



中国科学院大气物理研究所

Institute of Atmospheric Physics, Chinese Academy of Sciences

中国未来降水变化的情景预估

周天军

致谢：邹立维，张文霞，陈晓龙，胡帅，陈梓明，李东欢，陆静文

清华大学地球系统模式研发及应用国际暑期学校

2022年8月23日



报告提纲

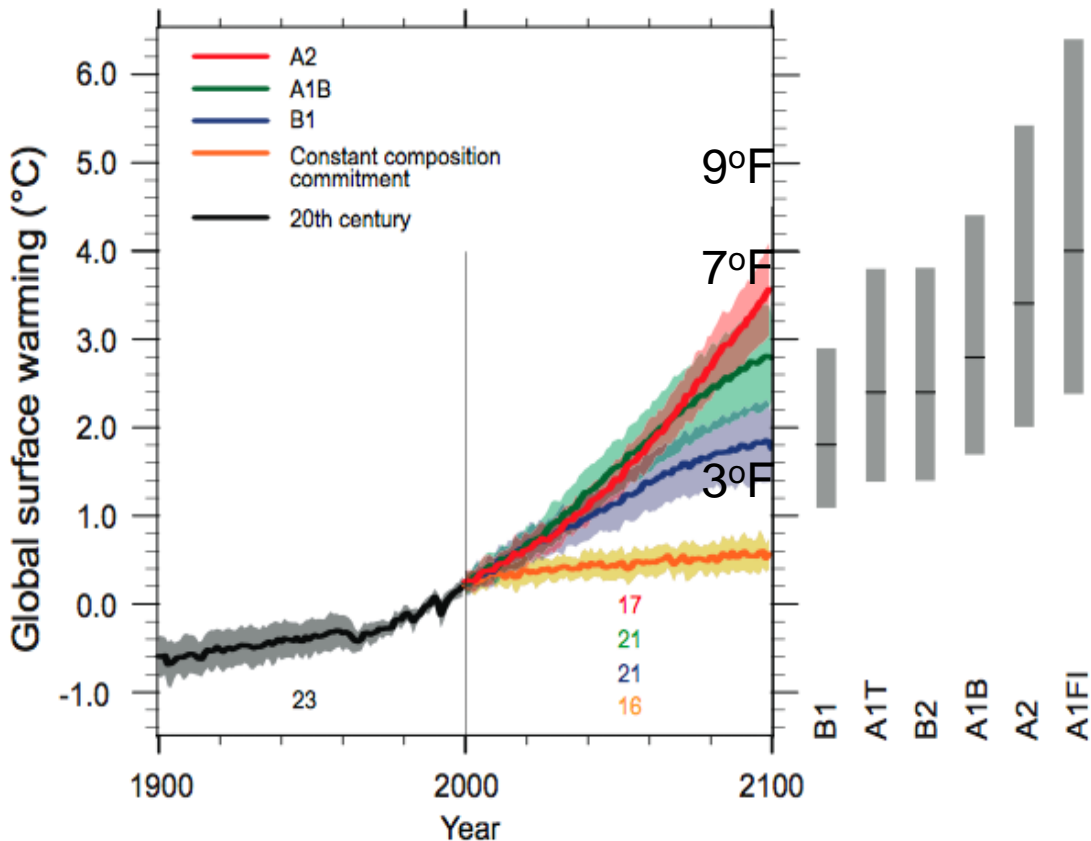
- ◆ 两类预估问题
- ◆ 近期年代际预测
- ◆ 中长期气候预估
- ◆ 基于温升阈值的预估
- ◆ 结语

应对气候变化需要对未来气候进行预估

- 气候预估：依赖于气候变化情景
- 不同情景：对应不同的社会经济发展路径

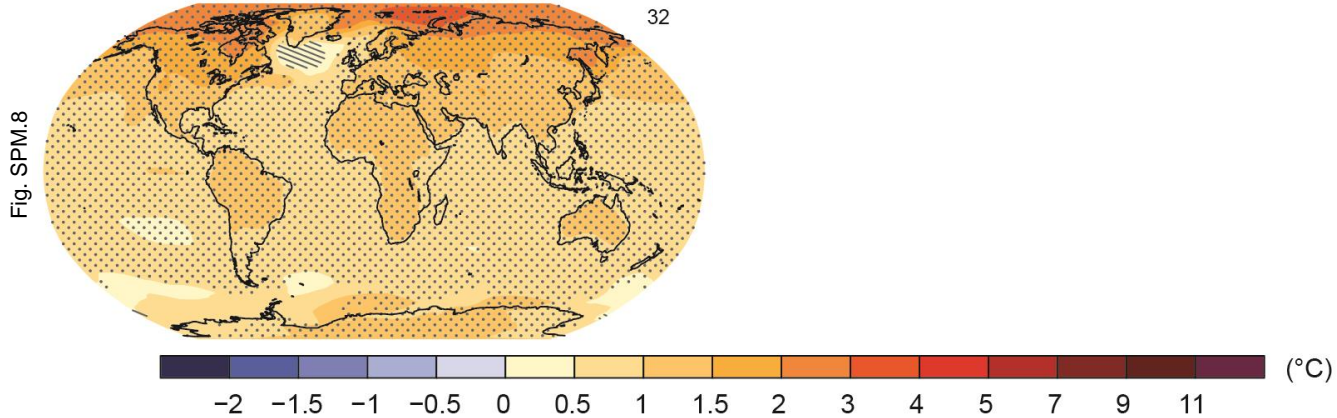


传统的基于情景的预估



RCP2.6

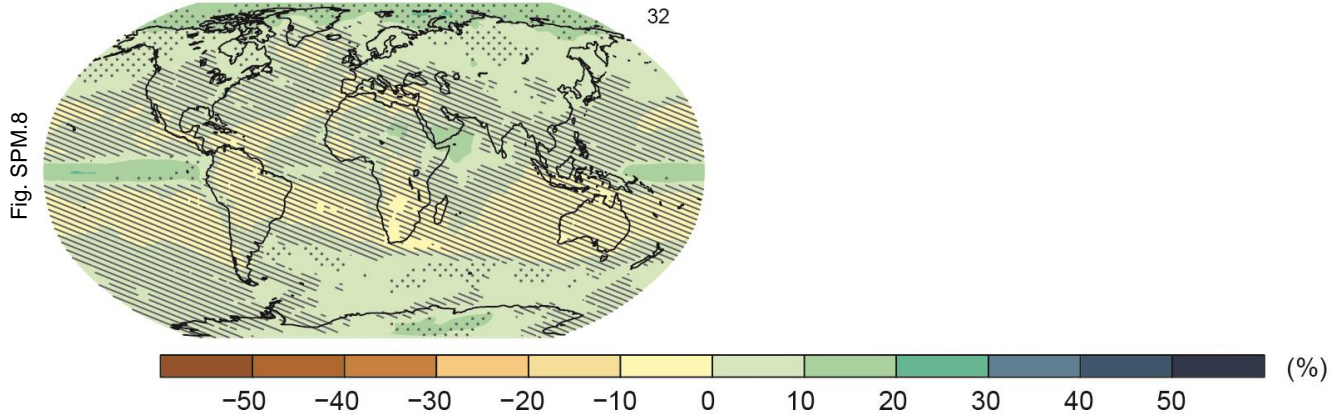
Change in average surface temperature (1986–2005 to 2081–2100)



We have a choice.

RCP2.6

Change in average precipitation (1986–2005 to 2081–2100)



We have a choice.

基于温升阈值的气候预估：新问题

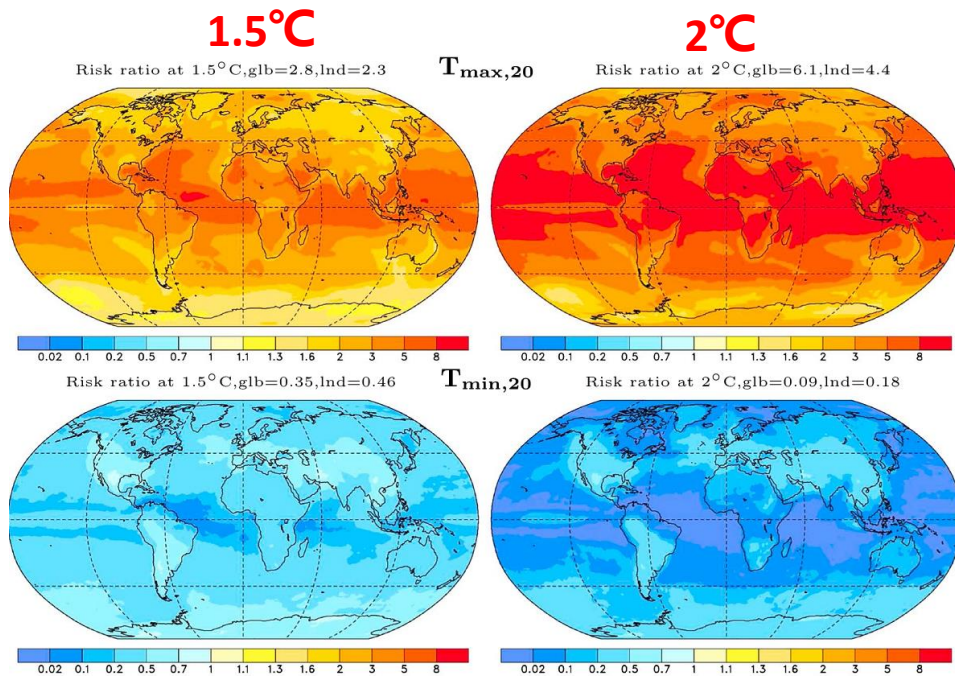


2016年4月22日《联合国气候变化框架公约》近200个缔约方签订《巴黎协定》，于2020年开始付诸实施。《协定》指出，把全球平均气温较工业化前温升水平控制在2°C之内，并为把温升控制在1.5°C之内而努力，以降低气候变化的风险与影响。

	1.5 °C	2 °C	
热浪持续时间增加	Heat wave (warm spell) duration [month] Global 1.1 [1.1;3] 1.5 [1.4;1.8]		Tropical regions up to 2 months at 1.5 °C or up to 3 months at 2 °C
水资源减少	Reduction in annual water availability [%] Mediterranean 9 [5;16] 17 [8;28]		Other dry subtropical regions like Central America and South Africa also at risk
强降水增强	Increase in heavy precipitation intensity [%] Global 5 [4;6] 7 [5;7] South Asia 7 [4;8] 10 [7;14]		Global increase in intensity due to warming; high latitudes (>45 °N) and monsoon regions affected most.
海平面上升	Global sea-level rise in 2100 [cm] 40 [30;55] 50 [35;65] 2081–2100 rate [mm/yr] 4 [3;5.5] 5.5 [4;6]		1.5 °C end-of-century rate about 30 % lower than for 2 °C reducing long-term SLR commitment.
珊瑚礁退化	Fraction of global coral reefs at risk of annual bleaching [Constant case, %] 2050 90 [50;99] 98 [86;100] 2100 70 [1;49;8] 99 [85;100]		Only limiting warming to 1.5 °C may leave window open for some ecosystem adaptation.
粮食产量降低	Changes in local crop yields over global and tropical present day agricultural areas including the effects of CO₂-fertilization [%]		
	Global	Tropics	Projected yield reductions are largest for tropical regions, while high-latitude regions may see an increase. Projections not including highly uncertain positive effects of CO ₂ -fertilization project reductions for all crop types of about 10 % globally already at 1.5 °C and further reductions at 2 °C.
Wheat	2 [-6;17]	0 [-8;2]	
	-9 [-25;12]	-16 [-42;14]	
Maize	-1 [-26;8]	-6 [-38;2]	
	-3 [-16;2]	-6 [-19;2]	
Soy	7 [-3;28]	1 [-12;34]	
	6 [-3;23]	7 [-2;27]	
Rice	7 [-17;24]	7 [-4;27]	
	6 [0;20]	6 [0;24]	

(Schleussner et al. 2016)

基于温升阈值的气候预估：新需求



20年一遇极端温度事件
发生概率比 (PR)

