Institute of Atmospheric Physics, Chinese Academy of Sciences

Future Changes in Global Monsoons

ZHOU Tianjun

Thanks to: CHEN Xiaolong, ZHANG Wenxia, NANGOMBE Shingirai, YAO Junchen, ZHANG Lixia

zhoutj@lasg.iap.ac.cn

http://www.lasg.ac.cn/staff/ztj/index_e.htm

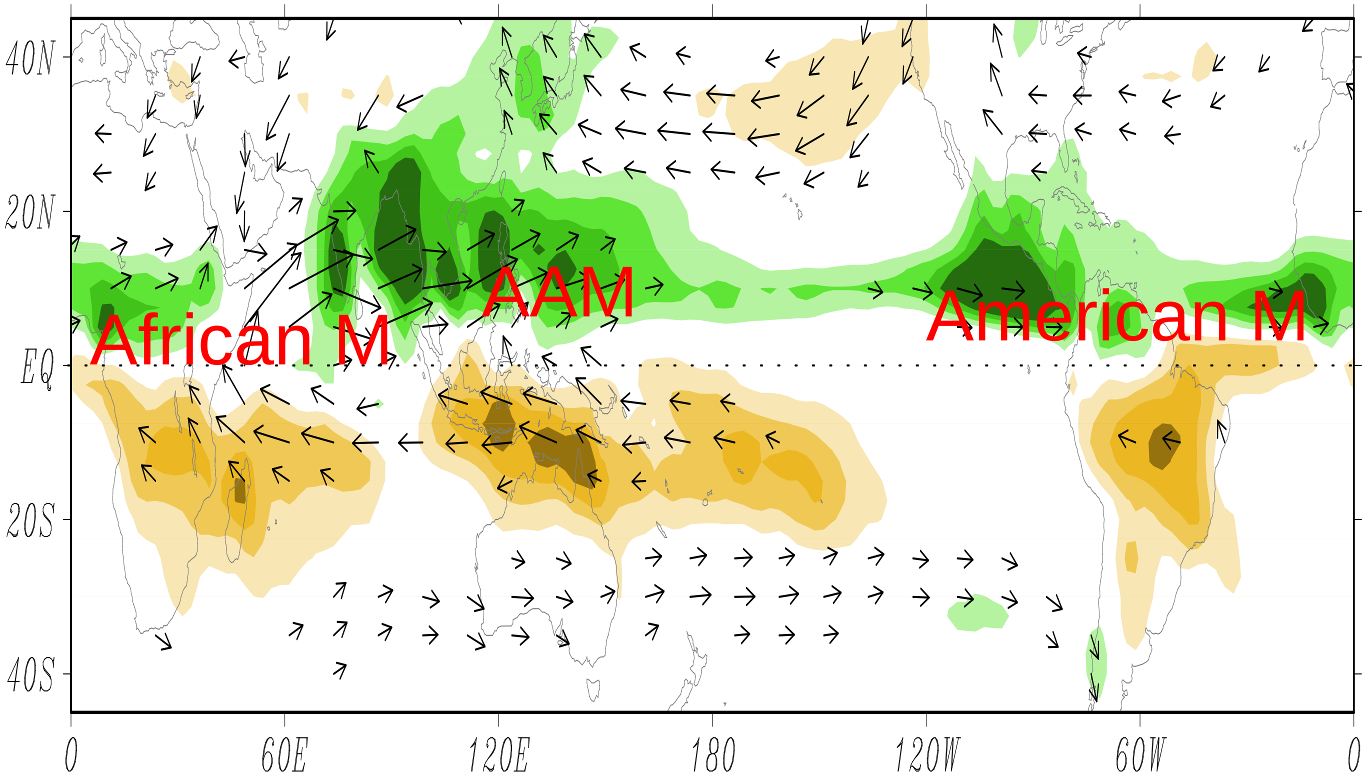
2nd WCRP Grand Challenge Meeting on Monsoons and Tropical Rain Belts

ICTP, Trieste, Italy, 2-5 July, 2018

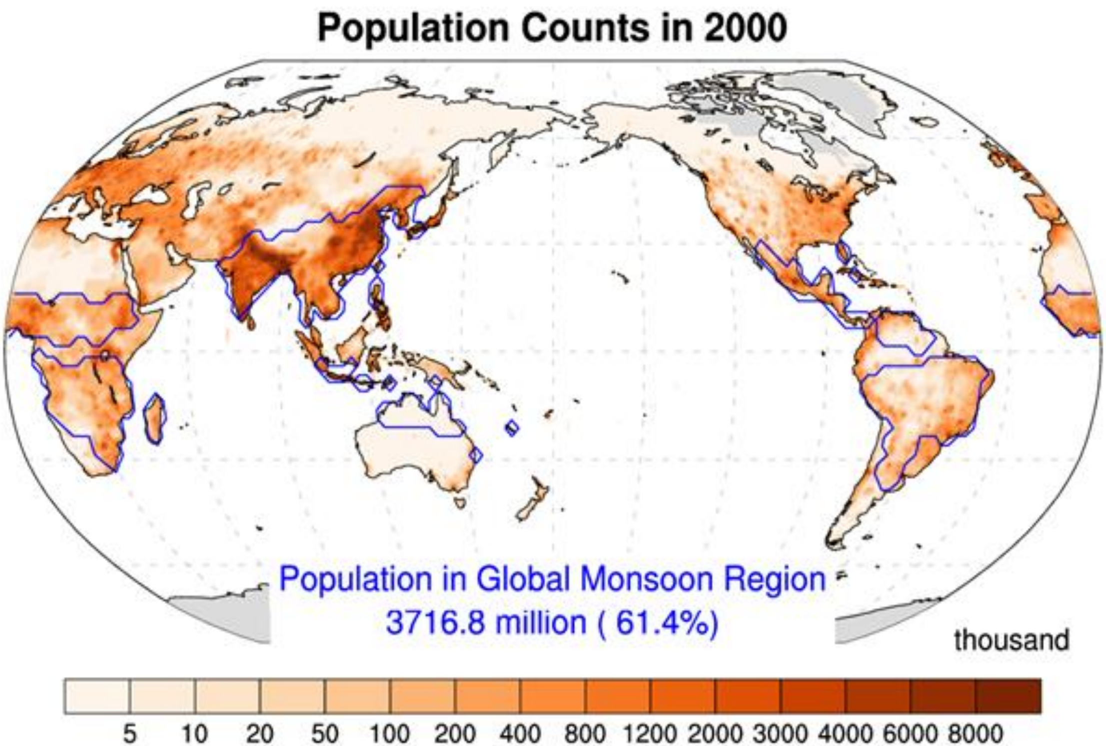
Outline

- Background: uncertainty in projection
- S. Asian monsoon: GW vs SST modulation
- E. Asian monsoon: model resolution
- Record-breaking events in Africa
- Extreme precipitation
- Summary

Global Monsoons

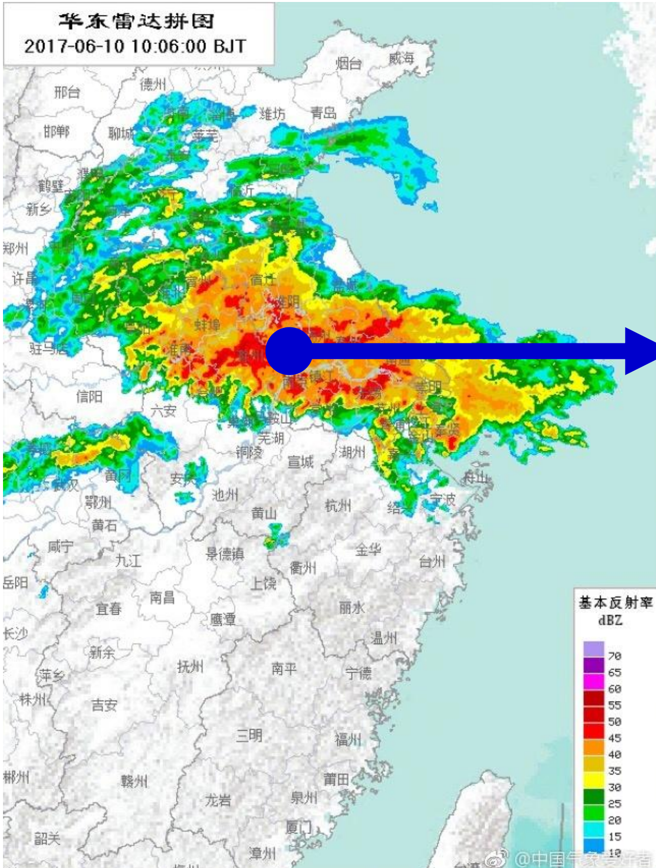


JJA –DJF UV850 & Precipitation

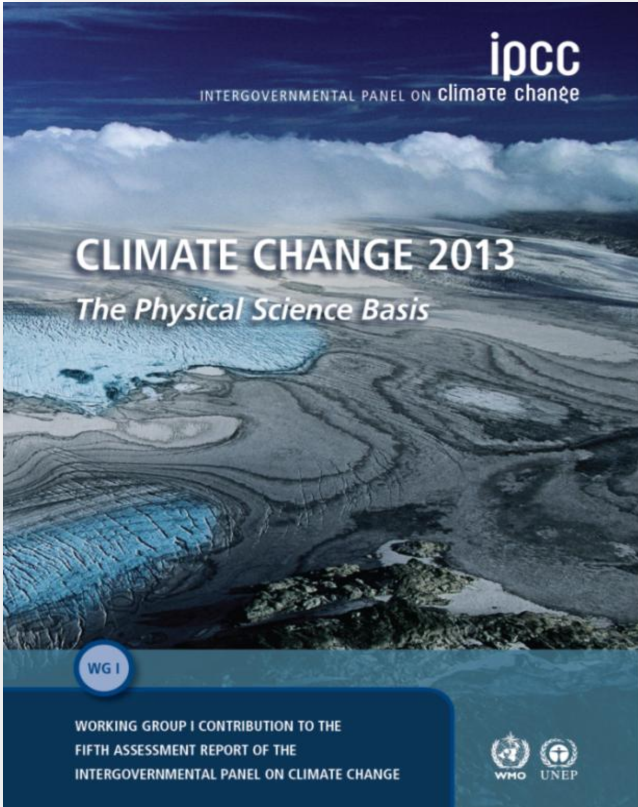


~2/3 of the population are affected by monsoon

June 10, 2017: CMA radar image, Nanjing

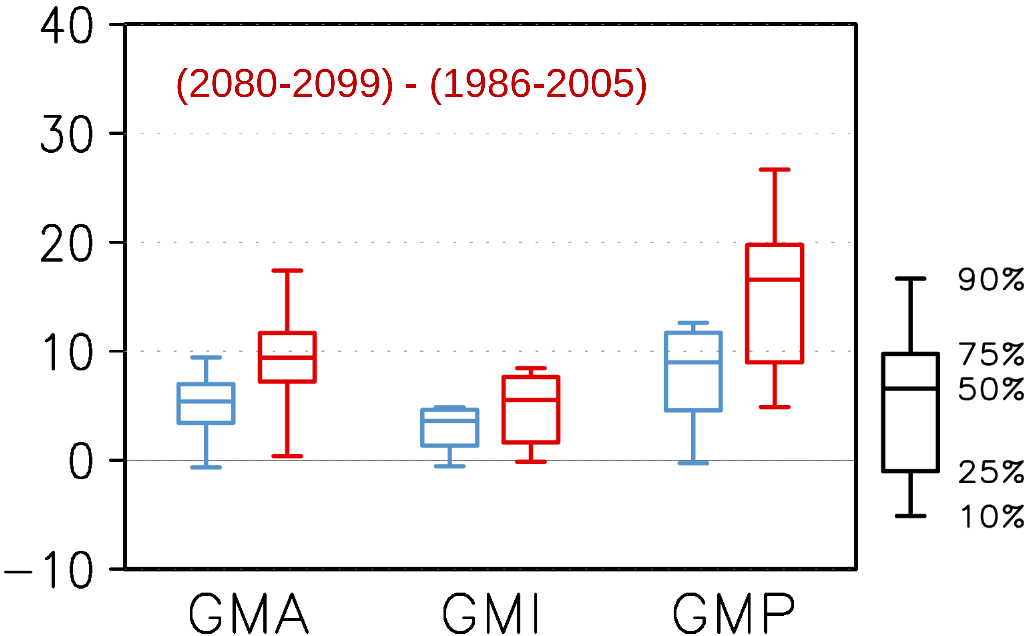



Monsoon Changes under Global warming



There is growing evidence of improved skill of climate models in reproducing climatological features of the global monsoon. *Taken together with identified model agreement on future changes, the global monsoon, aggregated over all monsoon systems, is likely to strengthen in the 21st century with increases in its area and intensity, while the monsoon circulation weakens*. *Monsoon onset dates are likely to become earlier or not to change much and monsoon retreat dates are likely to delay, resulting in lengthening of the monsoon season in many regions.*

