中国科学院大气物理研究所

气候模拟与气候变化科学

周天军

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

提纲

- ◆ 从气候变化简史看气候模拟
- ◆ 国际耦合模式比较计划
- ◆ 对气候变化科学的推动
- ◆ 气候模式的未来

The Nobel Prize in Physics 2021

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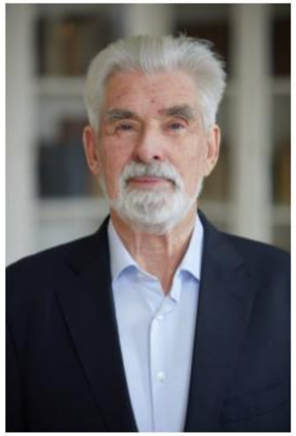
Syukuro Manabe

Prize share: 1/4



© Nobel Prize Outreach. Photo: Bernhard Ludewig

Klaus Hasselmann

Prize share: 1/4

© Nobel Prize Outreach. Photo: Laura Sbarbori

Giorgio Parisi

Prize share: 1/2

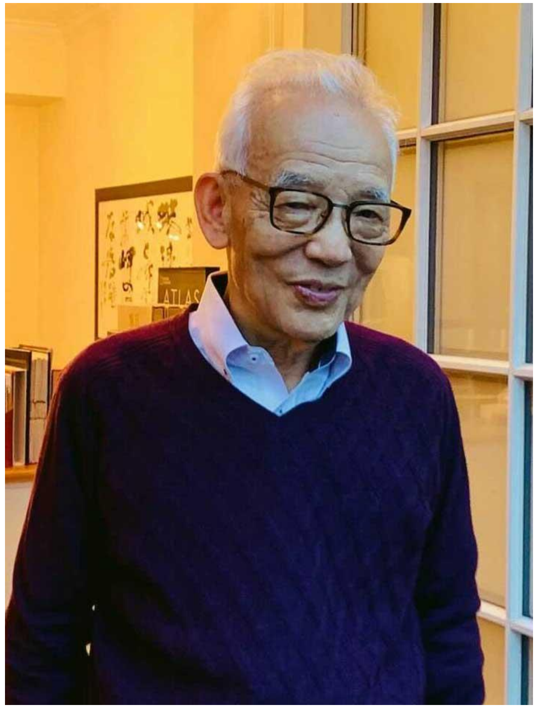
The Nobel Prize in Physics 2021 was awarded "for groundbreaking contributions to our understanding of complex systems" with one half jointly to Syukuro Manabe and Klaus Hasselmann "for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming" and the other half to Giorgio Parisi "for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales."

2021年诺贝尔物理学奖首次被授予气候学家，真锅淑郎（Syukuro Manabe）和克劳斯·哈塞尔曼（Klaus Hasselmann）获此殊荣，以表彰他们“**对地球气候的物理模拟、量化变率和可靠地预测全球变暖**”做出的贡献。

https://www.nobelprize.org/prizes/physics/2021/summary/

2021年的诺贝尔物理学奖

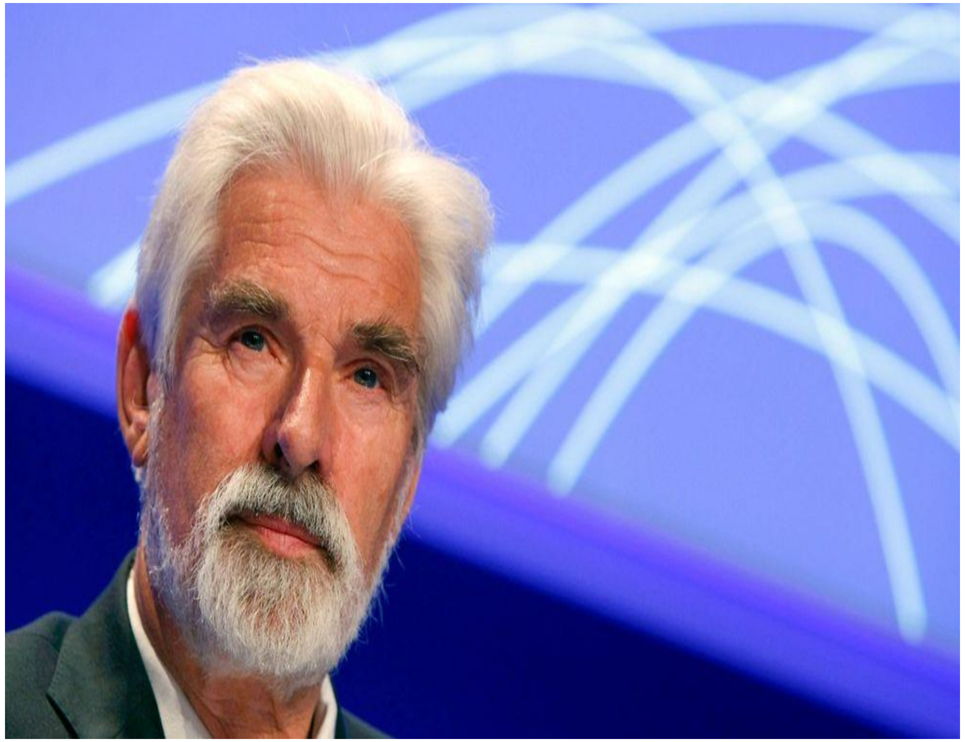
为何授予气候学家?