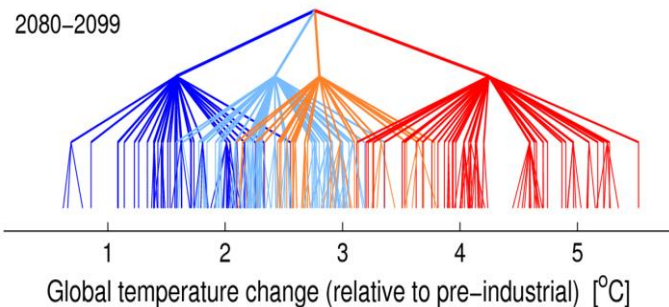
	1.5°C	2°C
T_{max_Ind}	2.3	4.4
T_{max_EA}	1.9	3.2
T_{min_Ind}	0.46	0.18
T_{min_EA}	0.54	0.26

(Kharin et al., 2018)

两类预估，各具挑战

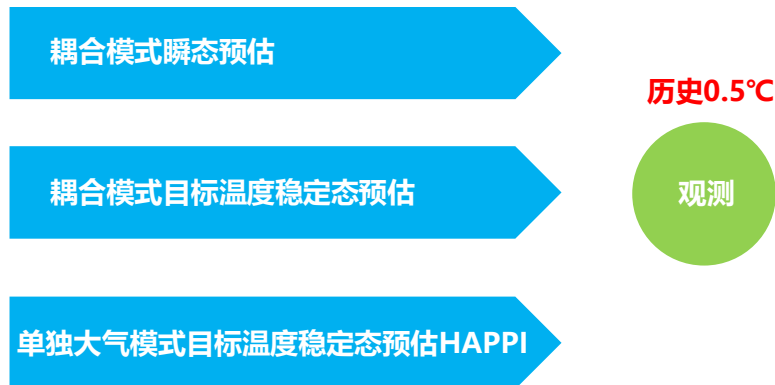
传统的基于情景的预估

- ◆ 信噪比问题：近期、中期、远期
- ◆ 近期预估：初始化的年代际预测
- ◆ 中远期预估：Emergent constraint



新提出的基于温升阈值的预估

1.5/2°C温升阈值的气候预估模拟策略



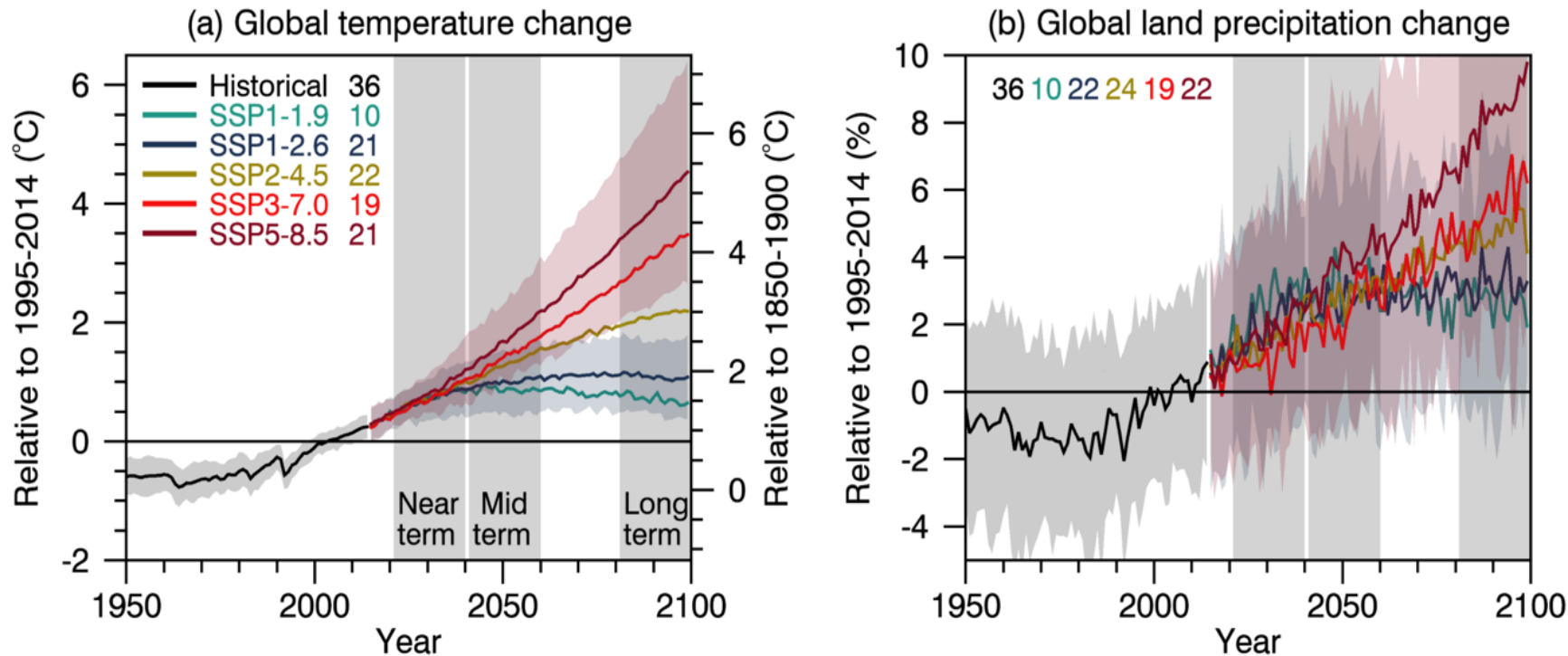
Zhao S, Zhou T. 2019: Are the Observed Changes in Heat Extremes Associated with a Half-Degree Warming Increment Analogues for Future Projections? [J]. *Earth's Future*, doi: 10.1029/2019EF001237



汇报提纲

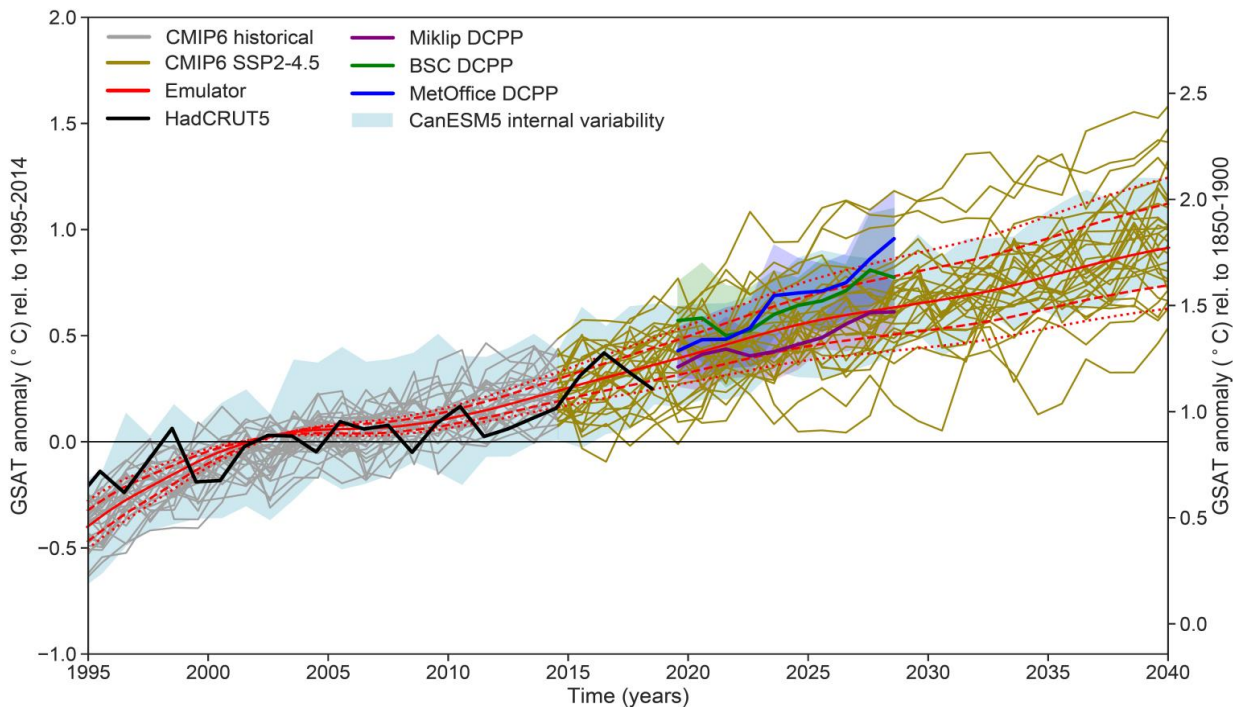
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全球平均温度和降水的预估：近期、中期、远期