Future change (%): GMA, GMI & GMP



GMP: global monsoon total precipitation

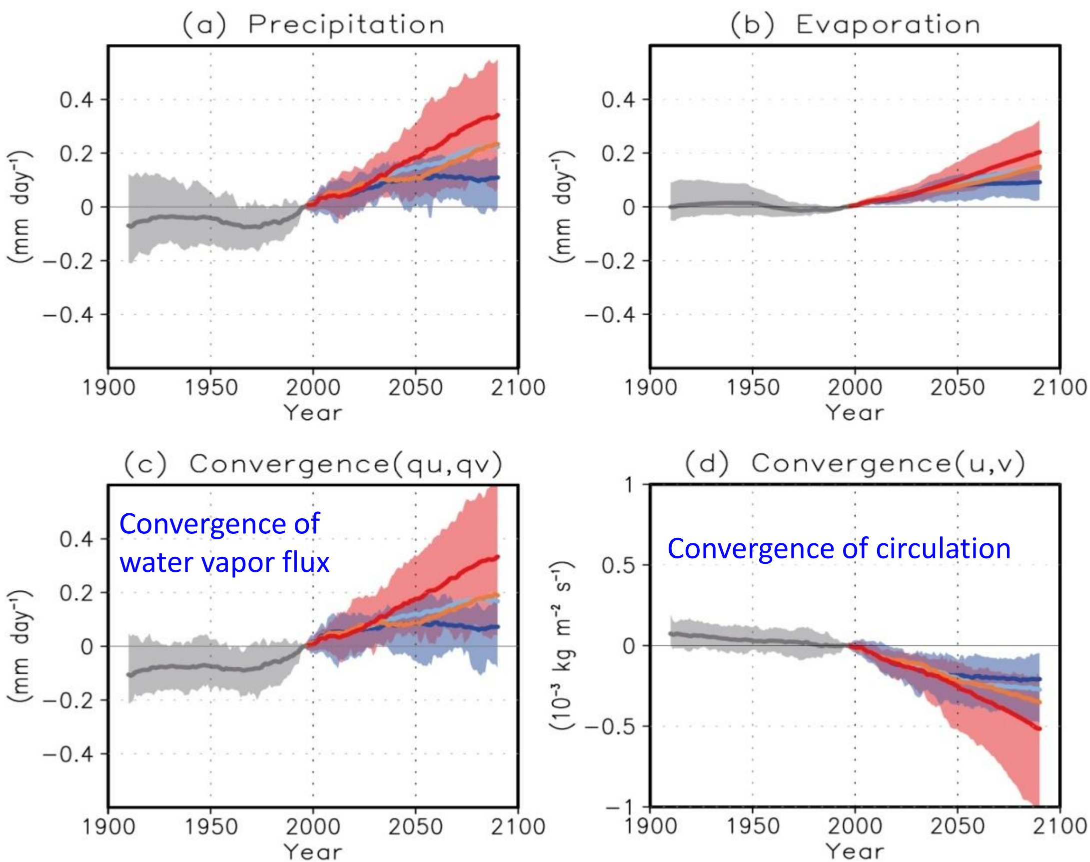
Blue: RCP4.5

Red: RCP8.5

Monsoon-related precipitation will significantly increase in a warmer climate

Kitoh, A., H. Endo, K. Krishna Kumar, I. F. A. Cavalcanti, P. Goswami, and T. Zhou, 2013: Monsoons in a changing world: a regional perspective in a global context. *J. Geophys. Res. Atmos.*, 118, doi:10.1002/jgrd.50258

An increase of moisture convergence due to increased surface evaporation and water vapor in the air column



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

Fig.14.2 IPCC AR5

Projected rainfall changes: regional difference and uncertainty

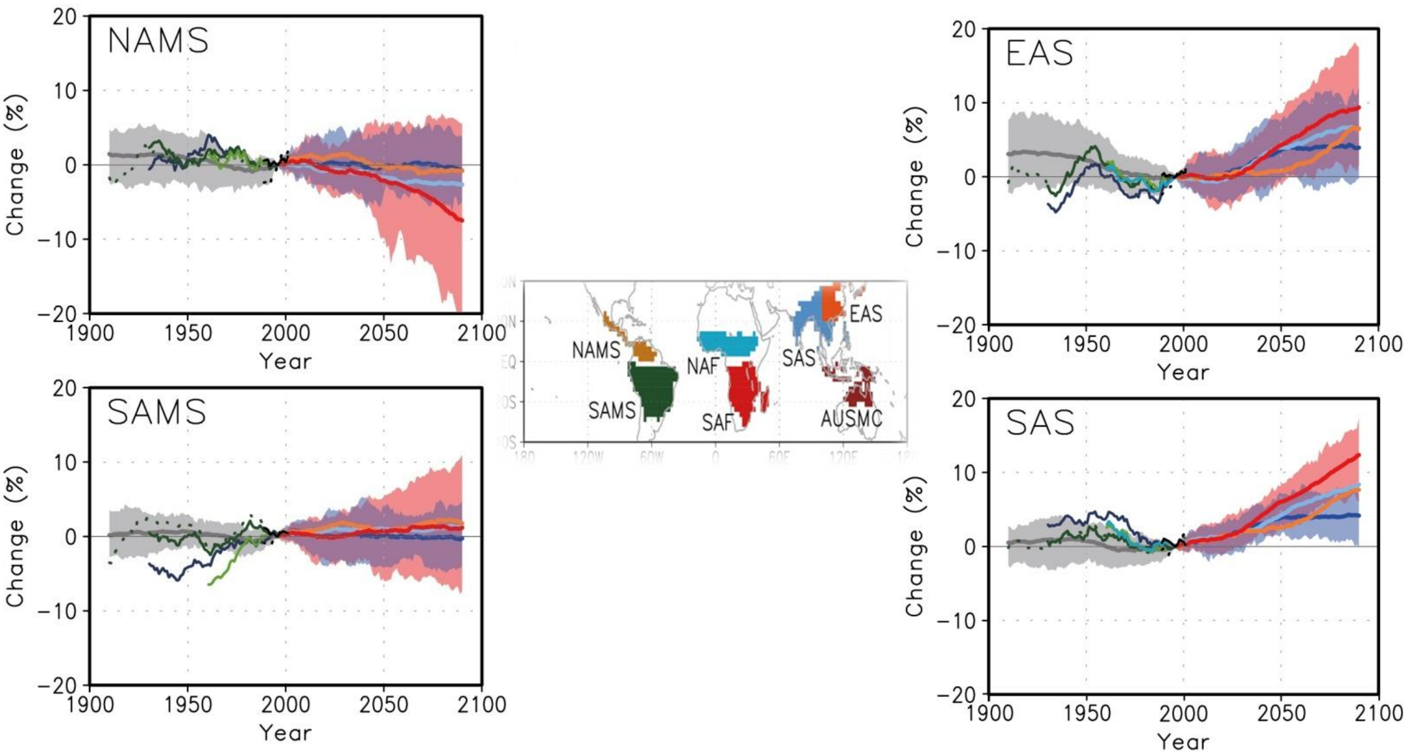
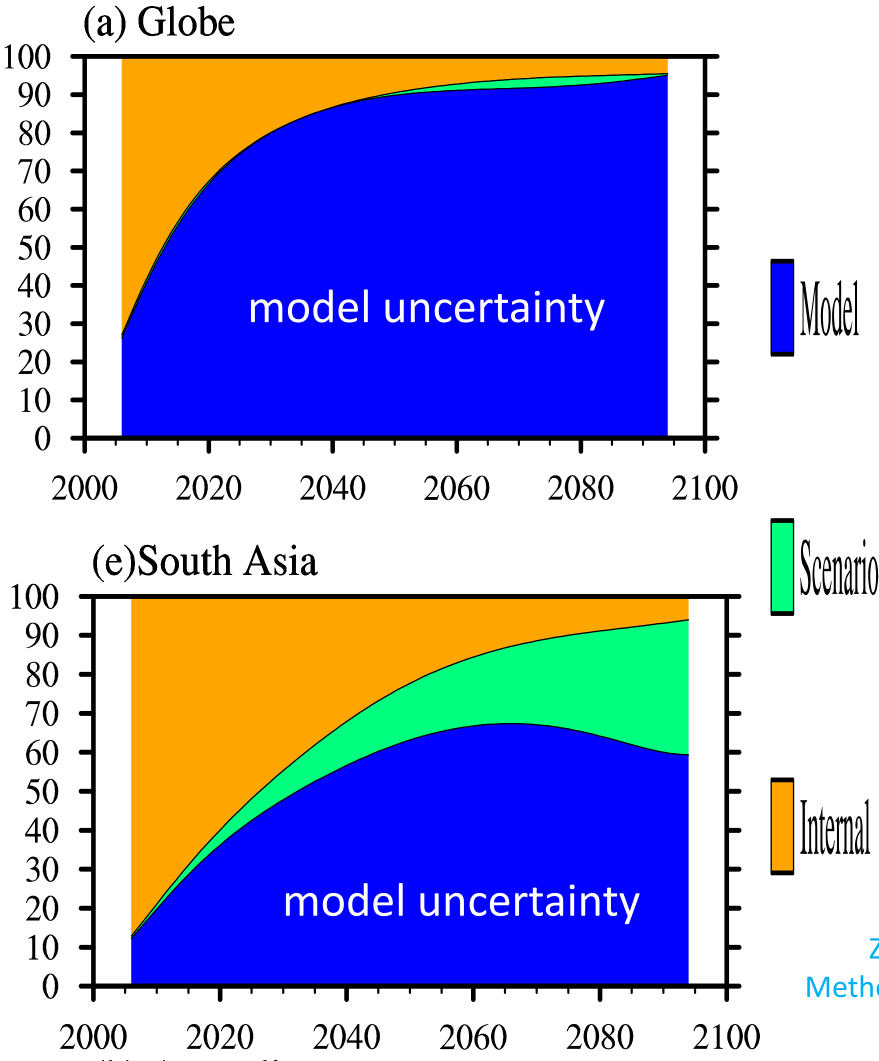


Fig.14.3, 14.4, 14.6 IPCC AR5



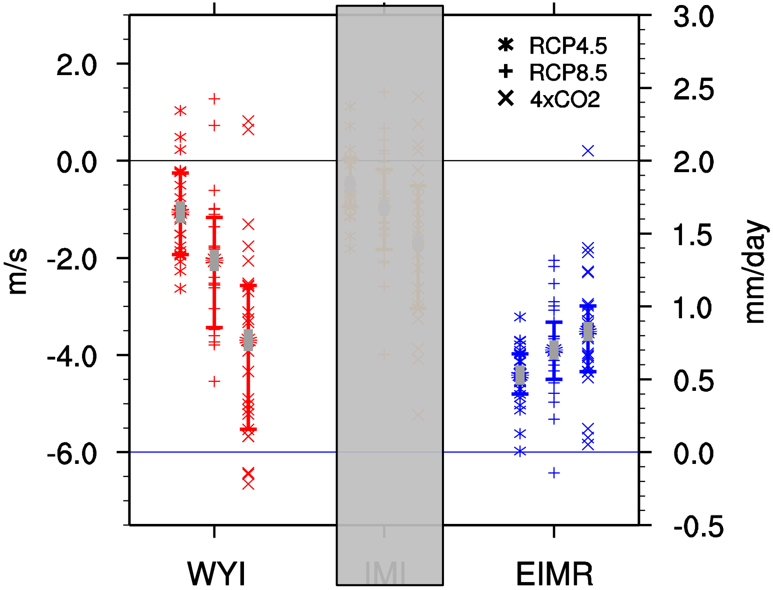
Fraction of total variance in decadal annual mean precipitation predictions **explained by the three components of total uncertainty** (relative to a 1986-2005 reference period)