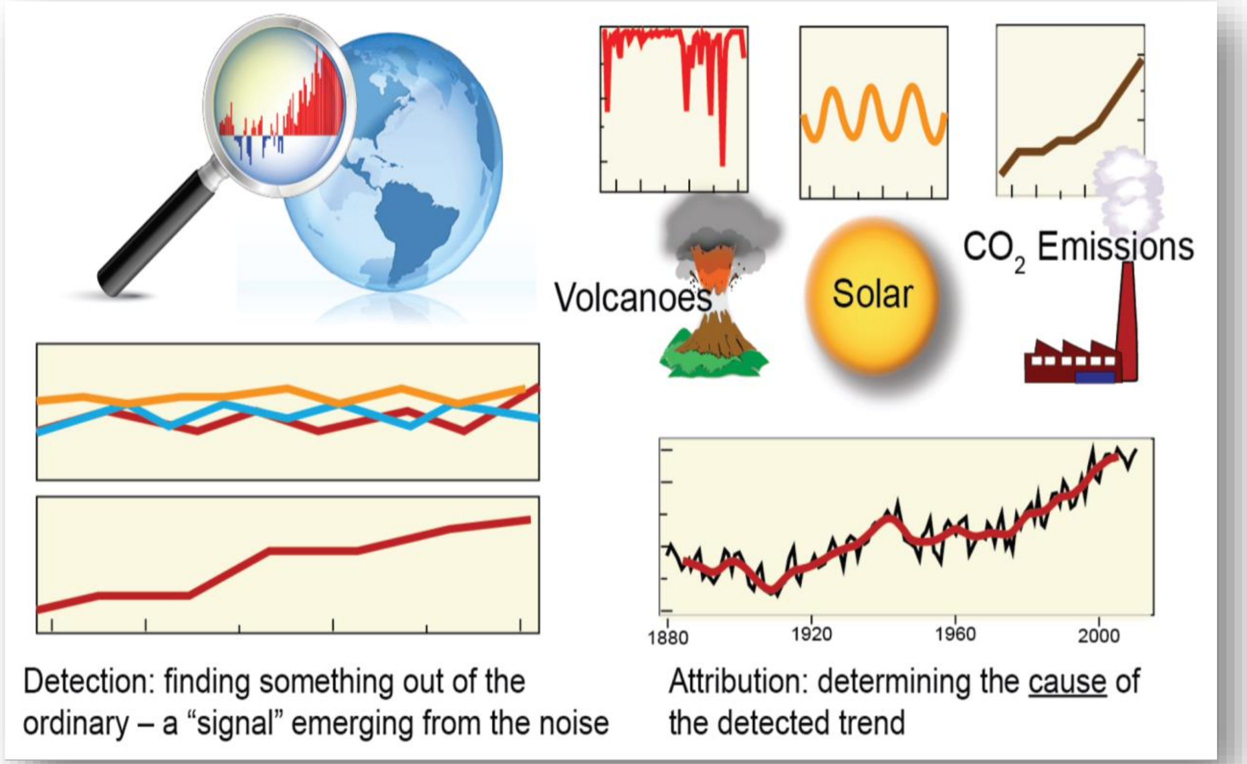
Syukuro Manabe，2021诺贝尔物理学奖

Richard Wetherald

- 1967年，真锅淑郎（Syukuro Manabe）和理查德•韦瑟尔德（Richard Wetherald）首次可靠地预测CO_2浓度加倍后所引起的变暖的大小，终结了此前关于二氧化碳是否导致全球变暖的辩论。
- 1975年，以真锅淑郎和韦瑟尔德（1975）的文章发表为标志，代表着三维大气环流气候模式的诞生。