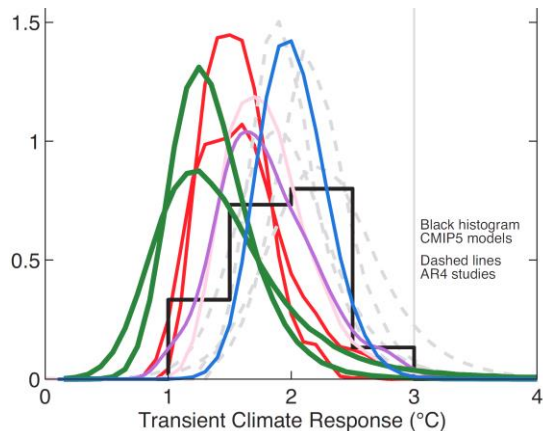
预估结果存在不确定性，不同时段不确定性来源不同

CMIP6模式模拟的年均全球GSAT变化

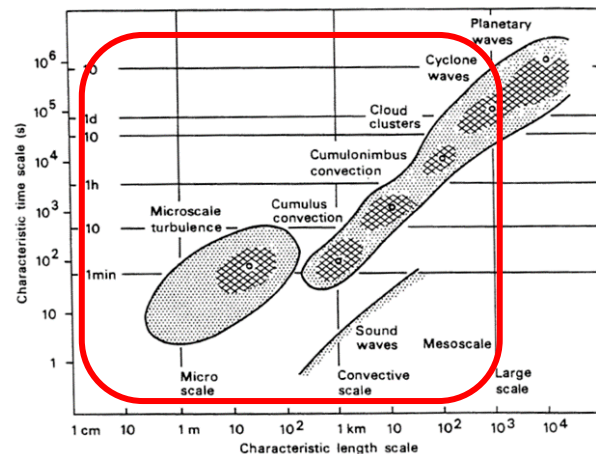


近期预估结果：离差大，内部变率强于外强迫信号

气候预估不确定性的来源：模式结构不确定性、关键模式参数的影响



CMIP模式的气候敏感度差异

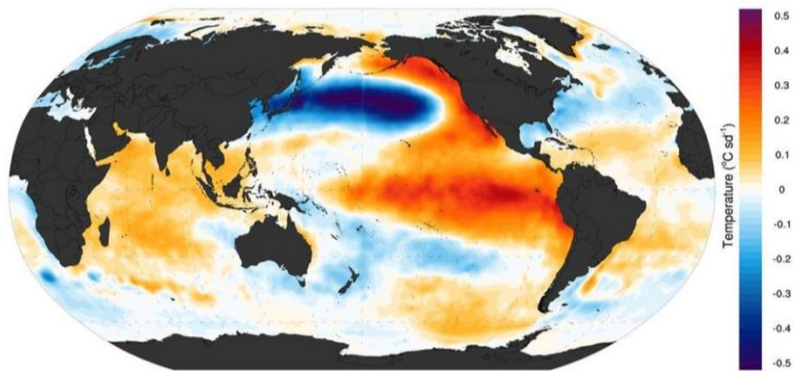


需要参数化的尺度

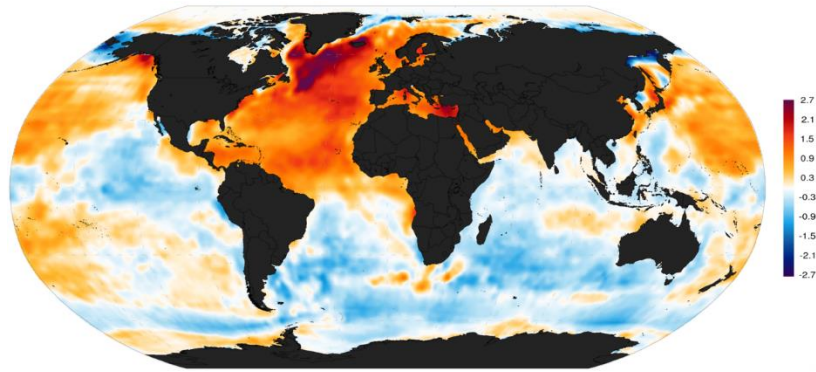
不同模式对于相同温室气体增加的增温响应不同

次网格物理过程的参数化

近期气候预估不确定性的来源：内部变率的影响



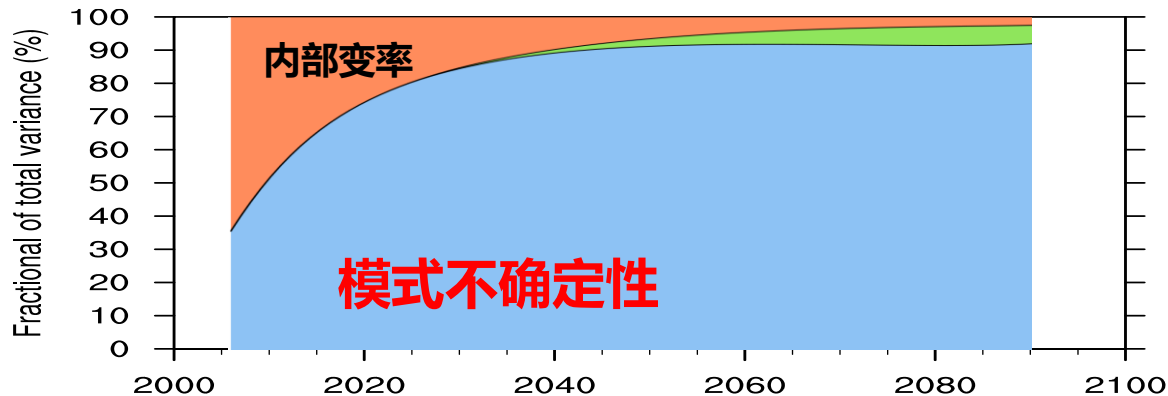
PDO(太平洋年代际振荡)



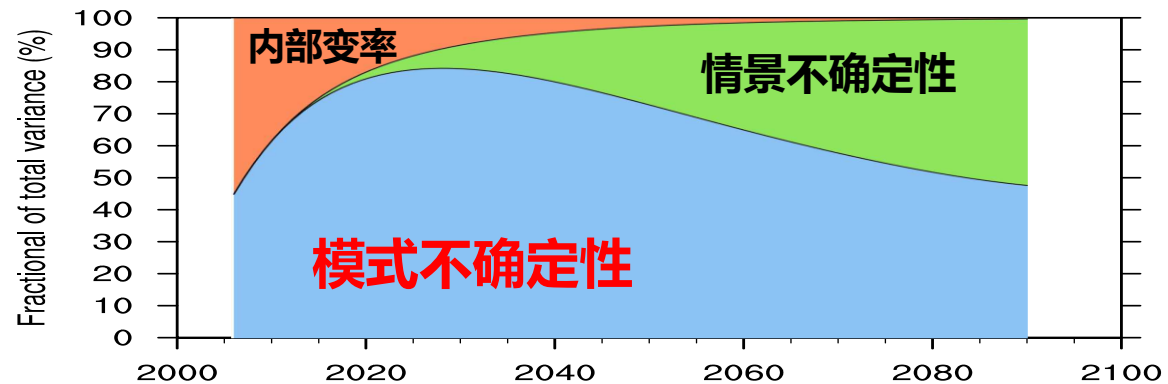
AMO (大西洋年代际振荡)

多圈层耦合的气候系统自身存在年代际的振荡

陆地季风区降水的预估不确定性来源：三种因子的方差贡献



平均降水 P_{av}

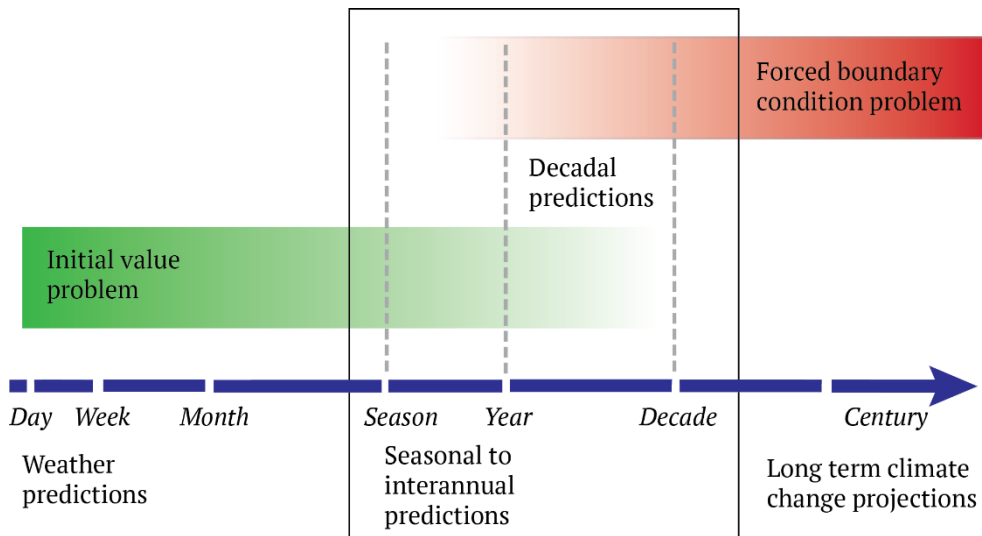


极端降水 $RX5day$



Near Term (decadal) Prediction

近期(10-30年)气候预测：可预报性、预测服务



How can we enhance the understanding of sources of decadal predictability?

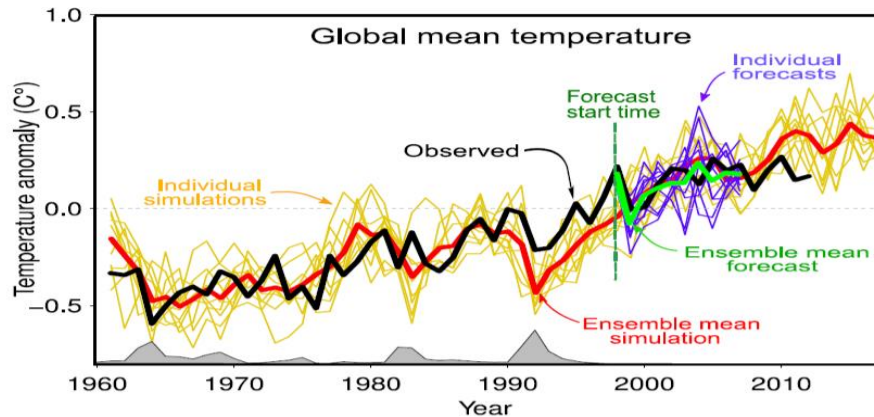
How can we serve decadal prediction information as is already done for seasonal prediction?

周天军, 陈晓龙, 吴波, 2018: 支撑“未来地球”计划的气候变化科学前沿问题. 科学通报, 63, 1 (2018); doi: 10.1360/N972018-00818

周天军, 吴波, 2017: 年代际气候预测问题: 科学前沿与挑战, 地球科学进展, 32(4),331-341

近期年代际气候预测

年代际预测-Decadal Prediction, 又称“近期年代际气候预测” (near term decadal climate prediction), 是利用气候系统模式, 综合考虑外强迫变化和初值, 对未来10-30年的气候异常进行预测。



人为强迫 + 自然强迫 + 初值影响

近期年代际预测问题

世界气象组织：未来5年升温暂时达到1.5°C的可能性增大



世界气象组织 Agusti Descarrega Sola 西班牙加泰罗尼亚地区海岸内罗三角洲的日出。

2021年5月27日 | 气候变化与环境

世界气象组织发布的最新气候报告指出，在未来五年，大约有40%的机率至少有一年的全球年平均气温上升暂时比工业化前水平高出1.5°C，而这一机率正随着时间的推移而增加。



WMO Lead Centre for Annual-to-Decadal Climate Prediction

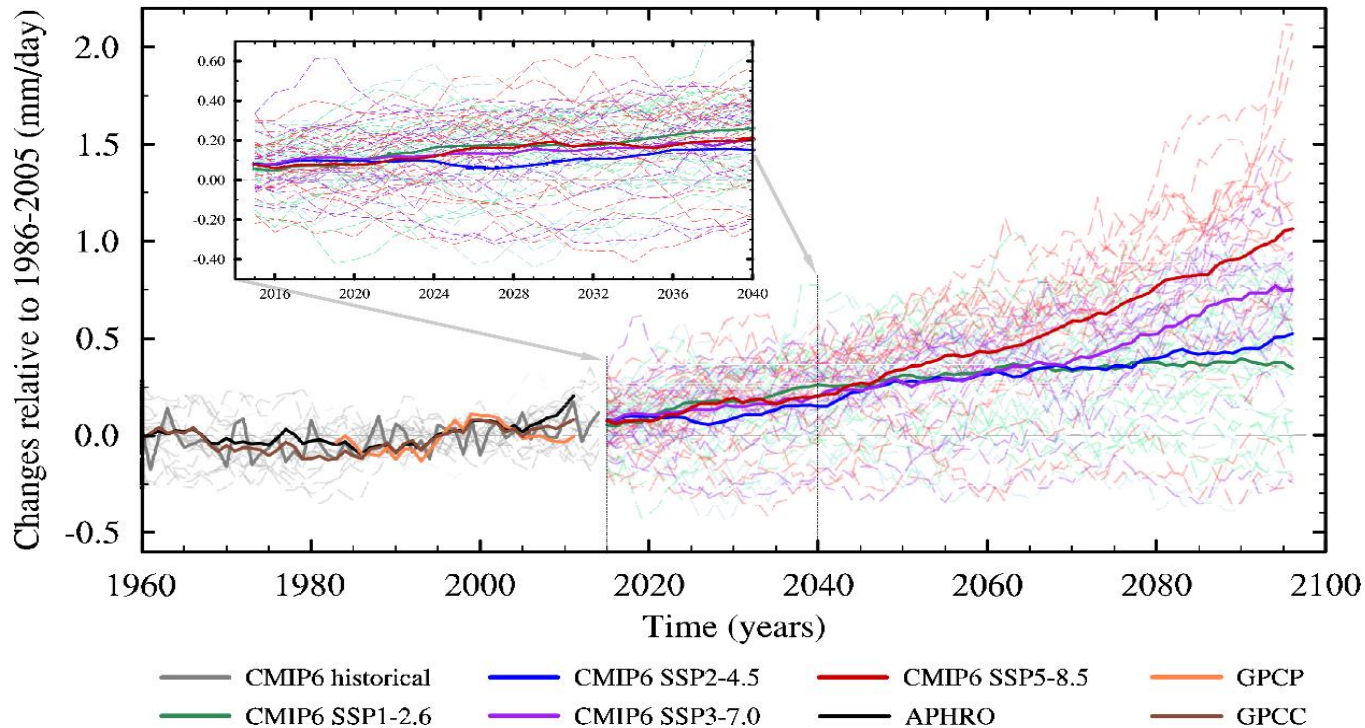
The Lead Centre for Annual-to-Decadal Climate Prediction collects and provides hindcasts, forecasts and verification data from a number of contributing centres worldwide.