Zhou and Lu, 2018 (in preparation):
Method following *Hawkins and Sutton (2009)*

Uncertainties in S. Asian monsoon projection

Uncertainty in SA Monsoon Projection

Three scenario: RCP4.5, RCP8.5, 4xCO2
Gray bar: uncertainty from internal variability

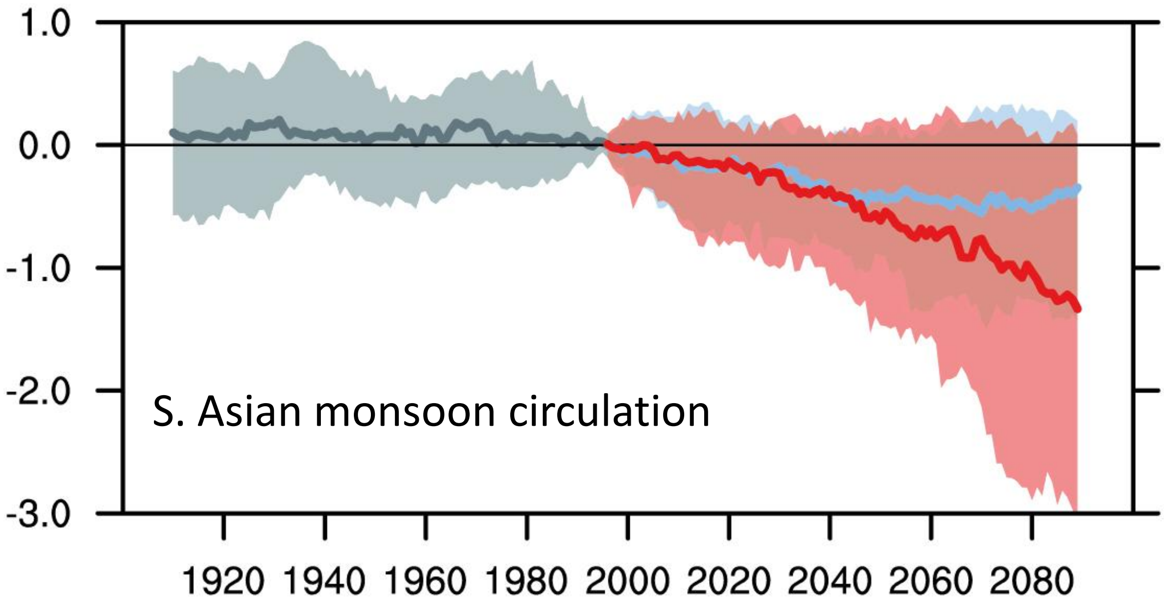


- **WYI**：Webster-Yang Index, vertical shear between 850hP and 200hPa zonal wind
- **IMI**：Indian Monsoon Index, meridional shear of 850hPa zonal wind (vorticity，monsoon trough)
- **EIMR**：Extended Indian Monsoon Rainfall, averaged rainfall over the SASM region

- **Multi-model mean: Circulation weakening and rainfall increasing.**
- **Large model spread which cannot be explained by internal variability.**

Chen, X., and T. Zhou (2015), Distinct effects of global mean warming and regional sea surface warming pattern on projected uncertainty in the South Asian summer monsoon, *Geophys. Res. Lett.*, 42, 9433–9439, doi:10.1002/2015GL066384.

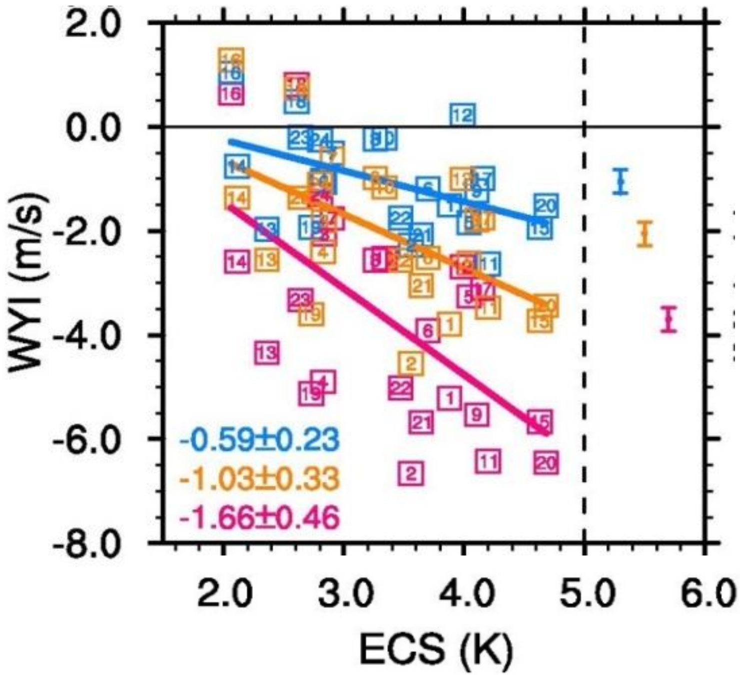
How to understand such large uncertainties in both circulation and precipitation?



Equilibrium Climate Sensitivity: $2CO_2$

SA monsoon circulation projection vs ECS across CMIP5 Models

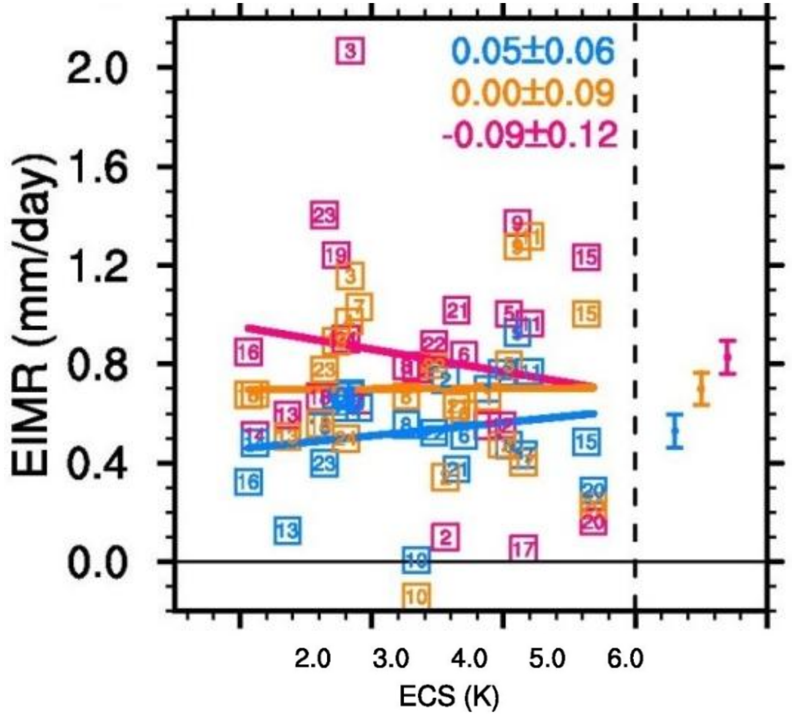
WY circulation index RCP4.5 RCP8.5 $4\times CO_2$



Higher ECS, weaker circulation.

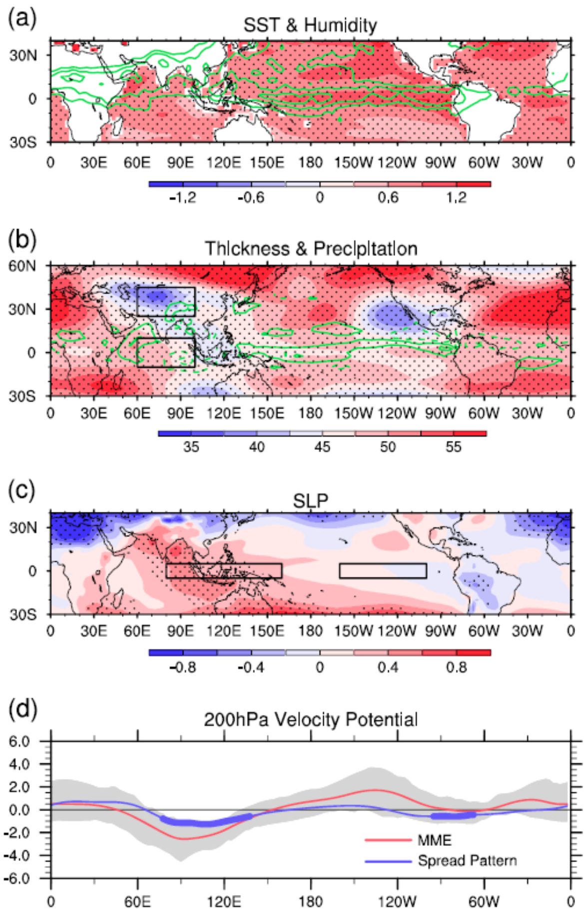
SA monsoon precipitation Projection vs ECS across CMIP5 models

Monsoon rainfall RCP4.5 RCP8.5 $4\times CO_2$



No evident relation between ECS and SASM rainfall projection

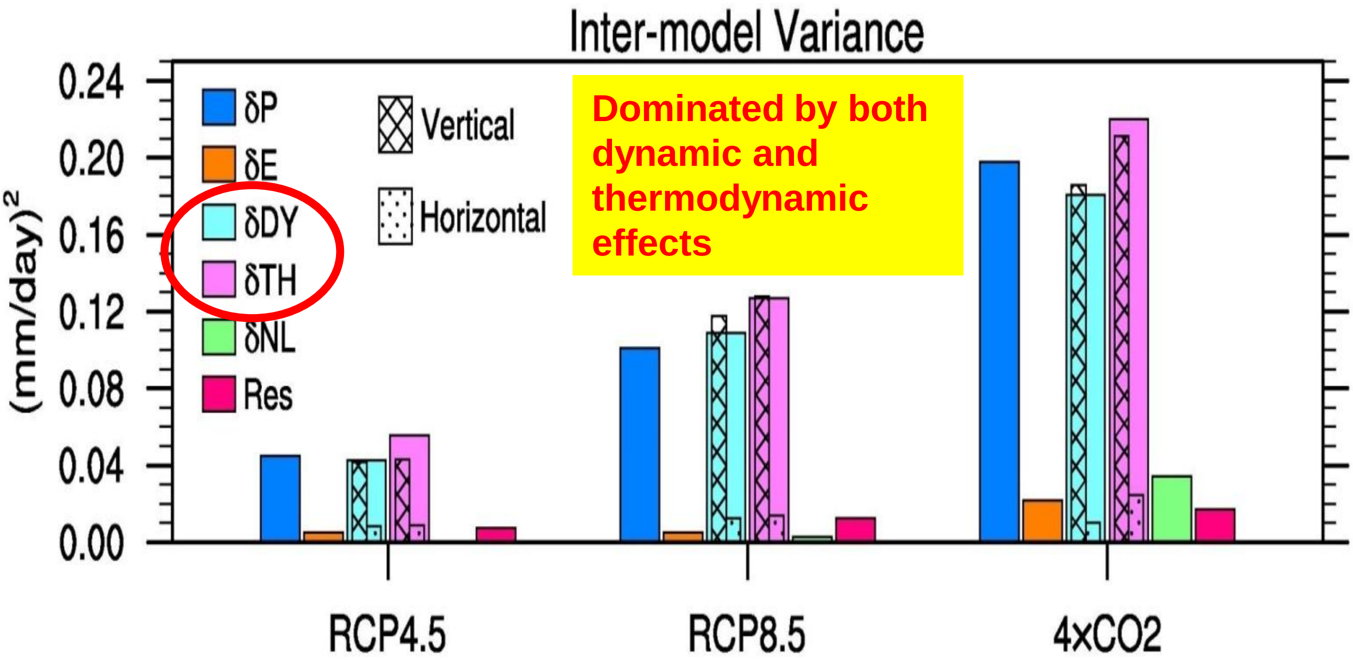
Q1: Weakened monsoon circulation associated with higher ECS?