克劳斯·哈塞尔曼（Klaus Hasselmann）
2021 诺贝尔物理学奖



检测归因：寻找人类活动影响的“指纹”

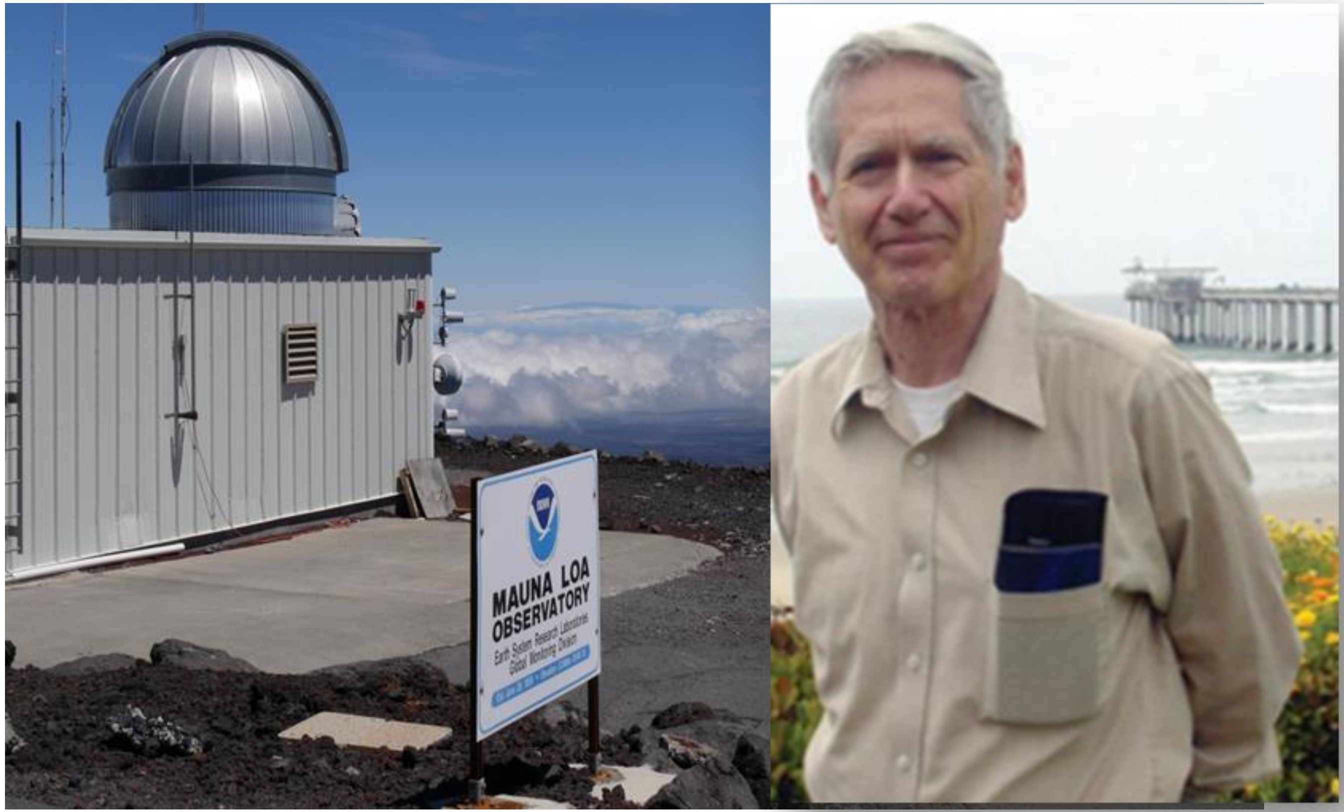
两大学术贡献：随机气候模型、最优指纹法

从1827年温室效应最早被提出，到气候学家首次被授予诺贝尔物理学奖，经历了漫长的195年的历程

周天军，张文霞，陈德亮，张学斌 等：**2021年诺贝尔物理学奖解读：从温室效应到地球系统科学**. 中国科学, 2021, 52, doi: 10.1360/SSTe-2021-0338