大气所年代际气候预测系统 (IAP-DecPreS) (吴波等, 2018)

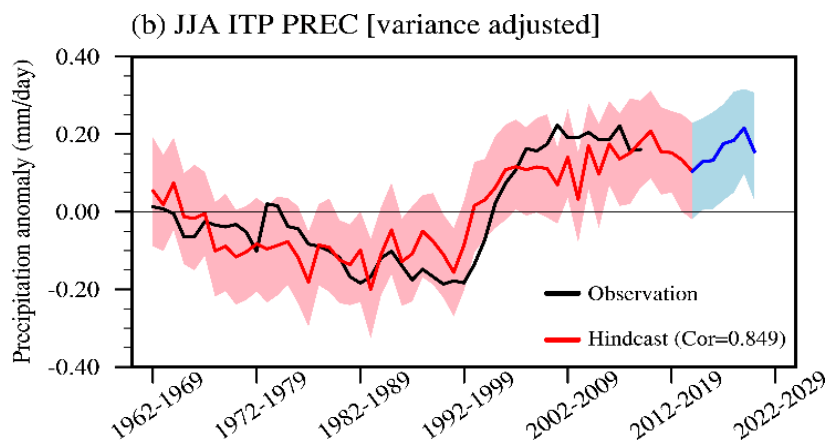
CMIP6 模式预估的青藏高原降水

近期气候预估离散度大

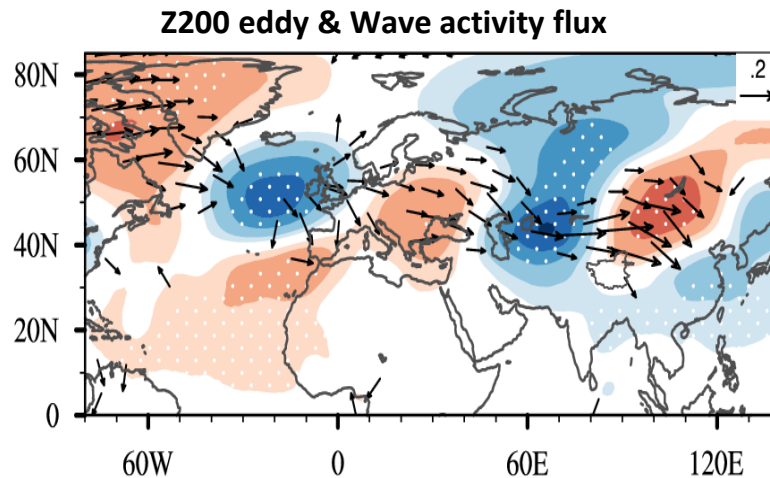


如何提升可靠性?

年代际预测试验回报的青藏高原降水变化



年代际青藏高原降水回报技巧

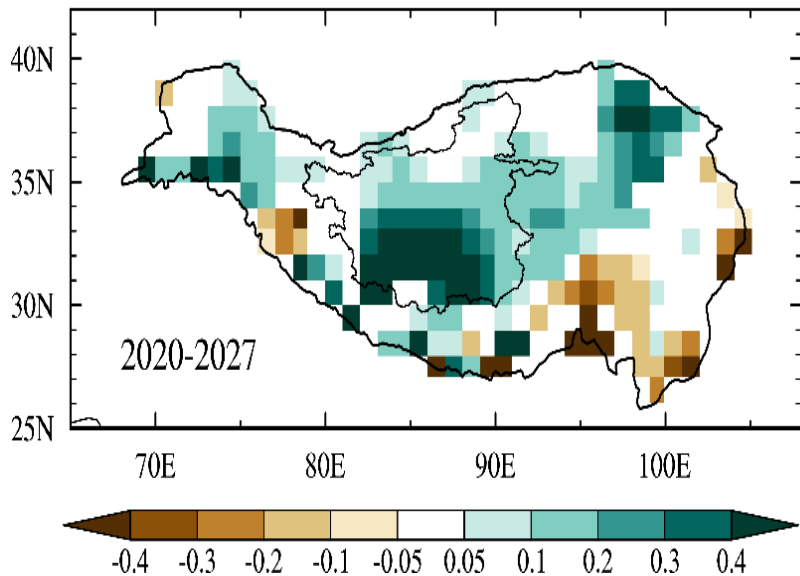


来自大西洋的波通量的传播

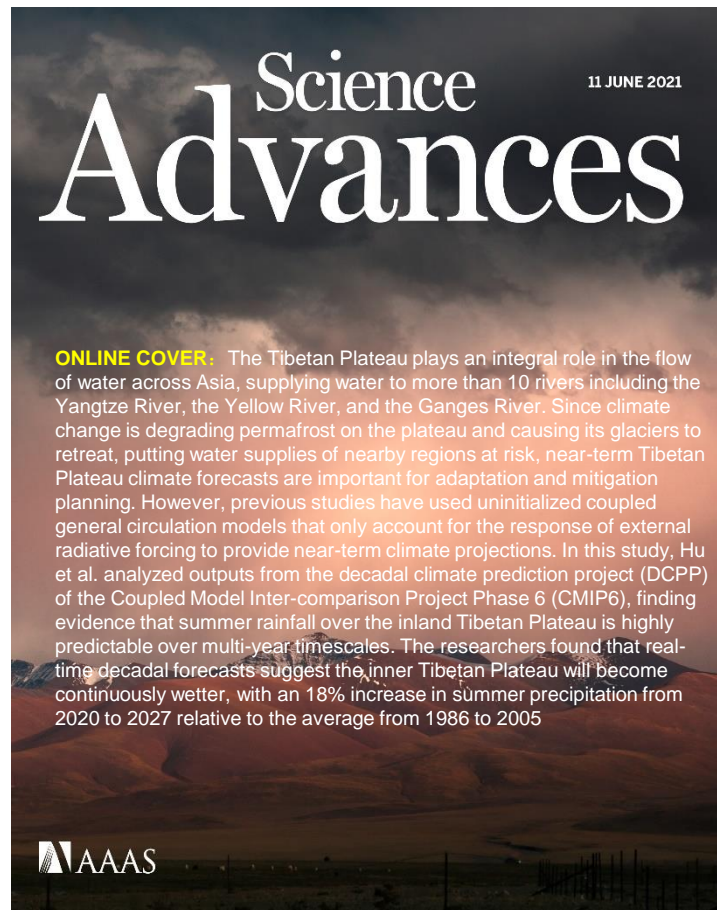
Hu S., T. Zhou*, 2021: Skillful prediction of summer rainfall in the Tibetan Plateau on multi-year timescales . *Science Advances*, 7, eabf9395 (2021).

Decadal real-time forecasts

高原降水的年代际预测



- optimum estimate of 0.27 mm/day during **2020–2027** relative to 1986–2005, indicating a **12.8% increase** in summer mean precipitation