Spread pattern regressed onto GMST

- ✓ Higher climate sensitivity, warmer upper tropical troposphere (water vapor feedback)
- ✓ weaker meridional thermal contrast , weaker tropical easterly jet.
- ✓ Stronger dry static stability, weaker Walker circulation as reported previously, weaker upper level divergence over SA
- ✓ Rossby wave response to downwelling over the maritime continent -- weaker SASM trough

Q2: Rainfall Uncertainty — Moisture Budget Diagnosis



$$\delta P = \delta E + \delta DY + \delta TH + \delta NL + Res;$$

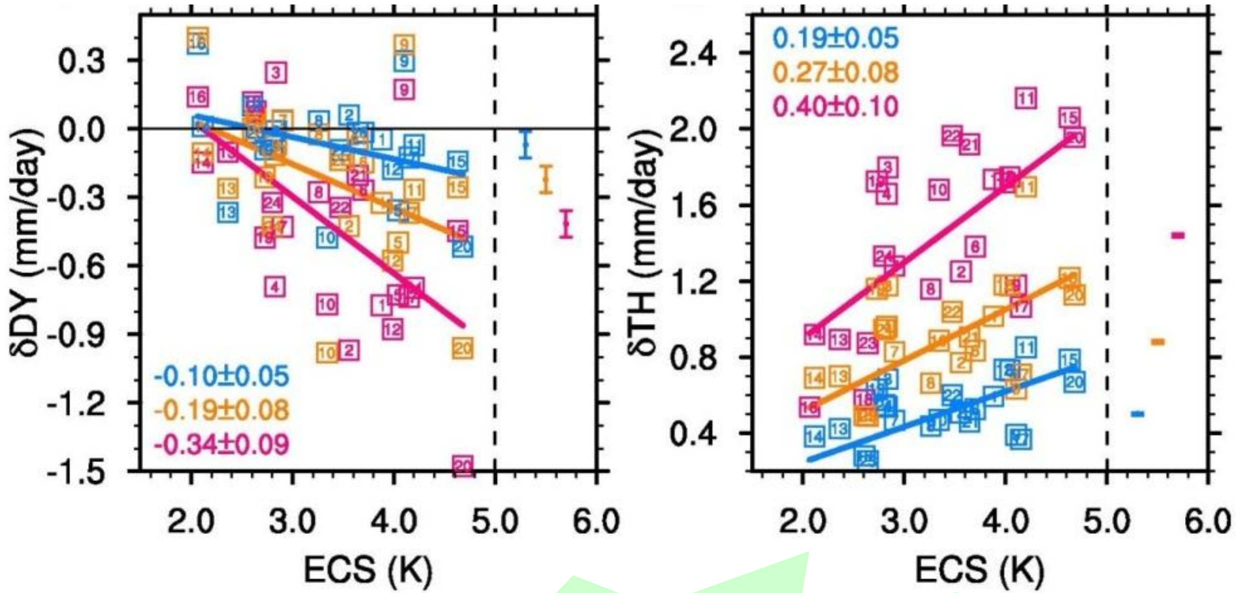
$$\delta DY = -\left(\left\langle \boxed{\delta\overline{\varpi}\partial}_{p}\overline{q}\right\rangle + \left\langle \boxed{\delta\overline{v}\bullet}\nabla\overline{q}\right\rangle\right);$$

$$\delta TH = -\left(\left\langle \overline{\varpi}\partial_{p}\boxed{\delta\overline{q}}\right\rangle + \left\langle \overline{v}\bullet\nabla\boxed{\delta\overline{q}}\right\rangle\right);$$

$$\delta NL = -\left(\delta\left\langle \overline{\omega'\partial_{p}q'}\right\rangle + \delta\left\langle \overline{v'\bullet\nabla q'}\right\rangle\right).$$

Rainfall Uncertainty — Moisture Budget Diagnosis

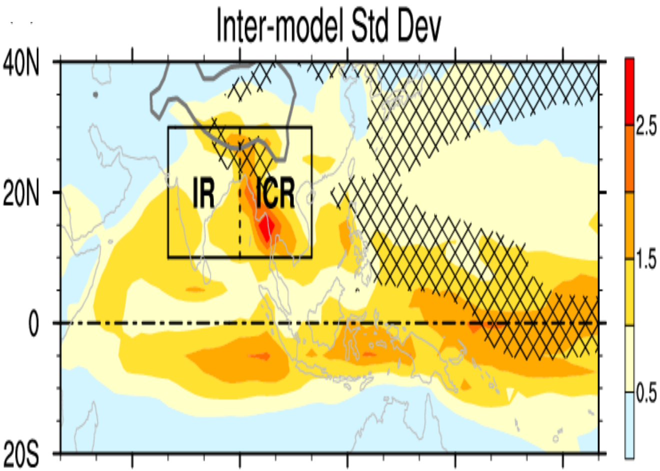
Dynamic **Thermodynamic**

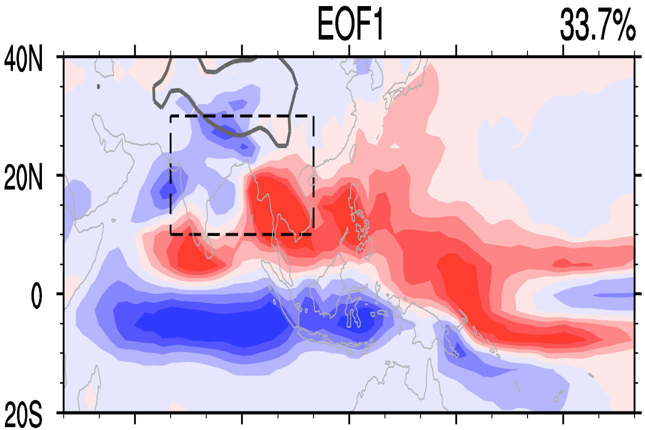


The offset between two terms: Weaker circulation but more water vapor

Uncertainty Mode of Rainfall: Inter-model EOF

RCP85

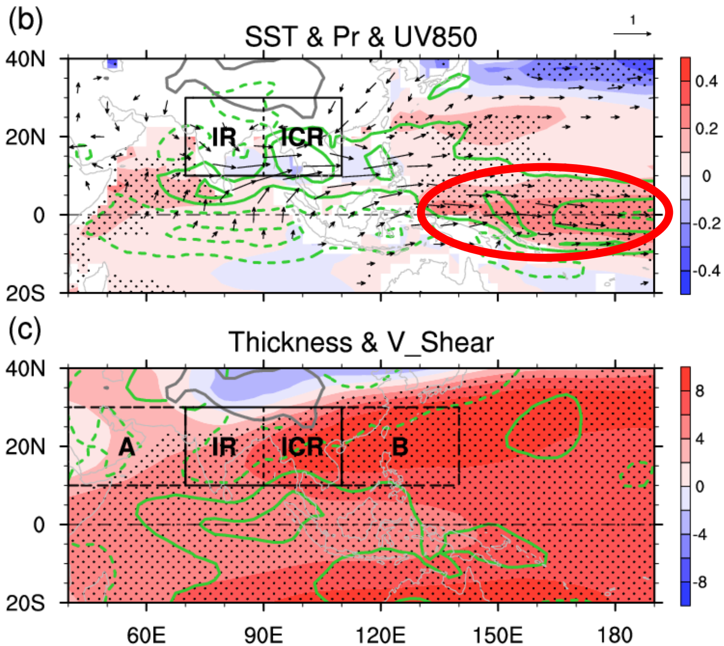




Cross shading: signal larger than noise

Uncertainty mode: dipole between Indian region (IR) and Indo-China region (ICR)

Inter-model Anomalies regressed onto PC1



Shading: SST

Contour：Rainfall

Vector：850hPa UV

Westerly anomalies as Lindzen-Nigam response

Shading: 500-200hPa Temp.

Contour：Vertical shear of meridional wind (Monsoon Hadley Circulation defined by Goswami et al. 1999**)**

Warmer SST in equatorial western Pacific → Stronger Convection

Stronger Convection → Descending over equatorial South Indian Ocean → Convergence of equator-crossing flow → Increasing ICR

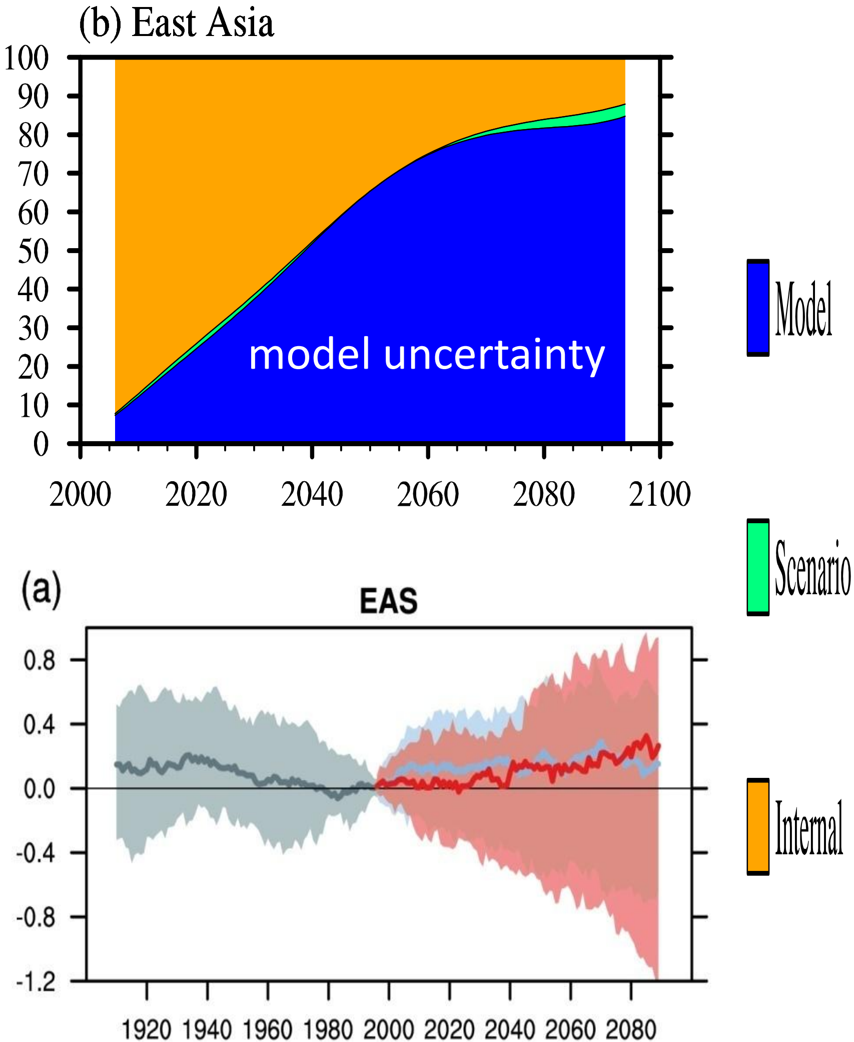
Stronger Convection → Weaker zonal temperature gradient → Weaker monsoon Hadley circulation → Decreasing IR

Interim summary 1

- Uncertainty in global mean warming (climate sensitivity) can explain most of the model spread in the projected SASM circulation except for the rainfall.
- Failure of global mean warming in scaling the regional rainfall spread is caused by equivalent effects of weakened circulation and increased moisture.
- The spread of SASM rainfall projection is resulted from the warming uncertainty in the equatorial western Pacific through modulating inter-hemispheric moisture transport and zonal temperature gradient over the SASM region.