CO_2增加，温室效应，能量平衡，现代气候学的开端

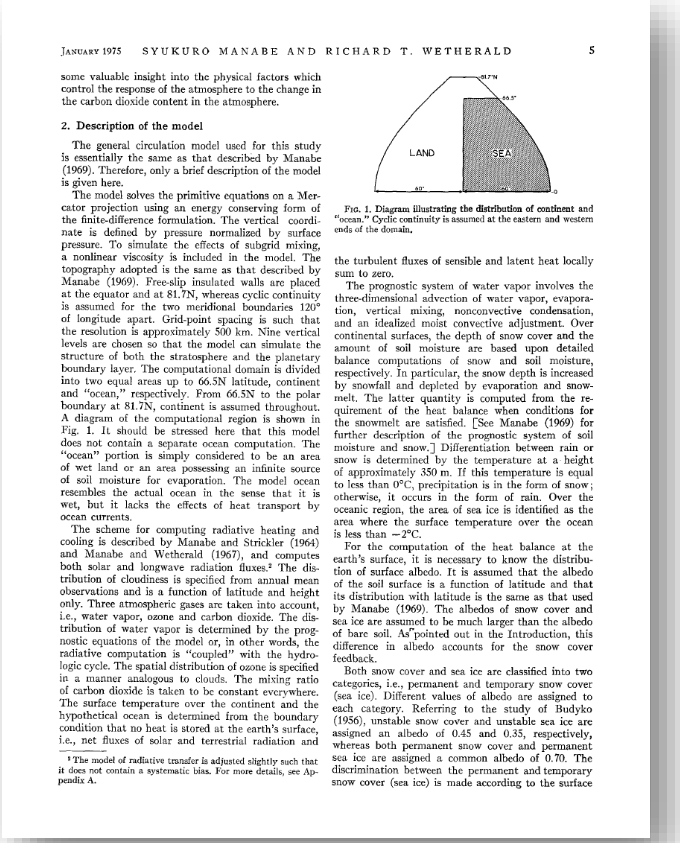
斯凡特•阿伦尼乌斯（1859-1927）：1896年，利用气候模型从能量平衡的角度解释二氧化碳造成的增暖



Keeling curve：查理斯•大卫•基林, 1957年开始CO_2的观测

https://gml.noaa.gov/ccgg/trends/

1975：第一个GCM的诞生



January 1975 SYUKURO MANABE AND RICHARD T. WETHERALD 5

some valuable insight into the physical factors which control the response of the atmosphere to the change in the carbon dioxide content in the atmosphere.

2. Description of the model

The general circulation model used for this study is essentially the same as that described by Manabe (1969). Therefore, only a brief description of the model is given here.

The model solves the primitive equations on a Mercator projection using an energy conserving form of the finite-difference formulation. The vertical coordinate is defined by pressure normalized by surface pressure. To simulate the effects of subgrid mixing, a nonlinear viscosity is included in the model. The topography adopted is the same as that described by Manabe (1969). Free-slip insulated walls are placed at the equator and at 81.7N, whereas cyclic continuity is assumed for the two meridional boundaries 120° of longitude apart. Grid-point spacing is such that the resolution is approximately 500 km. Nine vertical levels are chosen so that the model can simulate the structure of both the stratosphere and the planetary boundary layer. The computational domain is divided into two equal areas up to 66.5N latitude, continent and "ocean," respectively. From 66.5N to the polar boundary at 81.7N, continent is assumed throughout. A diagram of the computational region is shown in Fig. 1. It should be stressed here that this model does not contain a separate ocean computation. The "ocean" portion is simply considered to be an area of wet land or an area possessing an infinite source of soil moisture for evaporation. The model ocean resembles the actual ocean in the sense that it is wet, but it lacks the effects of heat transport by ocean currents.

The scheme for computing radiative heating and cooling is described by Manabe and Strickler (1964) and Manabe and Wetherald (1967), and computes both solar and longwave radiation fluxes.[2] The distribution of cloudiness is specified from annual mean observations and is a function of latitude and height only. Three atmospheric gases are taken into account, i.e., water vapor, ozone and carbon dioxide. The distribution of water vapor is determined by the prognostic equations of the model or, in other words, the radiative computation is "coupled" with the hydrologic cycle. The spatial distribution of ozone is specified in a manner analogous to clouds. The mixing ratio of carbon dioxide is taken to be constant everywhere. The surface temperature over the continent and the hypothetical ocean is determined from the boundary condition that no heat is stored at the earth's surface, i.e., net fluxes of solar and terrestrial radiation and the turbulent fluxes of sensible and latent heat locally sum to zero.