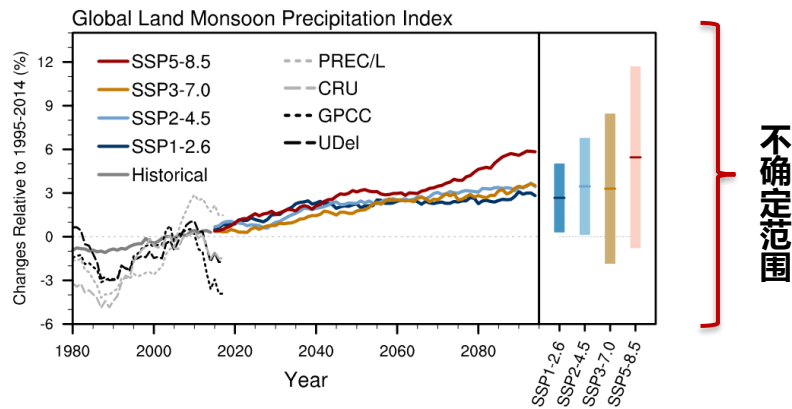




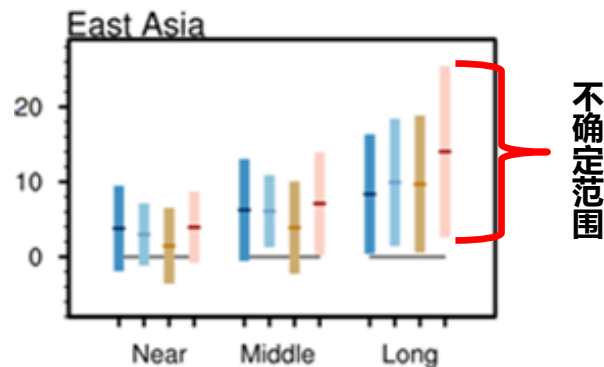
汇报提纲

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CMIP6全球季风降水预估

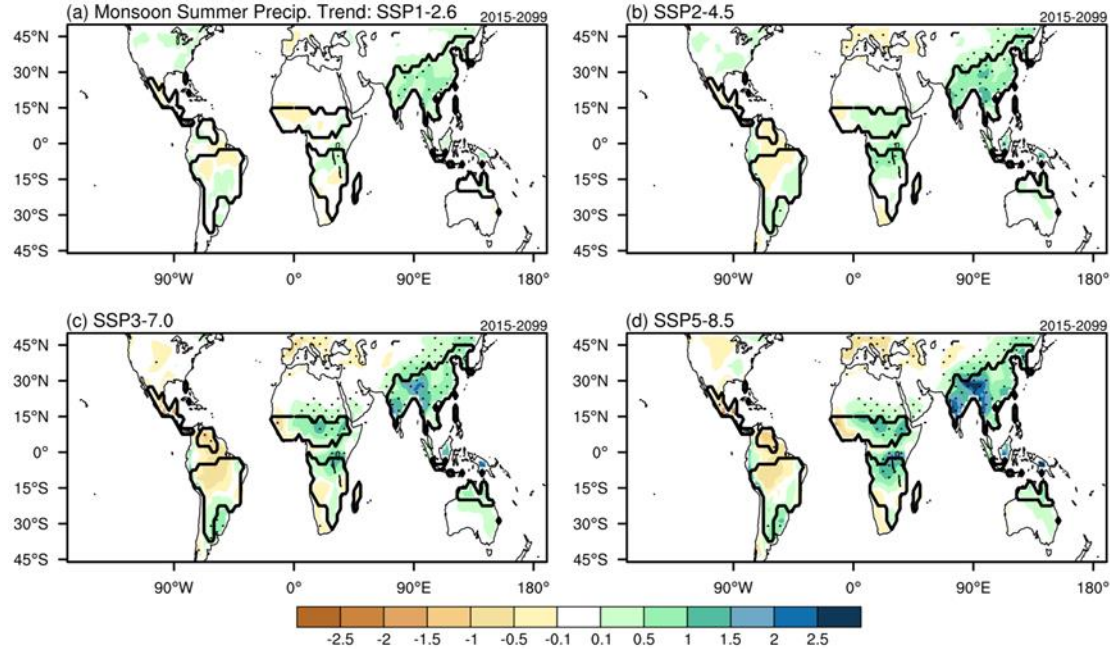


2080-2099年的不确定性



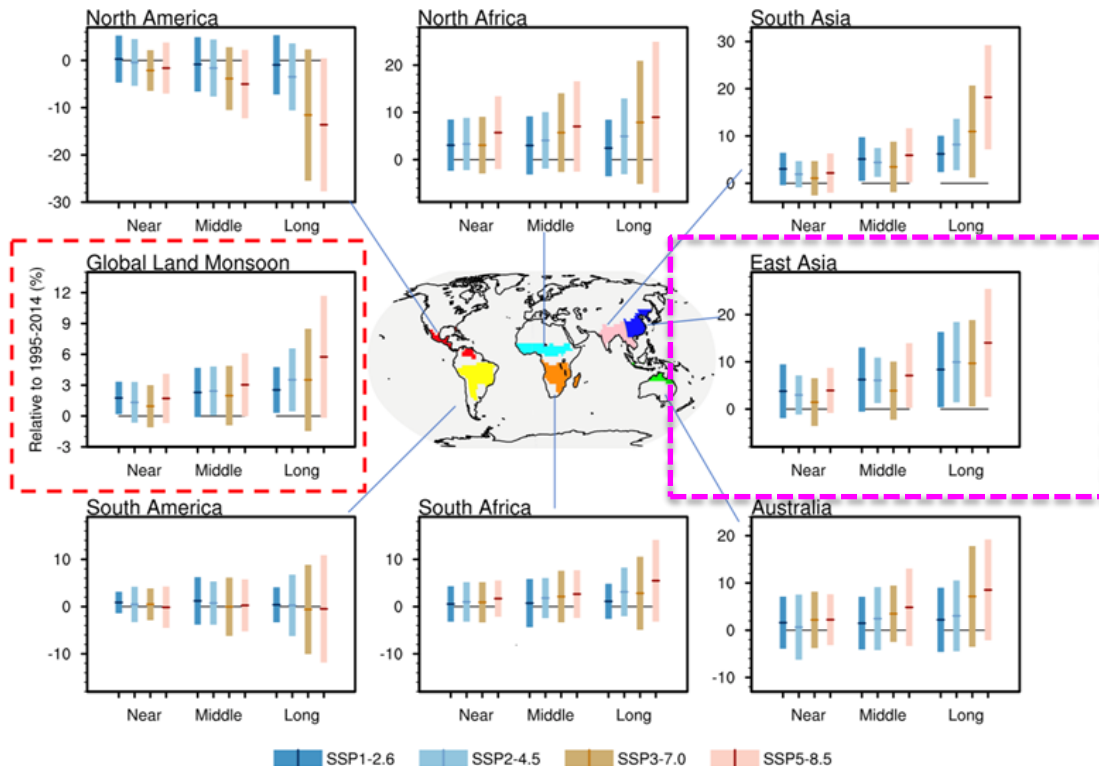
东亚季风区

2015-2099年陆地季风区降水变化趋势



Scaled by global mean SAT

CMIP6陆地季风区降水的预估



东亚季风区

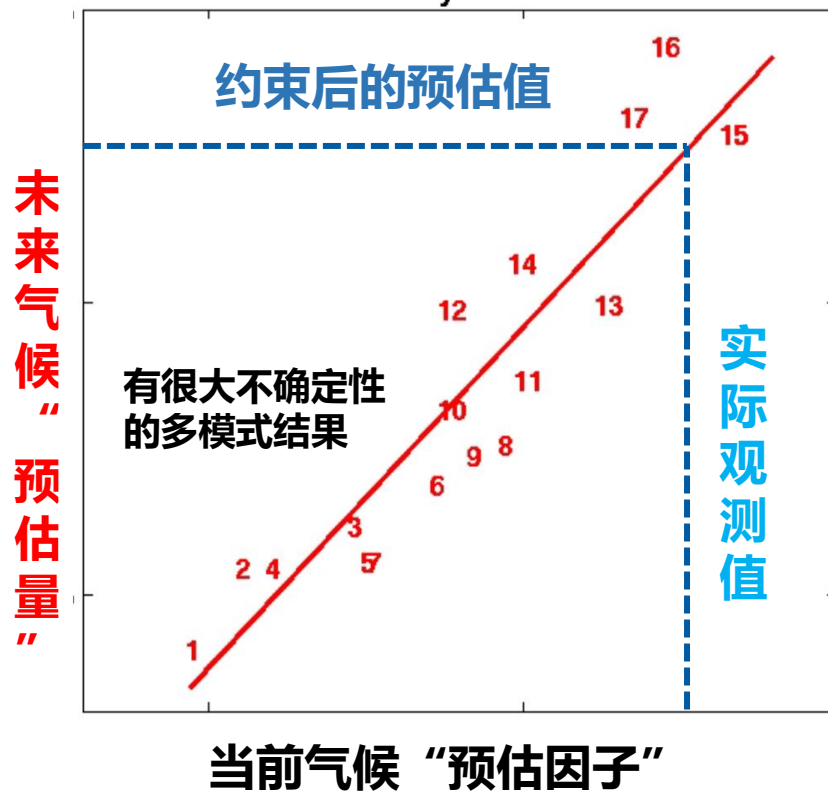
Emergent Constraints (涌现约束)

令多模式的预估结果为 P_i (预估量), 模式对当前气候某变量 (预估因子) 的模拟为 X_i 其中 $i = 1, 2, 3, \dots, N$ 。N 为模式数。利用最小二乘法建立P 与X 之间的关系, 即

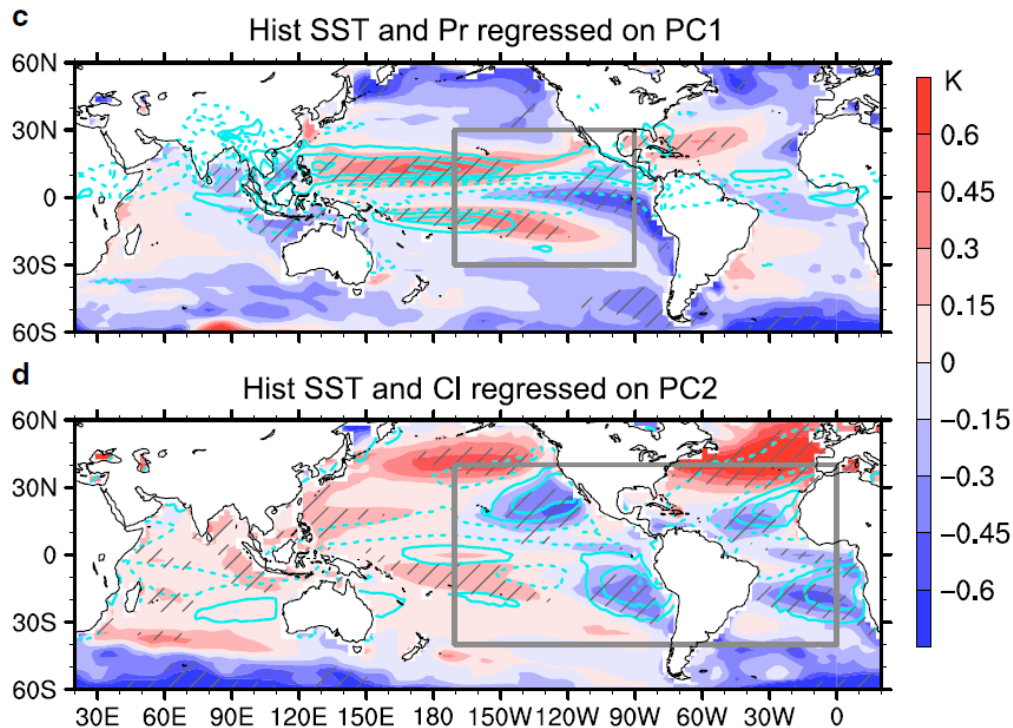
$$P \sim aX + b$$

其中a 为线性回归系数, b 为截距。若当前气候该变量的观测值为 X_0 , 那么可以用建立上述关系约束模式预估结果, 给出最优的预估值

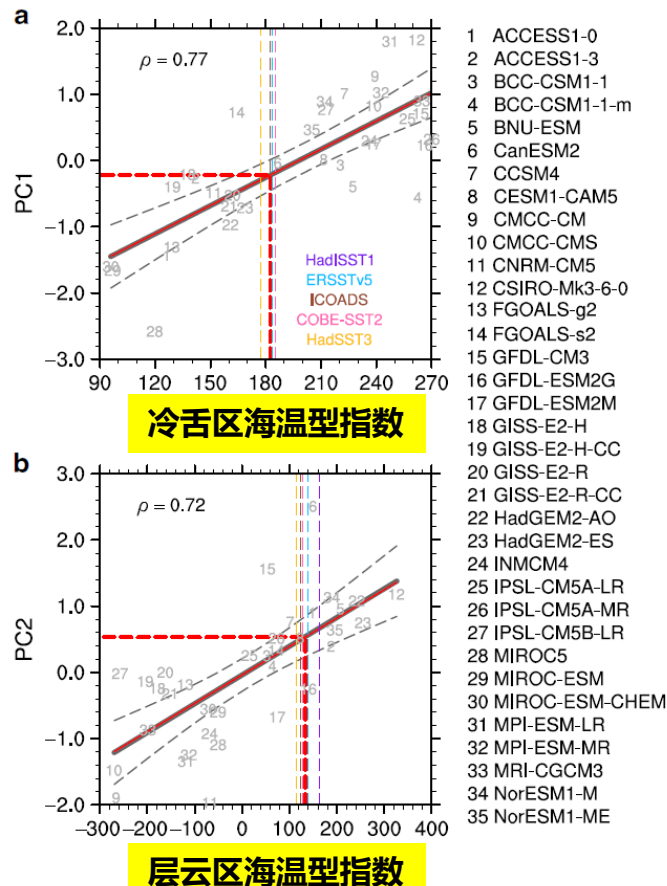
$$P^* = aX_0 + b$$

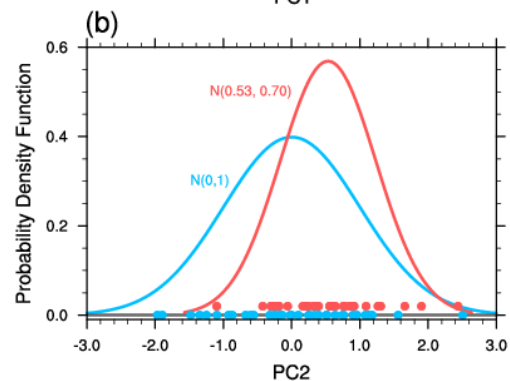
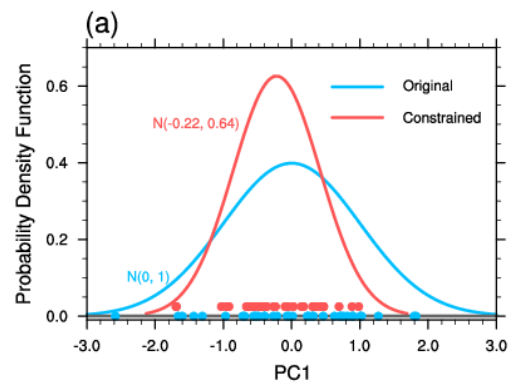


模式间PC与历史海温模拟的关系及涌现约束



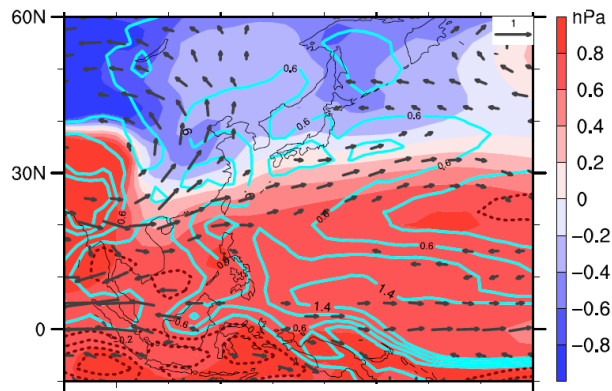
- PC1与历史模拟中**赤道中东太平洋的冷舌偏差**有关。
- PC2与历史模拟中**大洋东岸层云区**的海温偏差有关。