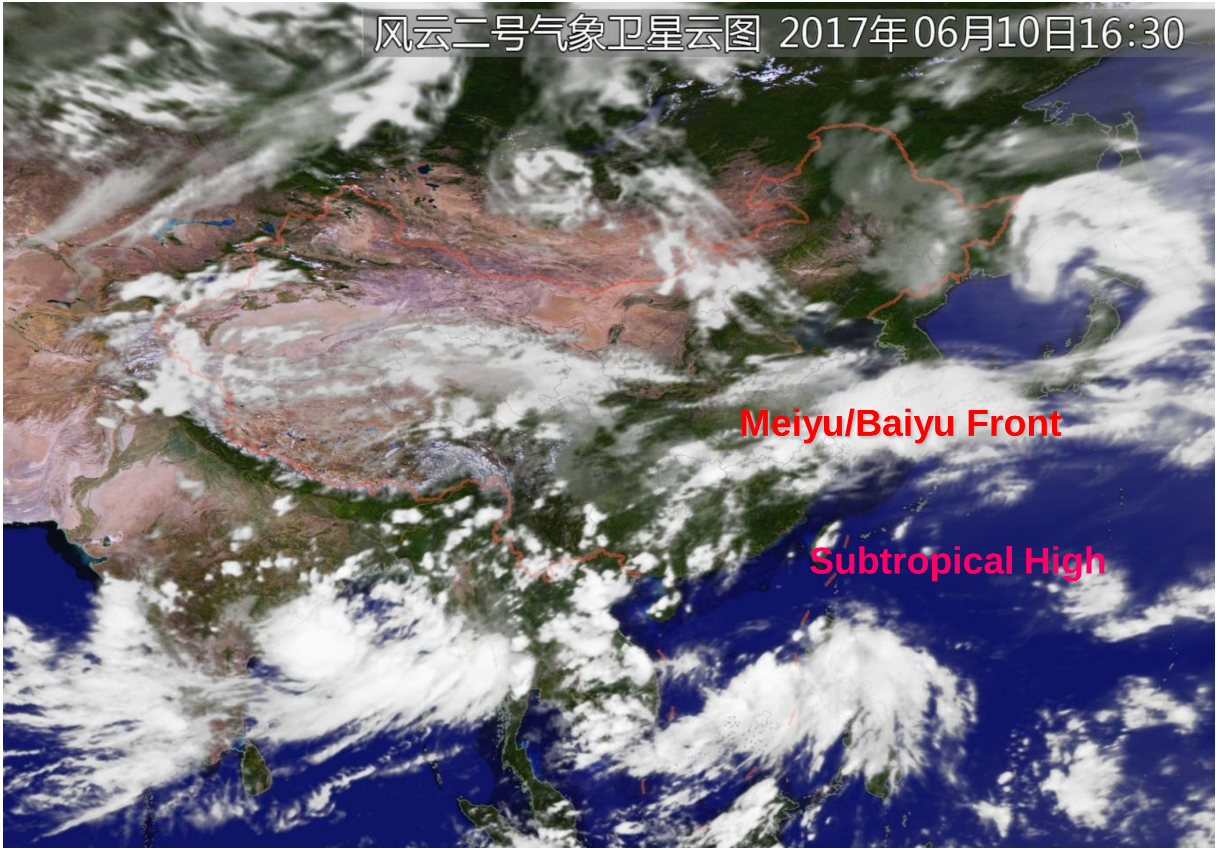
Chen, X., and T. Zhou (2015), Distinct effects of global mean warming and regional sea surface warming pattern on projected uncertainty in the South Asian summer monsoon, ***Geophys. Res. Lett.***, 42, 9433–9439, doi:10.1002/2015GL066384.

Uncertainties in E. Asian monsoon projection



Uncertainties in E. Asian summer monsoon projection

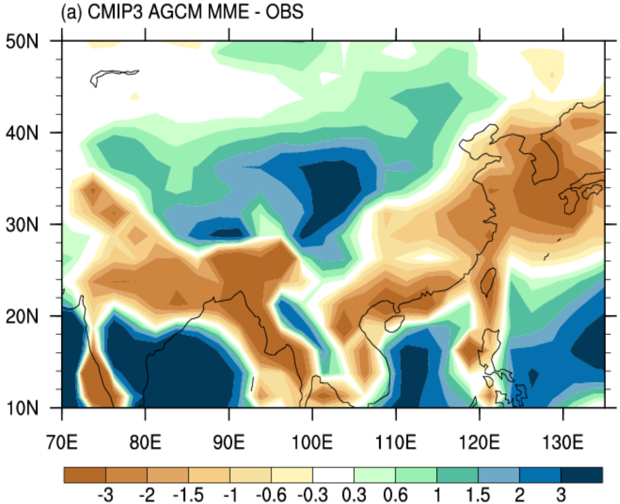
June 10, 2017: FY2 cloud image for the flooding along the Yangtze River valley



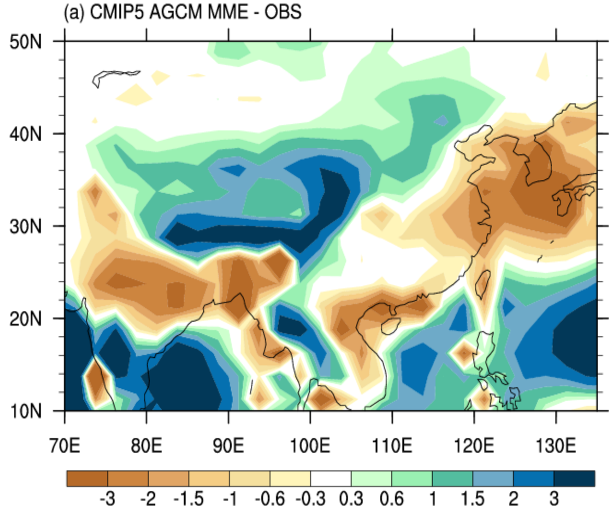
http://www.nmc.cn/publish/observations/china/dm/weatherchart-h000.htm

Challenges in the simulation of monsoon rain band

CMIP3



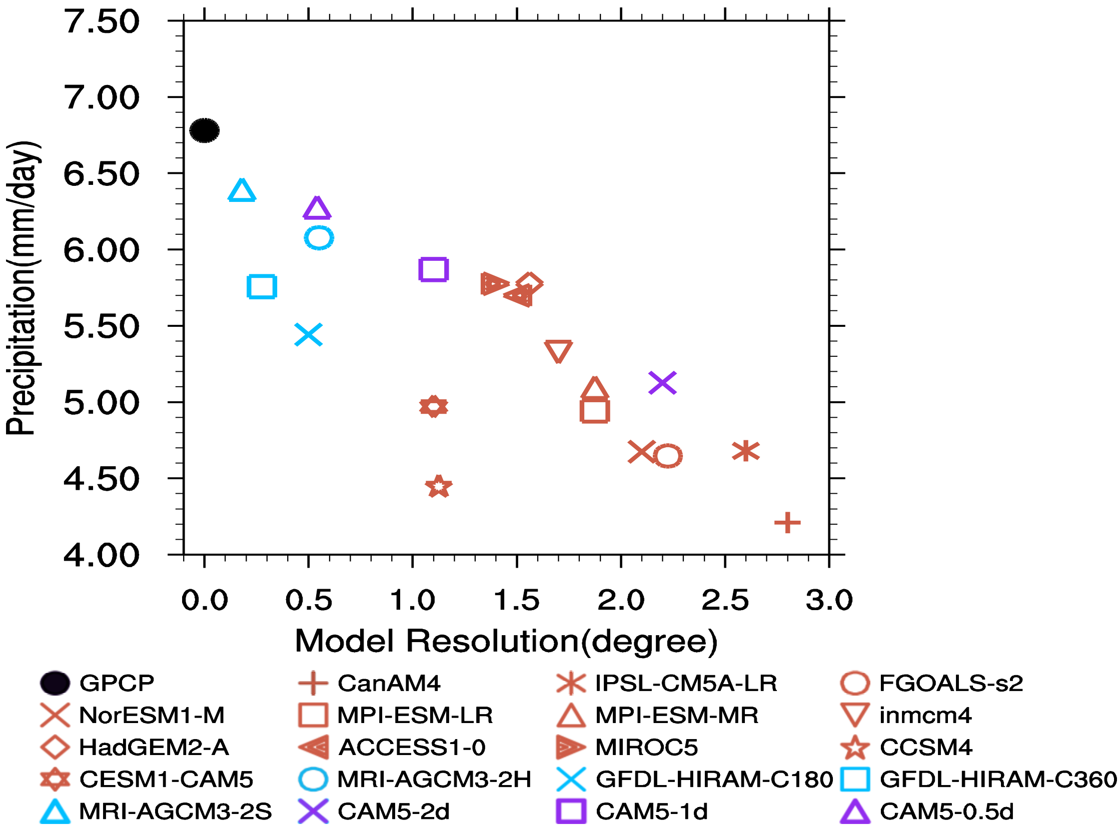
CMIP5



Mean state bias of JJA rainfall in CMIP3 & CMIP5 models

Zhou et al. 2018

Monsoon (Meiyu) rainfall across the models



Yao J., **T. Zhou***, Z. Guo, X. Chen et al. , 2017: Improved performance of High-Resolution Atmospheric Models in simulating the East-Asian Summer Monsoon Rainbelt. ***Journal of Climate*** 30(21), 8825-8840, https://doi.org/10.1175/JCLI-D-16-0372.1

Moist Static Energy (MSE) budget analysis

$$\overline{<\frac{\partial M}{\partial t}>} = \overline{F_{net}} - \overline{<v\cdot\nabla M>} - \overline{<\omega\frac{\partial h}{\partial p}>}$$

≈ 0

$<\frac{\partial h}{\partial p}>$ Usually <0 at deep convection area

thus where $\overline{\omega\left\langle\frac{\partial h}{\partial p}\right\rangle}$>0 represent for ascending motion area

The left hand of upper equation usually ≈0.Thus the right hand could be written as:

$$\overline{\omega\frac{\partial h}{\partial p}} = \overline{F_{net}} - \overline{<v\cdot\nabla M>}$$

The vertical motion can be estimated as the result of radiation and advection term.

Chou and Neelin 2003; Neelin 2007; Chou et al. 2013

Decomposition of horizontal moist enthalpy advection

$\boldsymbol{X}=c_pT+L_vq$ $\mathbf{V}=(u,v)$

$$<\overline{\mathbf{v}\cdot\nabla X}>=<[\overline{\mathbf{v}}]\cdot[\overline{\nabla X}]>+<[\overline{\mathbf{v}}]\cdot\overline{\nabla X^*}>+<\overline{\mathbf{v}^*}\cdot[\overline{\nabla X}]>+<\overline{\mathbf{v}^*}\cdot\overline{\nabla X^*}>+<\overline{\mathbf{v}'\cdot\nabla X'}>$$

- Pure zonal mean moist enthalpy advection (small magnitude)
- Advection of stationary eddy energy by the zonal-mean flow
- Advection of zonal-mean energy by eddy flow
- Pure stationary eddy term
- Pure transient term

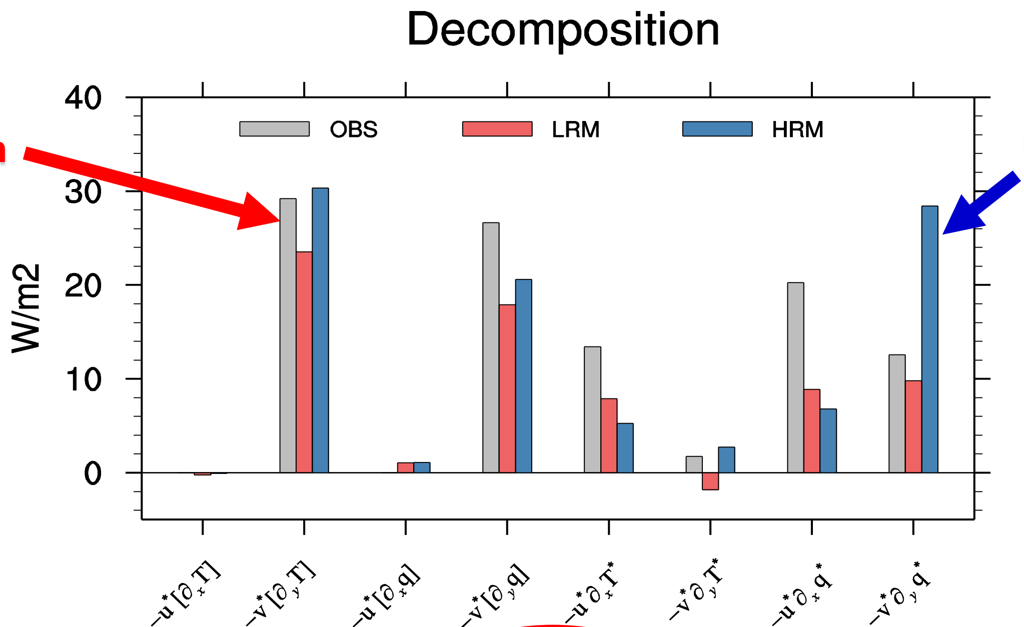
X' denotes the deviation from time $\bar{X}$ (two-month June and July mean for each individual year), and X^* denotes the deviation from the global zonal mean $[X]$. T and q are listed as energy units.