[2] The model of radiative transfer is adjusted slightly such that it does not contain a systematic bias. For more details, see Appendix A.

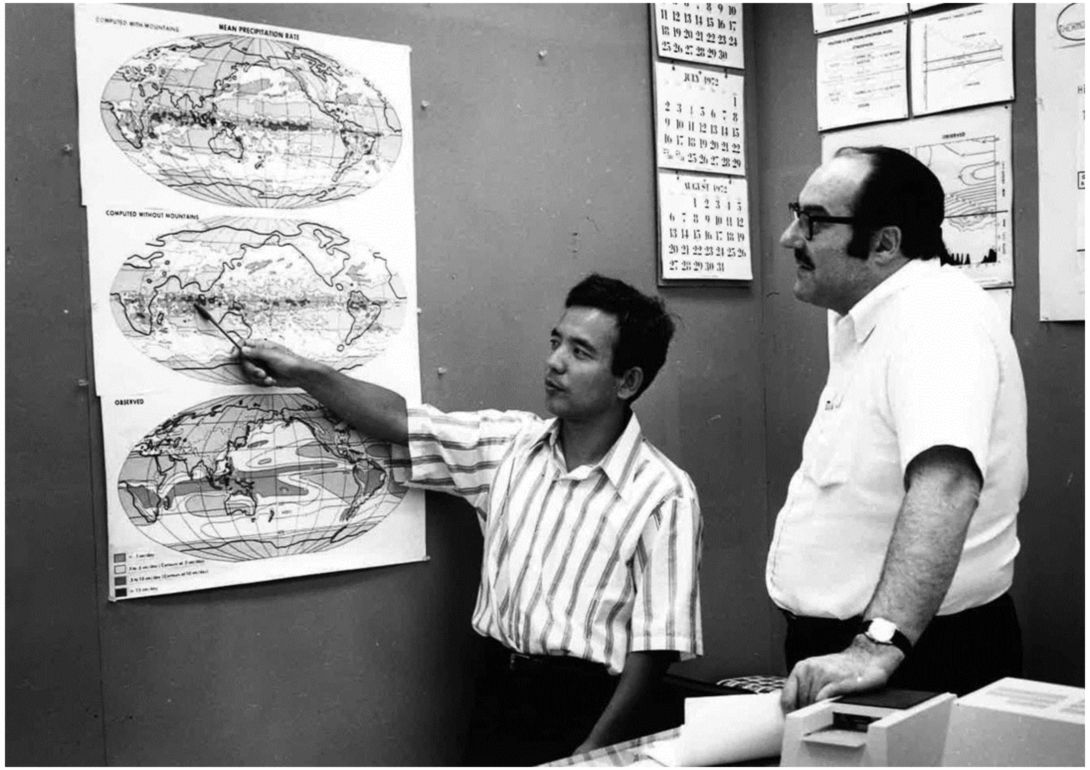
81.7°N
66.5°
LAND
SEA
60°
60°
0

Fig. 1. Diagram illustrating the distribution of continent and "ocean." Cyclic continuity is assumed at the eastern and western ends of the domain.

The prognostic system of water vapor involves the three-dimensional advection of water vapor, evaporation, vertical mixing, nonconvective condensation, and an idealized moist convective adjustment. Over continental surfaces, the depth of snow cover and the amount of soil moisture are based upon detailed balance computations of snow and soil moisture, respectively. In particular, the snow depth is increased by snowfall and depleted by evaporation and snowmelt. The latter quantity is computed from the requirement of the heat balance when conditions for the snowmelt are satisfied. [See Manabe (1969) for further description of the prognostic system of soil moisture and snow.] Differentiation between rain or snow is determined by the temperature at a height of approximately 350 m. If this temperature is equal to less than 0°C, precipitation is in the form of snow; otherwise, it occurs in the form of rain. Over the oceanic region, the area of sea ice is identified as the area where the surface temperature over the ocean is less than −2°C.