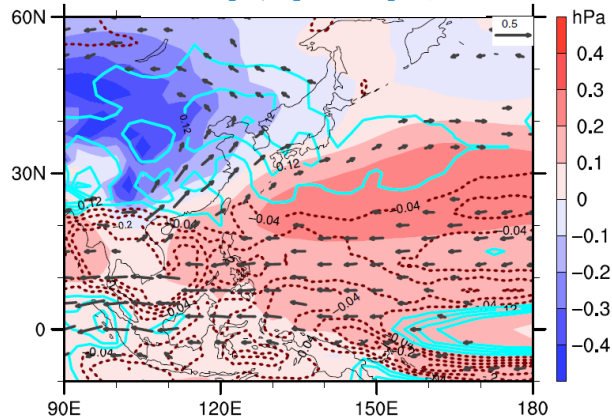


约束后，PC的不确定性显著减小，
总不确定性减少45%。

a 约束订正后的预估结果



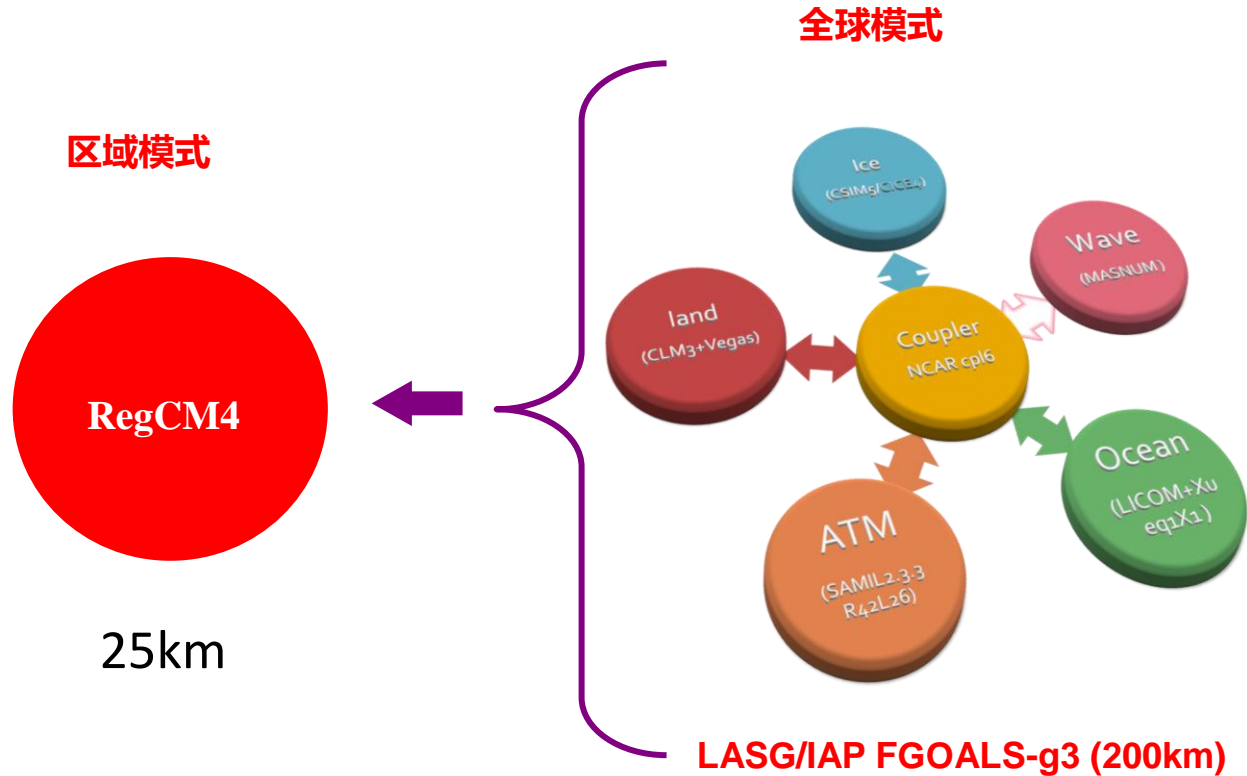
b 约束后-约束前



与约束前相比，约束后多模式
预估西北太平洋副高显著增强，
中国东部以及东亚梅雨带降水
更多，西北太平洋降水更小。

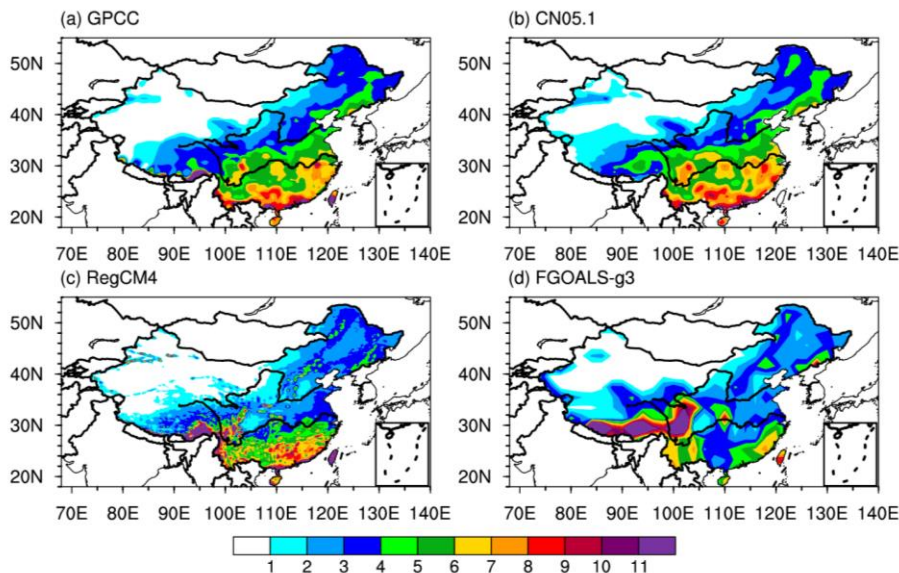
Chen, X., Zhou, T., Wu, P., Guo, Z. & Wang, M. (2020) Emergent constraints on future projections of the western North Pacific Subtropical High. *Nature Communications*, 11, 2802, doi: 10.1038/s41467-020-16631-9.

动力降尺度

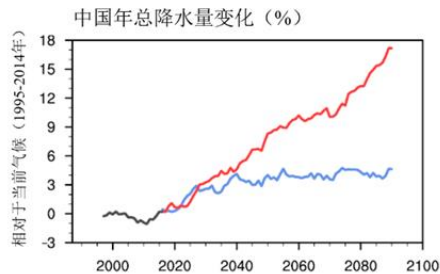
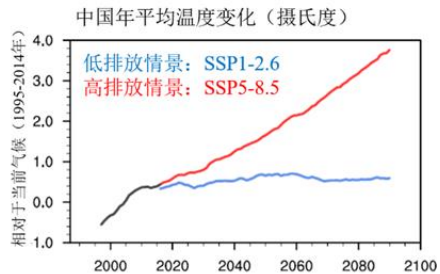


针对东亚区域开展的动力降尺度试验

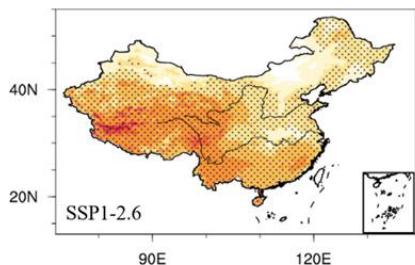
试验	时段
His	1986-2016
SSP1-26	2016-2100
SSP2-45	2070-2100
SSP5-85	2016-2100



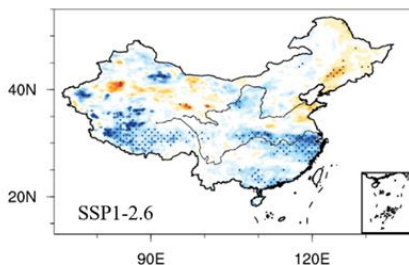
降尺度后的1987-2016夏季降水更接近观测



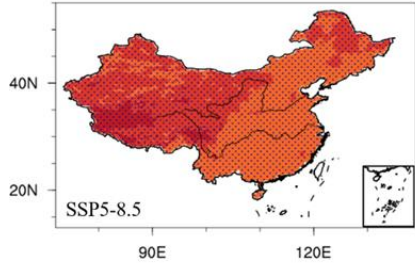
2040-2060年平均温度变化 (低排放情景)



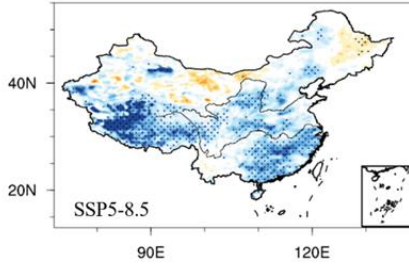
2040-2060年总降水量变化 (低排放情景)



2040-2060年平均温度变化 (高排放情景)



2040-2060年总降水量变化 (高排放情景)



(单位: 摄氏度)

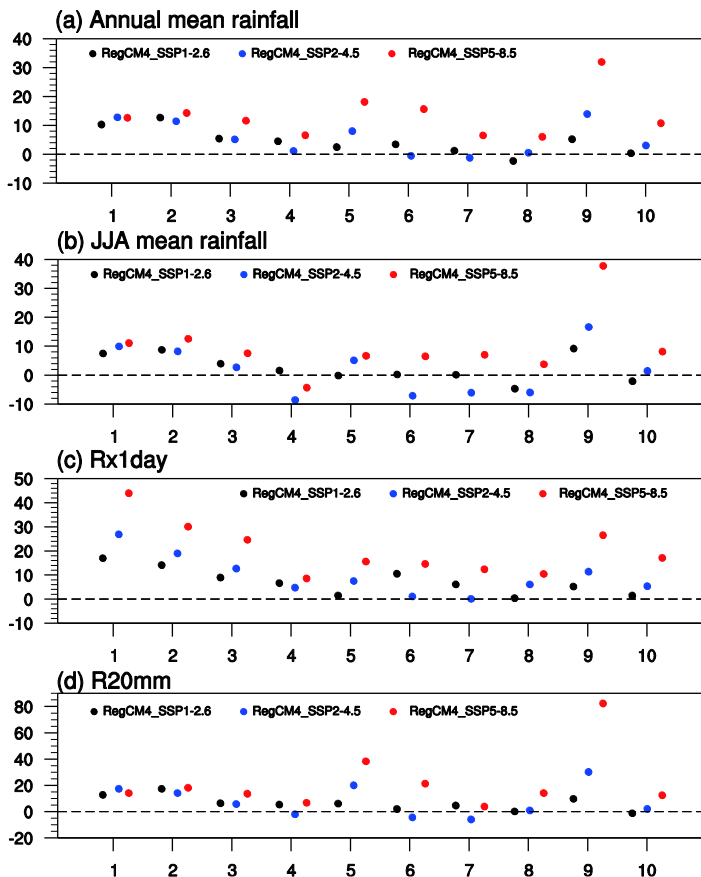


(单位: %)

Zou, L., and T. Zhou, 2022: Mean and extreme precipitation changes over China under SSP scenarios: results from high-resolution dynamical downscaling for CORDEX East Asia. *Climate Dynamics*, 58, 1015-1031

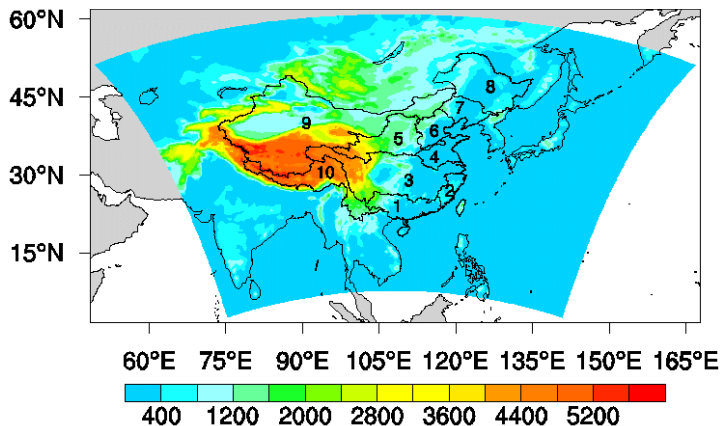
十大流域不同排放情景下平均降水和极端降水 (2071-2100) 的变化

平均降水



极端降水

十大流域示意图



- 流域9 (西北内河流域) 对情景最为敏感
- 相对SSP5-8.5, SSP2-4.5 将在海河流域、辽河流域、松花江流域避免80%以上的影响
- SSP1-2.6, 避免80%以上影响的区域将扩展到西北内河流域和西南流域

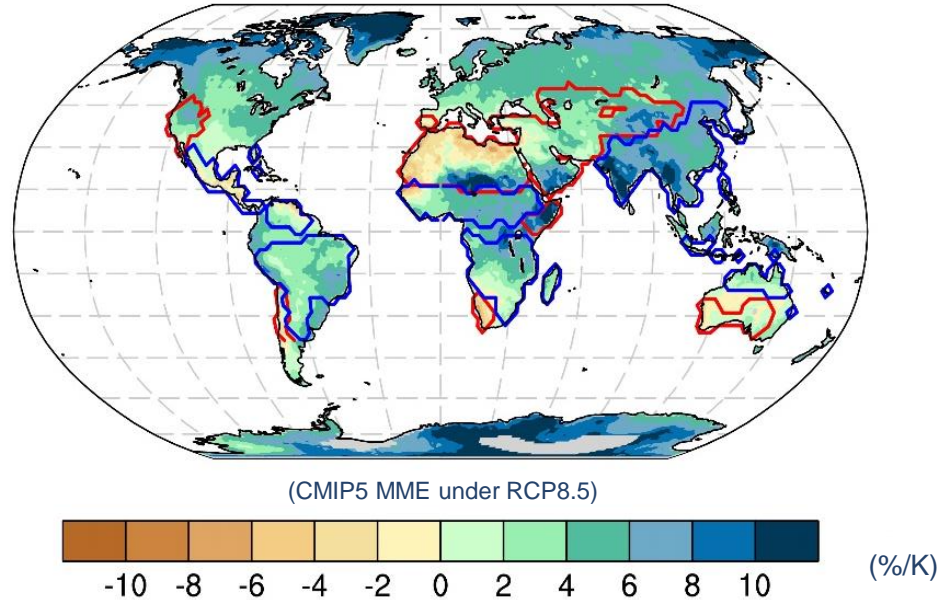


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Response of extreme precipitation to future warming