Eddy flow: deviation from the global zonal mean

Decomposition of total horizontal moist enthalpy advection term

dry term

Advection of zonal mean dry energy by eddy meridional flows



moist term

Advection of eddy moist energy by eddy meridional flows

Zonal mean energy by eddy flow

$$< \overline{\mathrm{v}^* \cdot [\nabla M]} > = < \overline{\mathrm{u}^* \cdot [\partial_x T]} > + < \overline{\mathrm{v}^* \cdot [\partial_y T]} > + < \overline{\mathrm{u}^* \cdot [\partial_x q]} > + < \overline{\mathrm{v}^* \cdot [\partial_y q]} >$$

Pure eddy advection

$$< \overline{\mathrm{v}^* \cdot \nabla M^*} > = < \overline{\mathrm{u}^* \cdot \partial_x T^*} > + < \overline{\mathrm{v}^* \cdot \partial_y T^*} > + < \overline{\mathrm{u}^* \cdot \partial_x q^*} > + < \overline{\mathrm{v}^* \cdot \partial_y q^*} >$$

Averaged over the enhanced rainfall region (25°~ 34°N, 120°~ 155°E; units: W/m^2). Each variable is vertically integrated. The observation is the mean of ERA-interim and JRA55.

Dry term versus Moist term

Shading

Contours

$-<\overline{v^* \cdot [\partial_y T]}>$

dry term

$<\overline{v^*}>$

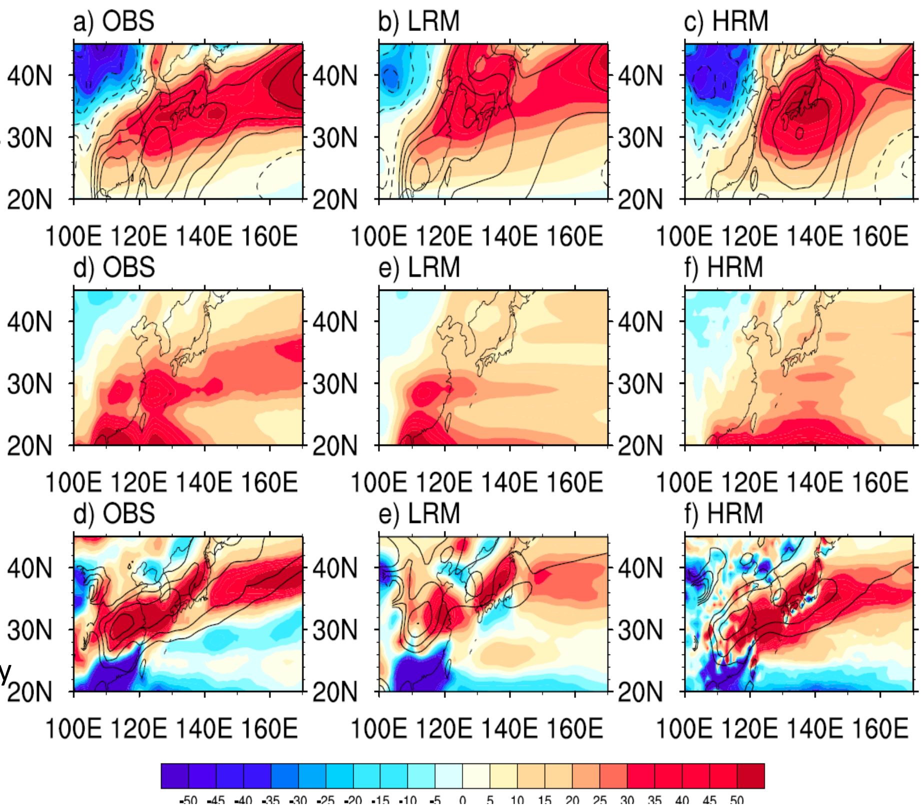
$-<\overline{v^* \cdot \partial_y q^*}>$

moist term

$-<\overline{\partial_y q^*}>$

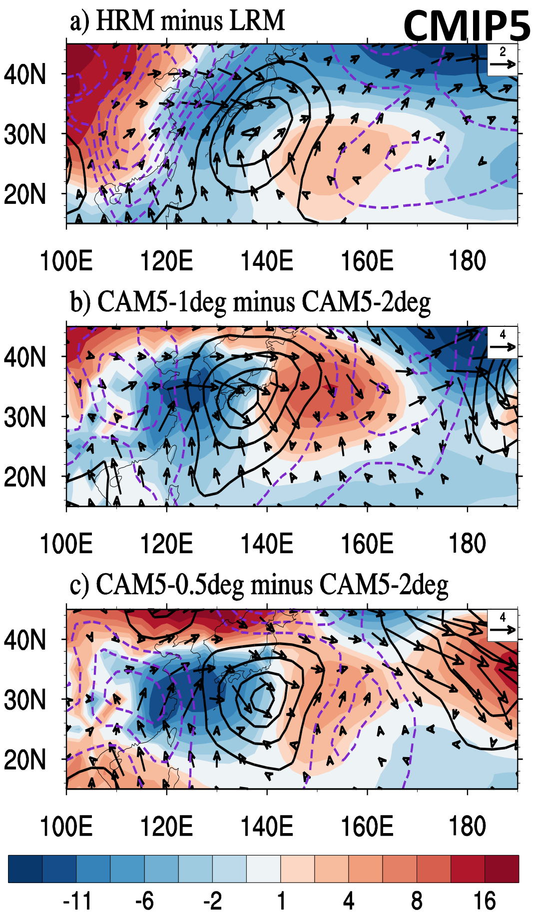
meridional eddy specific humidity gradient

$\overline{\partial_y v^*}$ at 700 hPa



The enhanced energy transport along the MB rain belt in the HRMs is resulted from **the enhanced meridional eddy velocity and its convergence in the HRMs**

Sensitivity Experiments: Mechanisms



500 hPa

Shaded: geopotential height

Contour: meridional eddy velocity

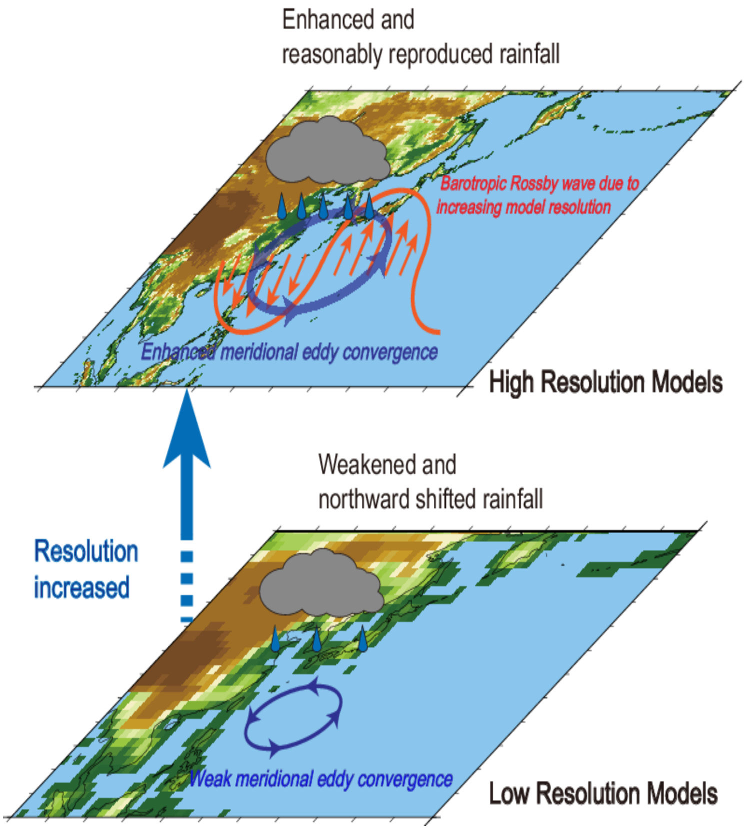
Vector: wave activity flux

The differences of Zg and v* between HRMs and LRMs.

◆Rossby wave like pattern generated downstream of Tibetan Plateau.

◆WAFs transport eastward from Tibetan Plateau to far east of North Pacific ocean.

Schematic of the mechanism for the improvement of high-resolution models



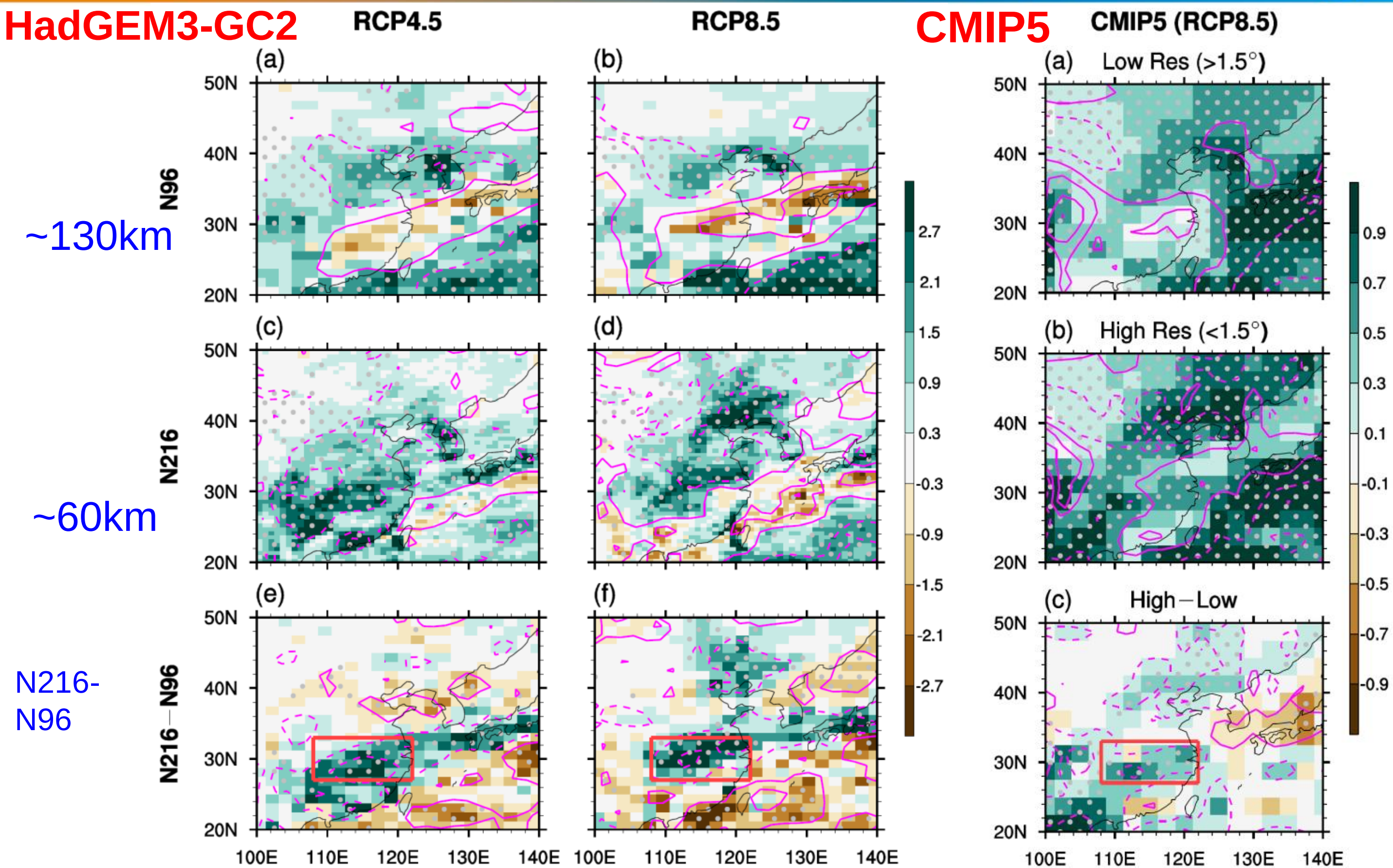
- Due to increasing model resolution, a barotropic Rossby wave like response downstream of the Tibetan Plateau is generated.
- It further intensifies meridional convergence and moisture convergence along the EASM rain belt.
- Thus, the EASM rain belt is improved in the high-resolution models.

