岛市
（来源：The Atlantic网站）

Reuers

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