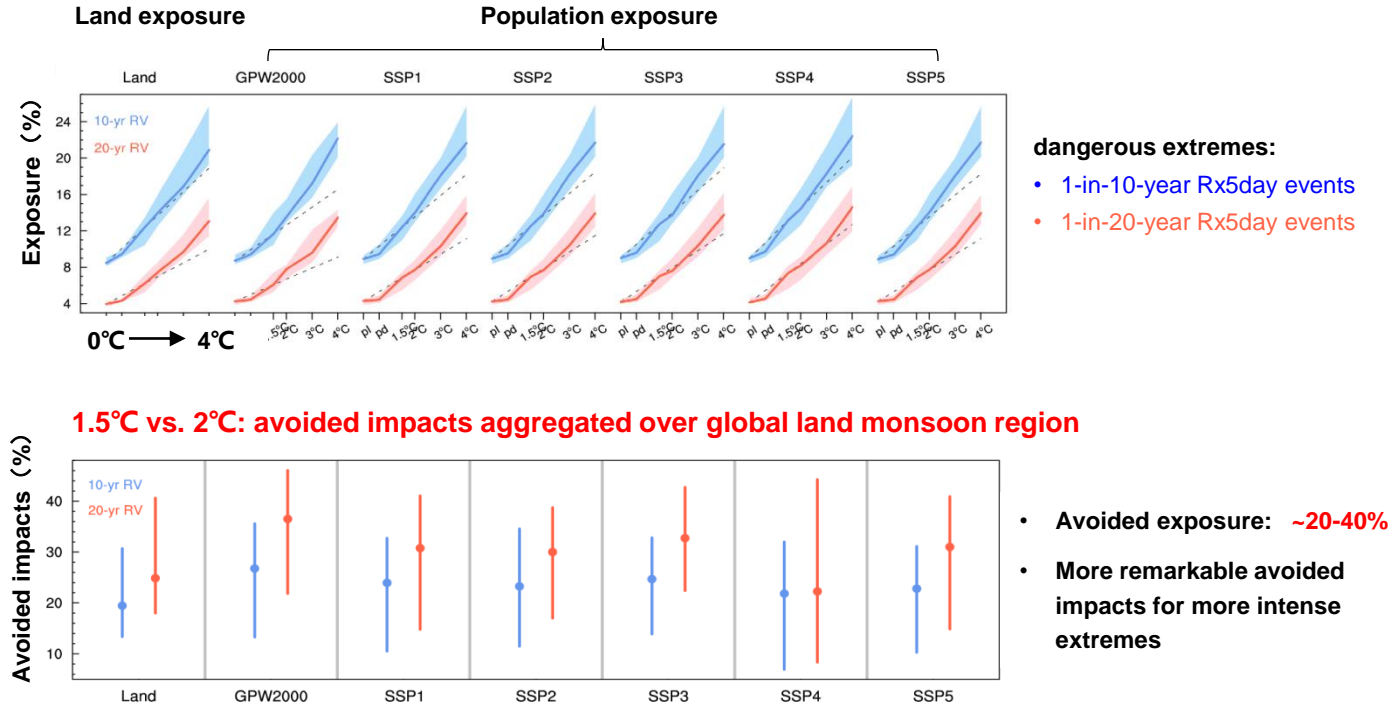
Response of extreme precip to GSAT



Extreme precipitation exhibits higher response to warming over global monsoon regions than most of the land regions

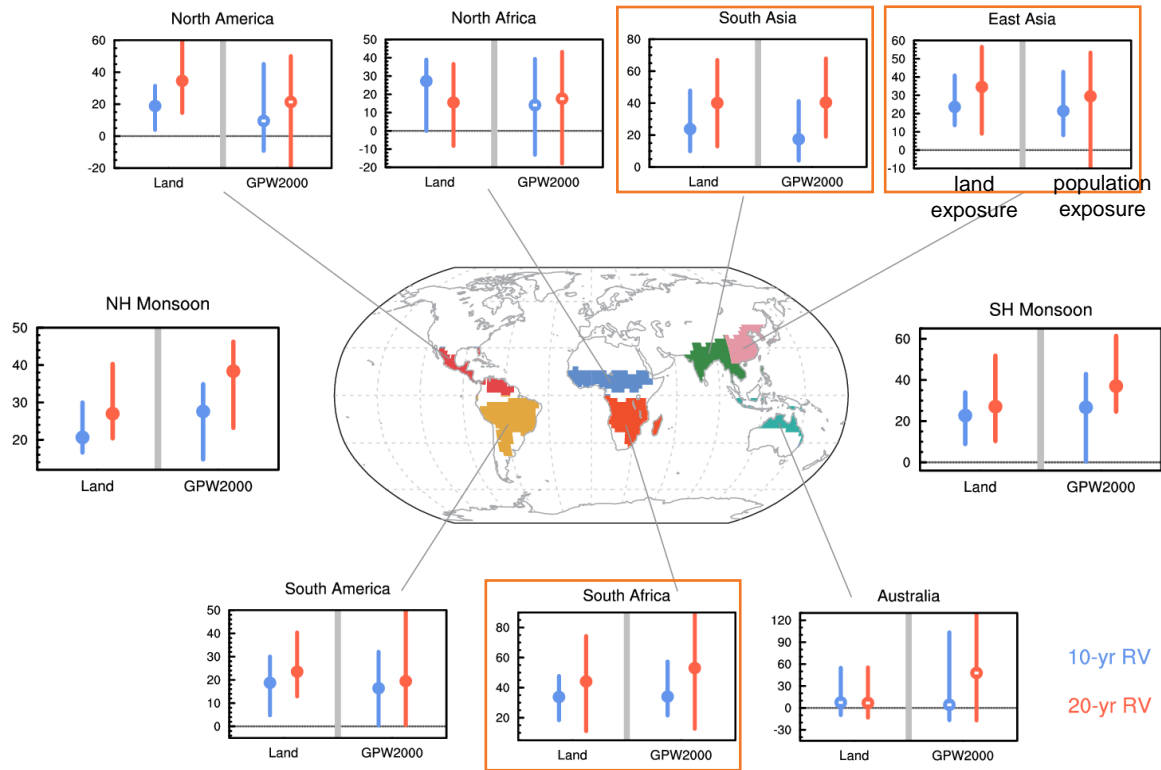
Increases in exposure with global warming

Exposure: area or population experiencing dangerous extremes



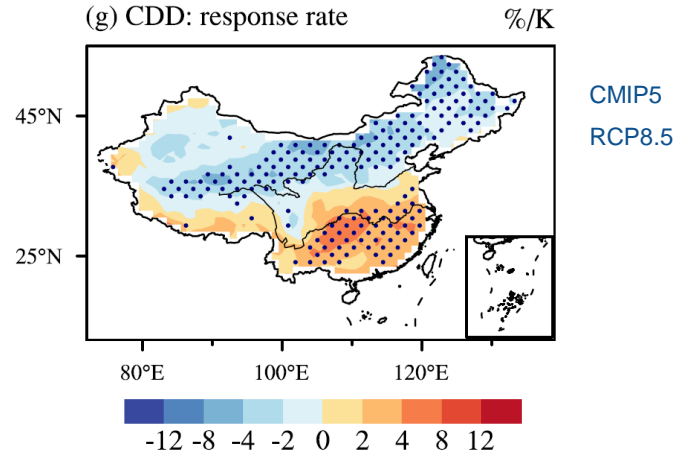
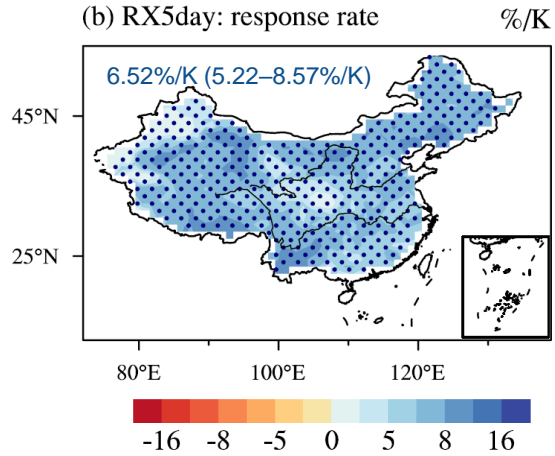
Aggregated over global monsoon regions

Avoided impacts between 1.5°C vs. 2°C : regional hotspots

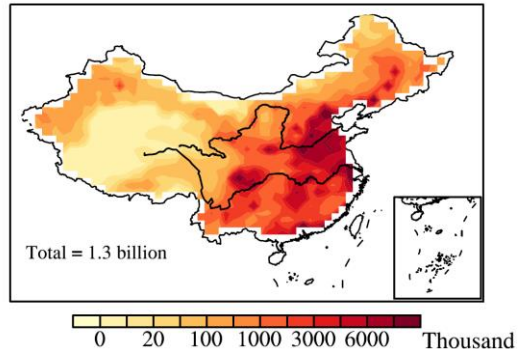


South African, South Asian, and East Asian monsoon regions would benefit most from lower global warming levels.

Impact determined by both climate change and population



(a) Population count in 2010



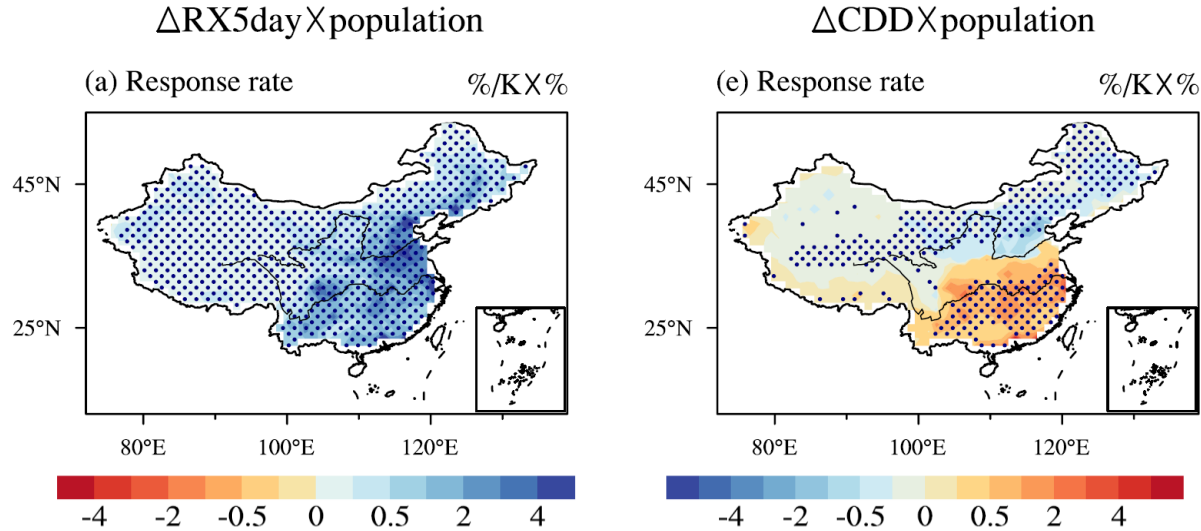
Population weighted impact:

Impact = climate change X population fraction

Zhang W, Zhou T. 2020. Increasing impacts from extreme precipitation on population over China with global warming. *Science Bulletin*, 65(3): 243-252

Impact of extreme precipitation changes on population

Population weighted extreme precipitation changes

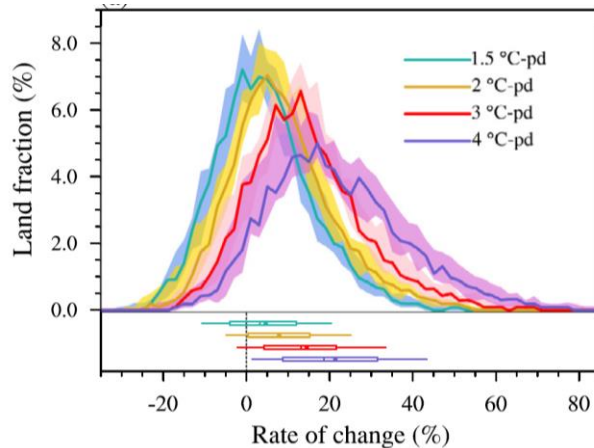


- Greater impact in Eastern China due to dense population
- Greater impact in southern and eastern China associated with longer CDD