Yao J., **T. Zhou***, Z. Guo, X. Chen et al. , 2017: Improved performance of High-Resolution Atmospheric Models in simulating the East-Asian Summer Monsoon Rainbelt. ***Journal of Climate*** 30(21), 8825-8840, https://doi.org/10.1175/JCLI-D-16-0372.1

Implications?

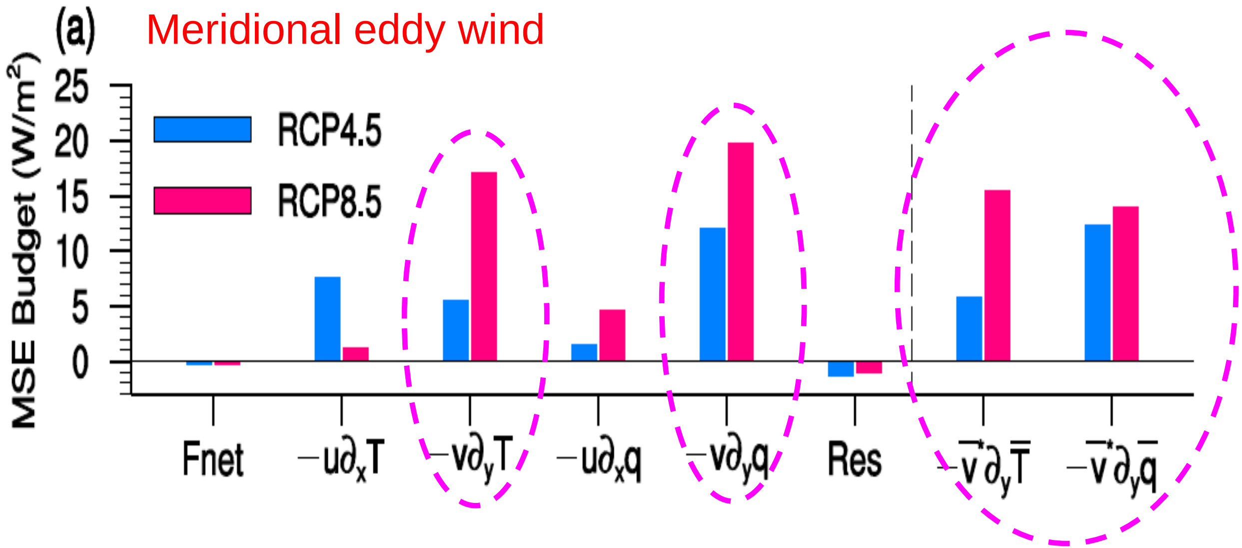
Potential underestimation of future monsoon rainfall with CMIP5 models

Dependence of rainfall projection on model resolution



Shading: rainfall Contour: p-velocity

Difference between N216 and N96 projection: MSE Diagnosis



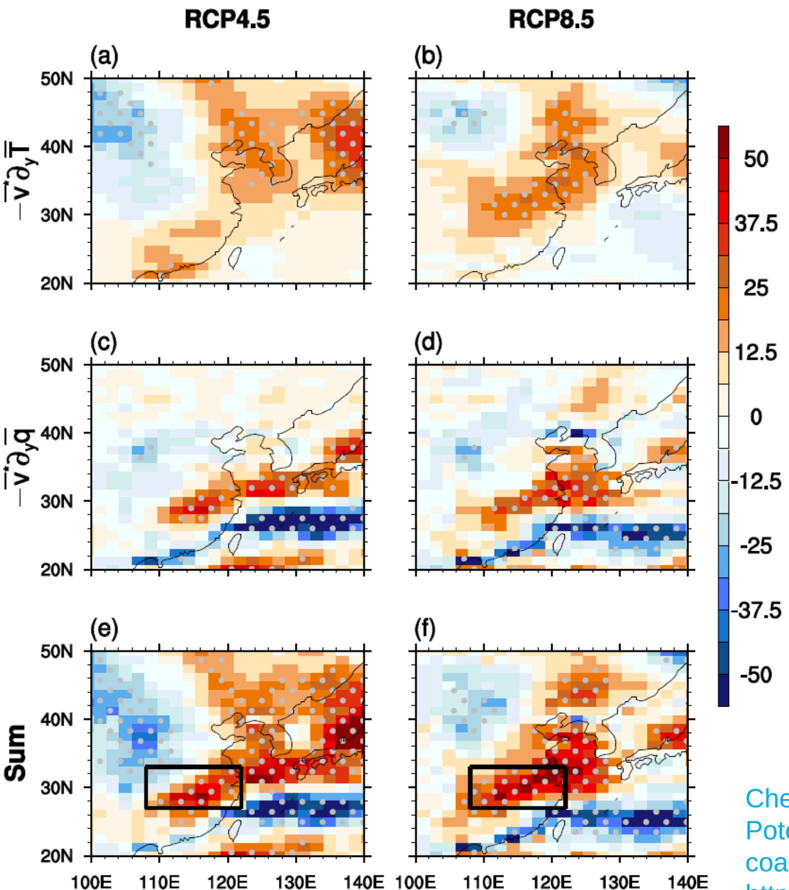
$$\overline{\langle \omega \partial_p h \rangle} = \overline{F_{\mathrm{net}}} - C_{\mathrm{p}}\overline{\langle \boldsymbol{V} \cdot \nabla T \rangle} - L_{\mathrm{v}}\overline{\langle \boldsymbol{V} \cdot \nabla q \rangle}$$

$$h = c_p T + L_v q + gz$$

h always increases with height.

$\overline{\langle \omega \partial_p h \rangle}$ > 0 means upward motion

Difference between N216 and N96 projection: MSE Diagnosis



Meridional eddy wind advects climatological temperature and moisture to the Meiyu front

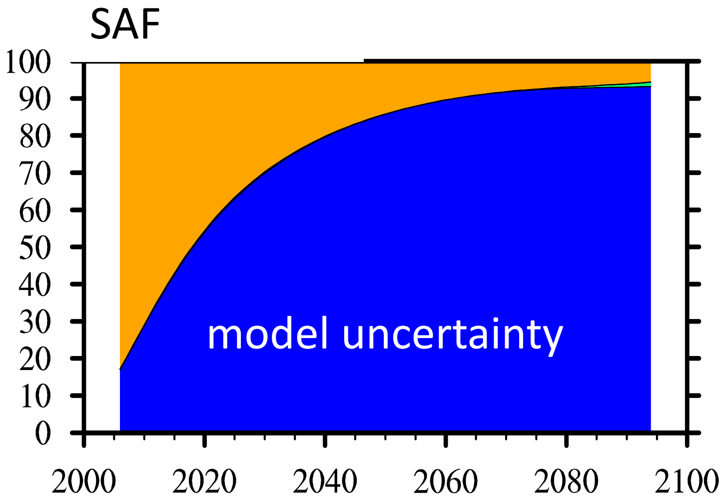
$$-\bar{v}^*\partial_y\bar{T} \;\&\; -\bar{v}^*\partial_y\bar{q}$$

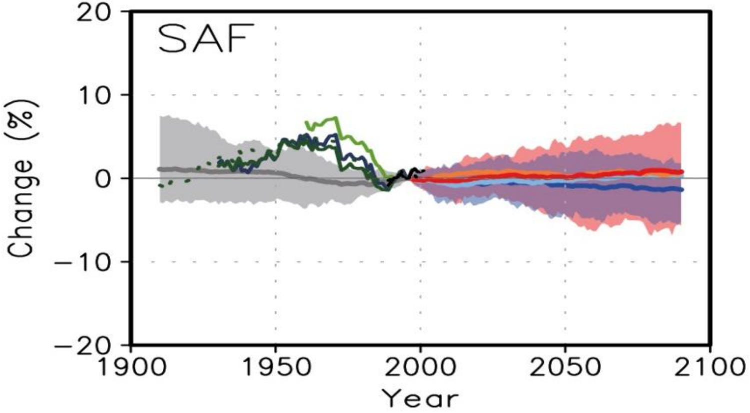
Chen, X., P. Wu, M.J. Roberts, and T. Zhou*, 2018: Potential underestimation of future Mei-yu rainfall with coarse resolution climate models. ***J. Climate***, https://doi.org/10.1175/JCLI-D-17-0741.1

Interim Summary 2

- A Rossby wave like response to realistic orography of the Tibetan Plateau helps to improve the simulation of monsoon rainband over East Asia.
- The projections of E. Asian summer monsoon rainfall has been underestimated by CMIP5 models.
- A higher resolution is favorable for transporting more moisture to the monsoon front region, thus increasing the projected rainfall over there.

Chen, X., P. Wu, M.J. Roberts, and T. Zhou*, 2018: Potential underestimation of future Mei-yu rainfall with coarse resolution climate models. ***J. Climate***, https://doi.org/10.1175/JCLI-D-17-0741.1





Implication for the projection of African rainfall

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

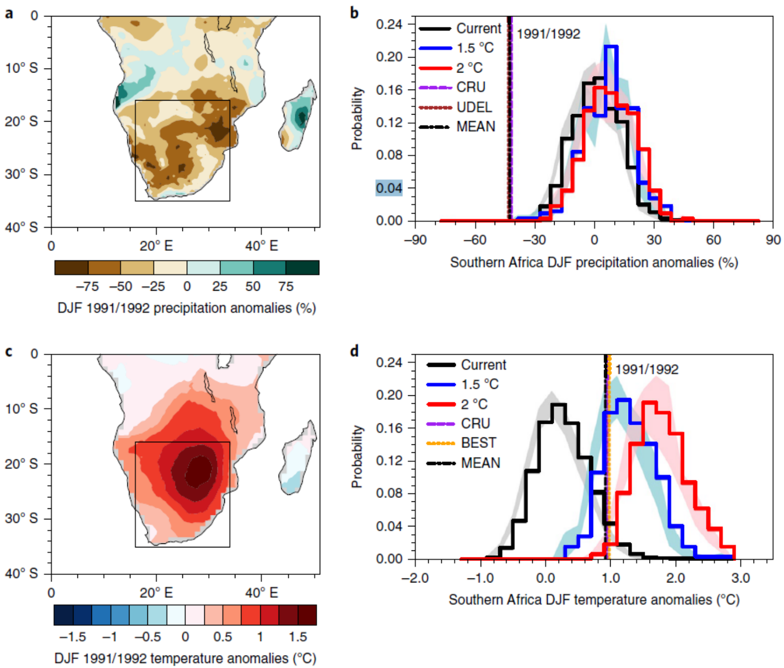
(4) Severe drought of 1991/92 over southern Africa