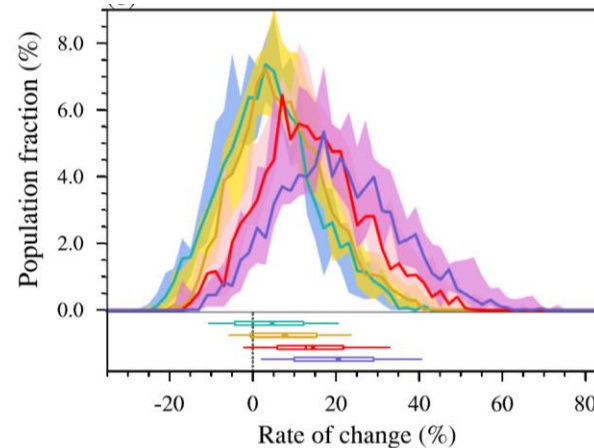
Aggregated impact over China – RX5day

Spatially aggregated probability distributions

Areal exposure



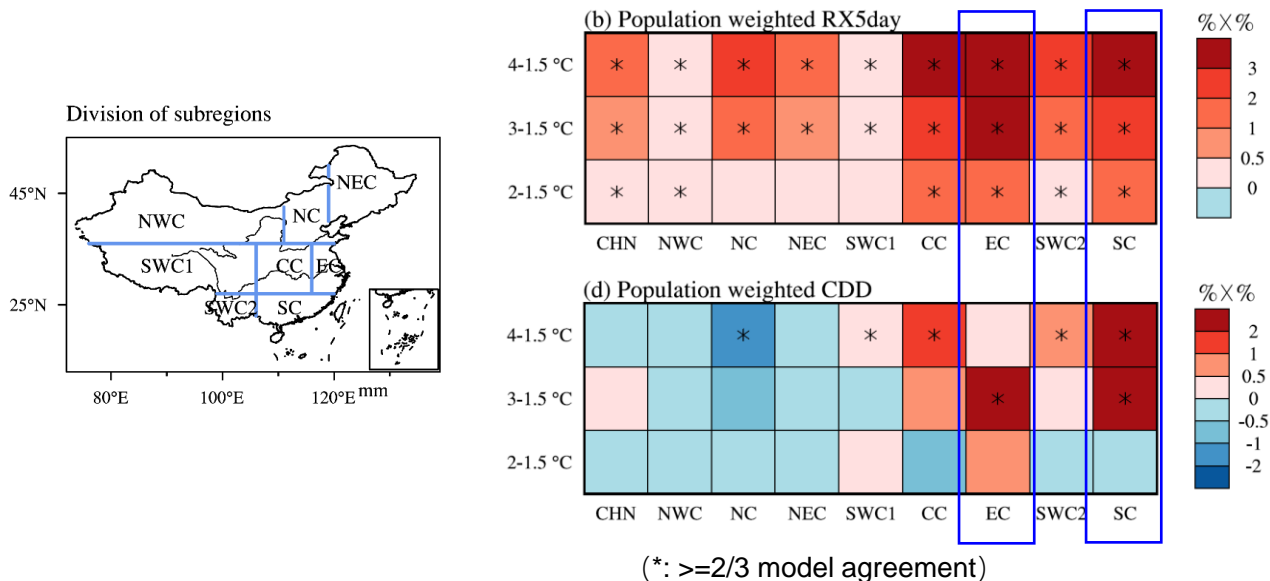
Population exposure



- Areal and population PDFs shift towards heavier rainfall events
- More than 1/4 of the population would experience a ~12%, 15%, 22% and 29% intensification in RX5day under 1.5, 2, 3 and 4°C warming, respectively

Regional hotspots

Population weighted extreme precip changes between 1.5°C and higher warming levels

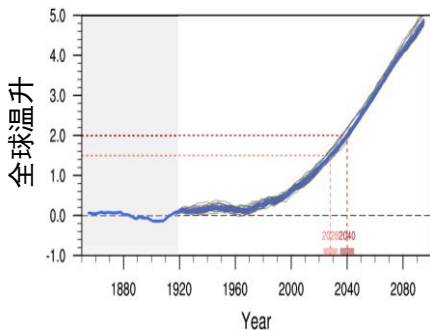


- **Southeastern China is the hotspot that is impacted greatly by additional warming from both wet and dry extremes.**

实现1.5/2°C温升的三种模拟策略: 结果间的差异

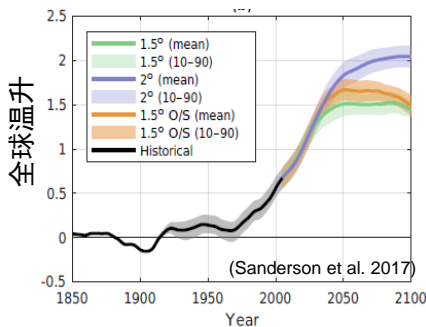
CESM-LE

- **CESM large ensemble**
- Transient, coupled simulations
- 'time sampling' approach



CESM-LW

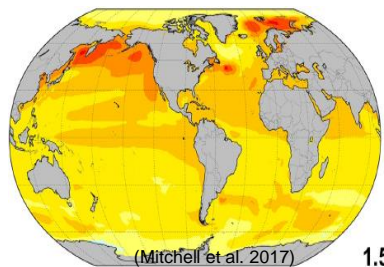
- **CESM Low Warming**
- Short-term stabilized, coupled simulations



HAPPI-CAM5

- **HAPPI project**
- Time-slice experiment
- atmosphere-only runs

1.5°C 增温对应的海温型



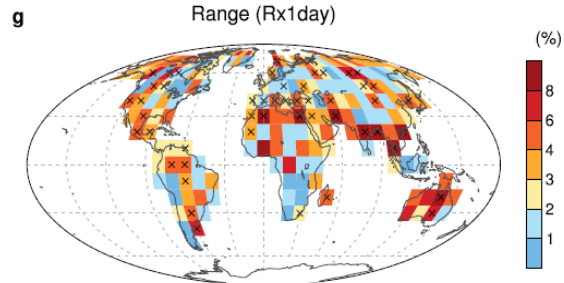
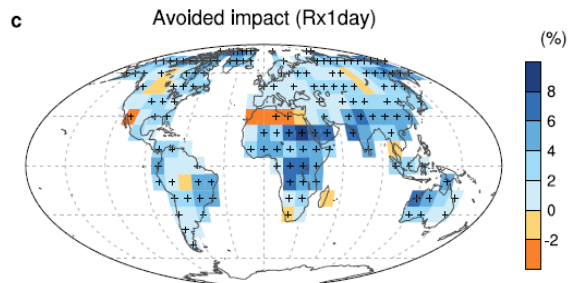
- 基于相同模式 (CESM-CAM5) , 消除了模式不确定性
- 每组大样本试验提供多个成员, 减小内部变率的影响
- 三组试验间的差异代表不同模拟策略的影响

1.5 vs. 2°C温升：极端降水的变化

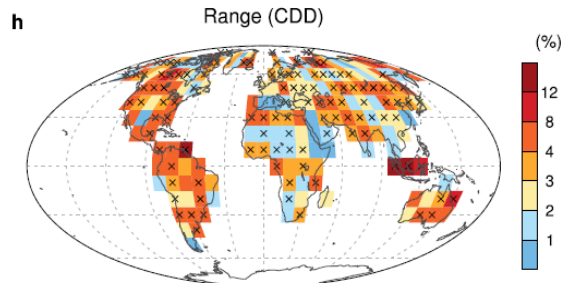
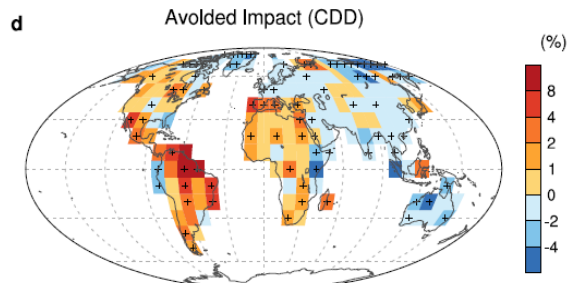
三种模拟策略平均

三种模拟策略的方法间差异

极端强降水 (Rx1day)



极端干事件 (CDD)



+: 不同方法预估变化符号一致

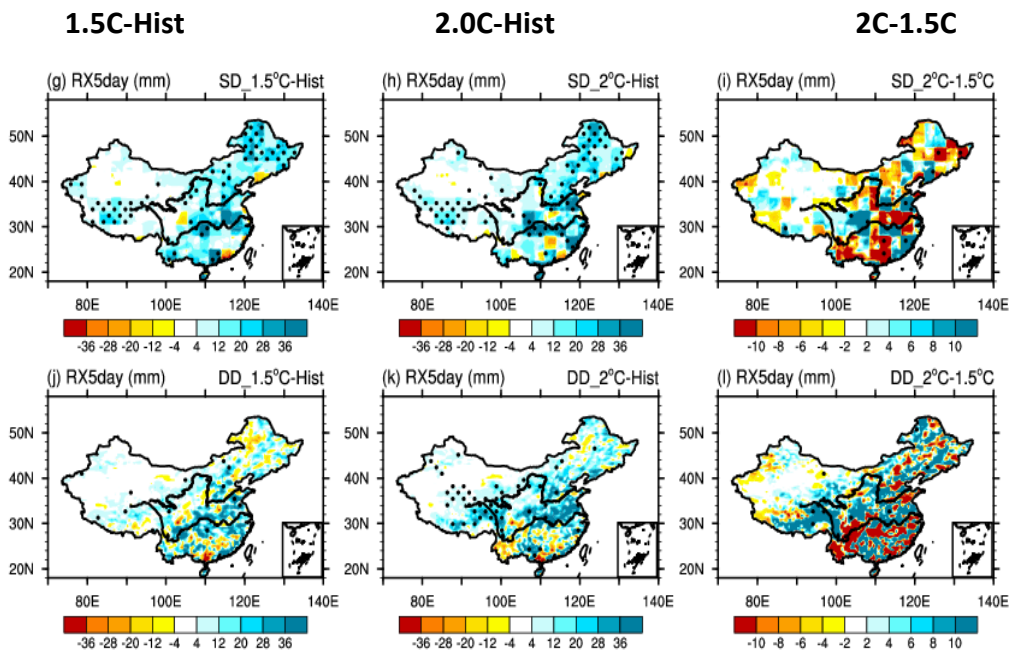
x: 不同方法预估变化符号不一致

- 部分区域变化显著 (高信度)
- 方法不确定性大 (变化符号不一致)

统计降尺度、RCM动力降尺度比较

统计降尺度

动力降尺度



统计降尺度方法: (观测-粗分辨率模拟) 回归模型

利用高阶多项式拟合观测和模拟的降水

将现代状况下的统计关系推广到预估的气候 (气温和降水)

Dettinger et al. (2004)

RX5day 在青藏高原西北部地区、黄河和长江流域将增加



汇报提纲

- ◆ 两类预估问题
- ◆ 近期年代际预测
- ◆ 中长期气候预估
- ◆ 基于温升阈值的预估
- ◆ 结语

Summary

- 降水的预估较之温度的预估更富有挑战性，两类预估结果的不确定性来源不同。
- 基于情景的近期预估：不确定性来自内部变率，初始化的近期预测试验显著提高区域技巧。
- 基于情景的中远期预估：不确定性来自模式自身，涌现约束技术是行之有效的选择。动力降尺度在东亚地区具有显著的Added value。
- 基于温升阈值的预估：大尺度特征一致，区域尺度结果受模拟策略影响大，需要关注不同试验设计的影响、动力和统计降尺度的差异。

Implementing the WCRP Strategy

WCRP will prioritize its science and implement its Strategy by pursuing a series of Lighthouse Activities, along with other core research activities, to deliver and achieve critical outcomes over the next decade

A photograph of a lighthouse on a rocky island at dusk. The lighthouse is illuminated, and its light is visible. A stone walkway leads from the foreground towards the lighthouse. The ocean is visible in the background, with waves crashing against the rocks. The sky is dark blue.

灯塔行动

Explaining and
Predicting Earth
System Change

My Climate Risk

Digital Earths

Safe Landing
Climates

WCRP Academy

Lighthouse Activities 五大灯塔行动：区域到局地尺度的气候预估