✓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

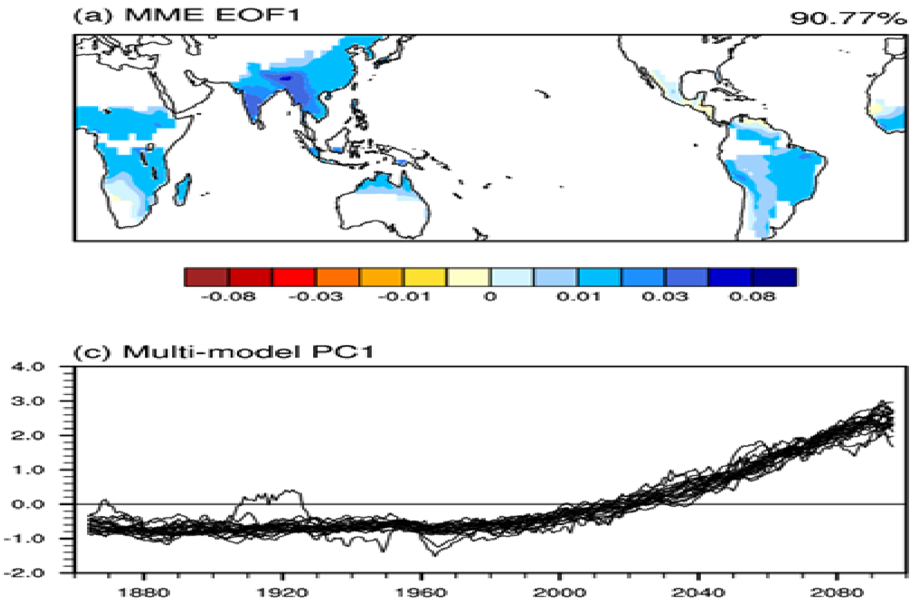
- **1991/92 DJF extreme high temperature over southern Africa**
- 1.5°C: 74% (70%-78%)
- 2°C: 98% (97%-100%)

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

Nangombe Shingirai, Tianjun Zhou*, W. Zhang, B. Wu, S. 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 rainfall projection

The leading EOF of RX5day in CMIP5 RCP8.5 Projection



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

Data: daily precipitation from 27 CMIP5 models: *historical* + *RCP4.5/RCP8.5*

Zhang et al., 2018:

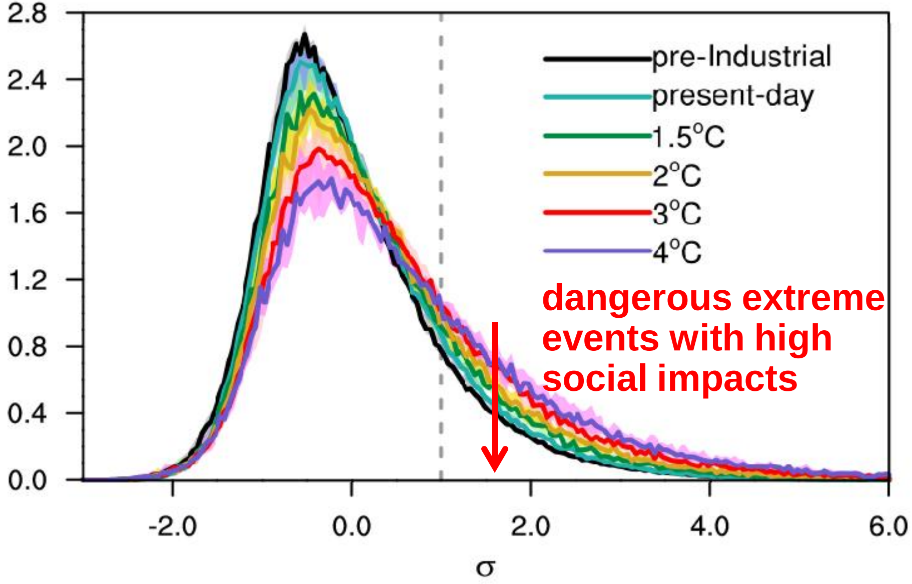
The Goal of Paris Climate Agreement

"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".

What are the reduced exposure to extreme precipitation in 0.5° C less warming?

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

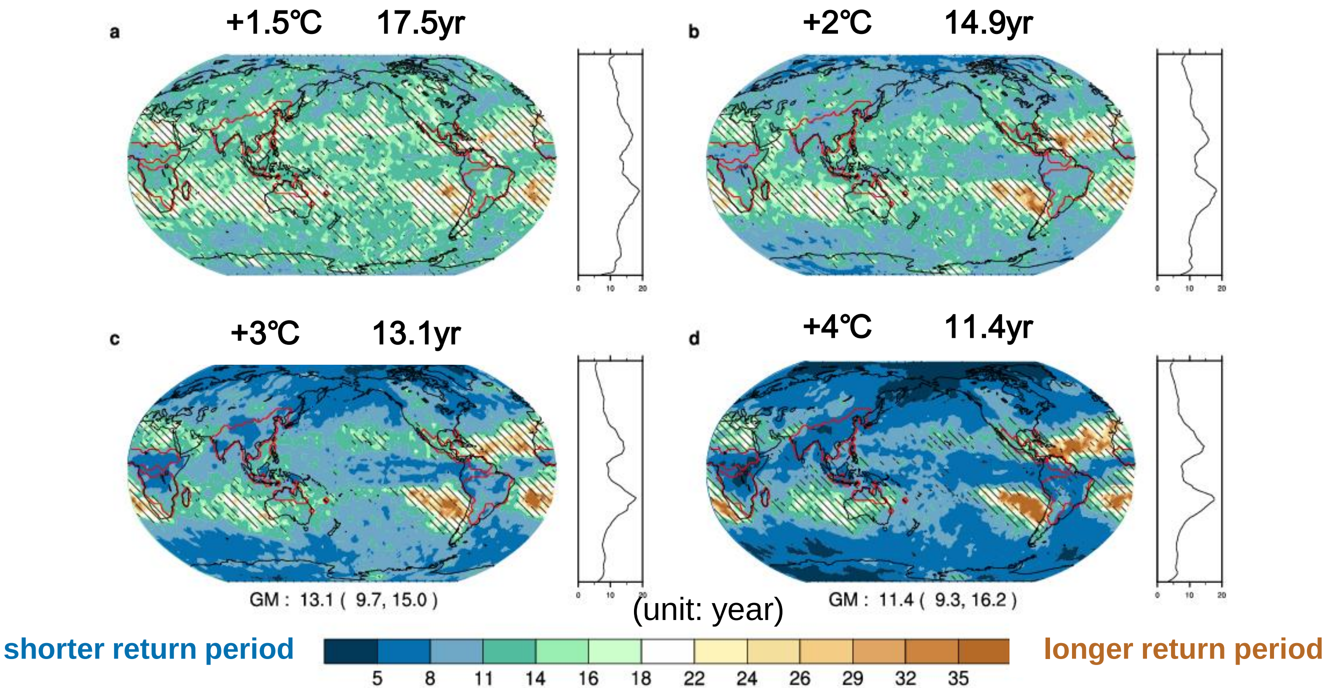
Two-folded response of extreme precipitation

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

Zhang et al., 2018:

Changes in return periods under warming conditions

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



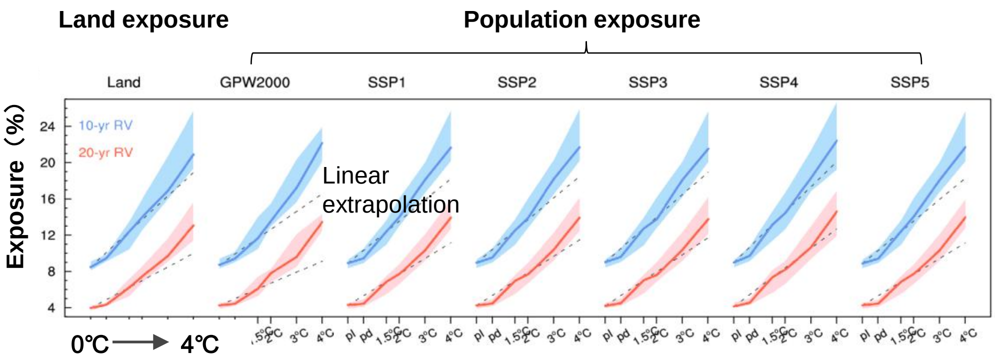
Shorter return periods for dangerous extremes are expected under further warming conditions.

Zhang et al., 2018:

Increases in exposure with global warming levels

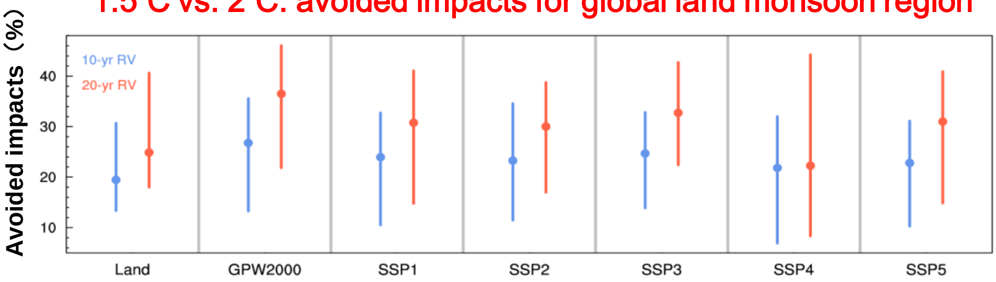
once-in-10-year events

once-in-20-year events



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

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

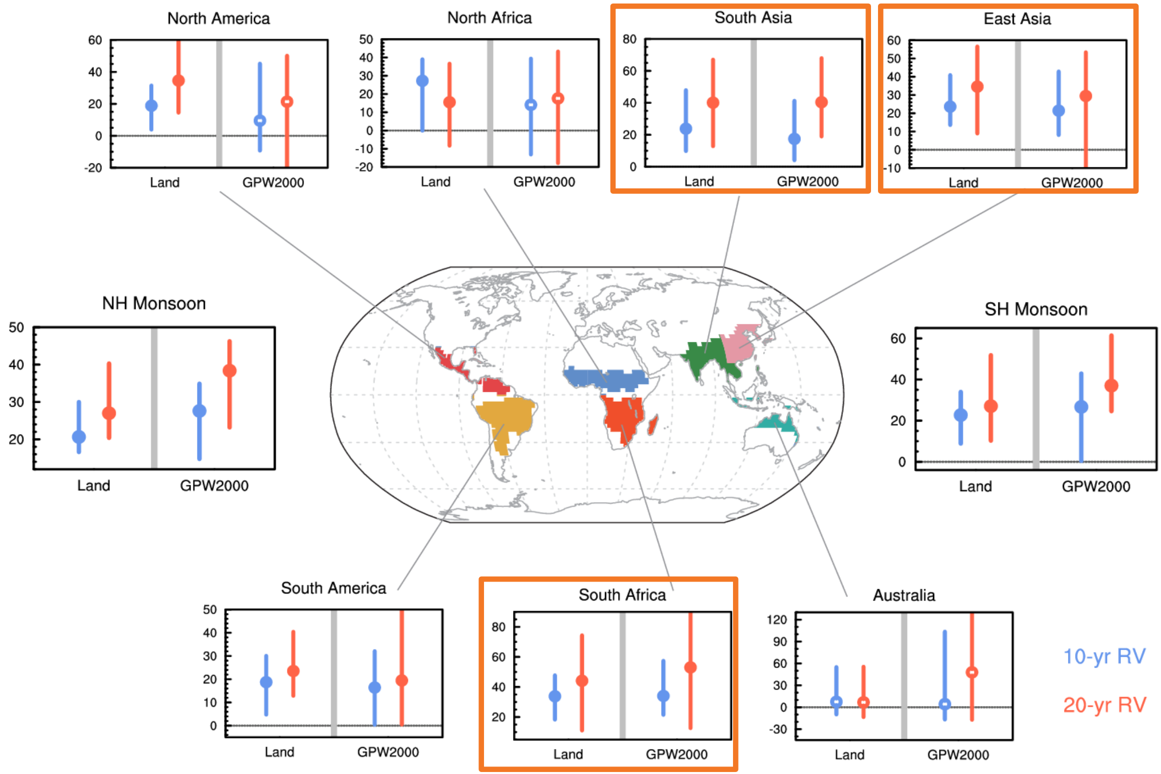


$$Avoided\ Impact = \frac{EXP_{2^\circ C} - EXP_{1.5^\circ C}}{EXP_{present-day}} \times 100\%$$

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

Zhang et al., 2018:

Avoided impacts: regional hotspots



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

Zhang et al., 2018:

Interim Summary 3

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 highlights 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*** (in press)

Taking home messages

- ◆*Projected changes of global land monsoon rainfall do not scale with global mean surface temperature.*
- ◆*SST gradient associated with ECS can dominate regional patterns.*
- ◆*High resolution is needed for the projection of monsoon rainfall.*
- ◆*Limiting global warming to 1.5°C instead of 2.0°C would reduce exposures to precipitation extremes in global land monsoon domain.*