For the computation of the heat balance at the earth's surface, it is necessary to know the distribution of surface albedo. It is assumed that the albedo of the soil surface is a function of latitude and that its distribution with latitude is the same as that used by Manabe (1969). The albedos of snow cover and sea ice are assumed to be much larger than the albedo of bare soil. As pointed out in the Introduction, this difference in albedo accounts for the snow cover feedback.

Both snow cover and sea ice are classified into two categories, i.e., permanent and temporary snow cover (sea ice). Different values of albedo are assigned to each category. Referring to the study of Budyko (1956), unstable snow cover and unstable sea ice are assigned an albedo of 0.45 and 0.35, respectively, whereas both permanent snow cover and permanent sea ice are assigned a common albedo of 0.70. The discrimination between the permanent and temporary snow cover (sea ice) is made according to the surface



Suki Manabe & Joseph Smagorinsky

https://www.princeton.edu/news/2021/10/05/great-fun-manabe-wins-nobel-prize-physics-modeling-climate-change

1975：第一个GCM的诞生

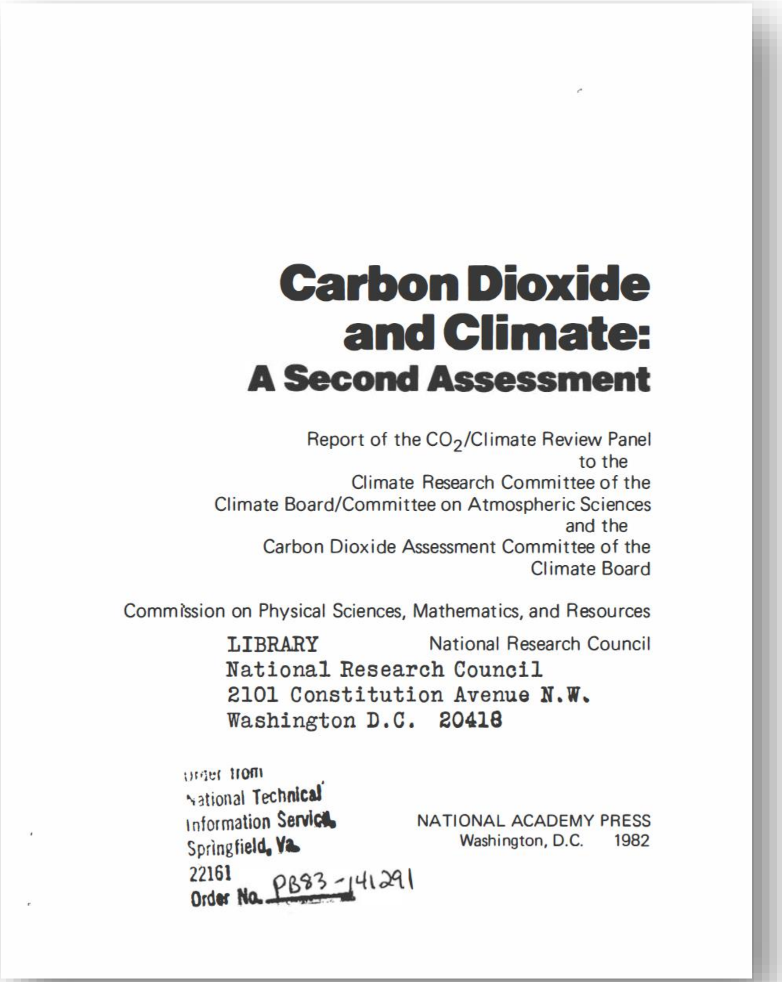
Pioneering meteorologist Joseph Smagorinsky, who developed influential methods for predicting weather and climate conditions, founded the [Geophysical Fluid Dynamics Laboratory] (GFDL) in 1968.

Joseph Smagorinsky 于1958年邀请刚从东京大学毕业的Manabe加入他的团队

https://www.princeton.edu/news/2021/10/05

1979：《二氧化碳与气候》查尼报告出版

基于两个气候模式的结果，“没有理由怀疑大气CO_2浓度加倍会导致全球平均温度出现显著改变，CO_2浓度加倍将令全球温度升高1.5~4.5°C（此即我们现在所说的“气候敏感度”）“



Carbon Dioxide and Climate: A Second Assessment

Report of the CO_2/Climate Review Panel
to the
Climate Research Committee of the
Climate Board/Committee on Atmospheric Sciences
and the
Carbon Dioxide Assessment Committee of the
Climate Board

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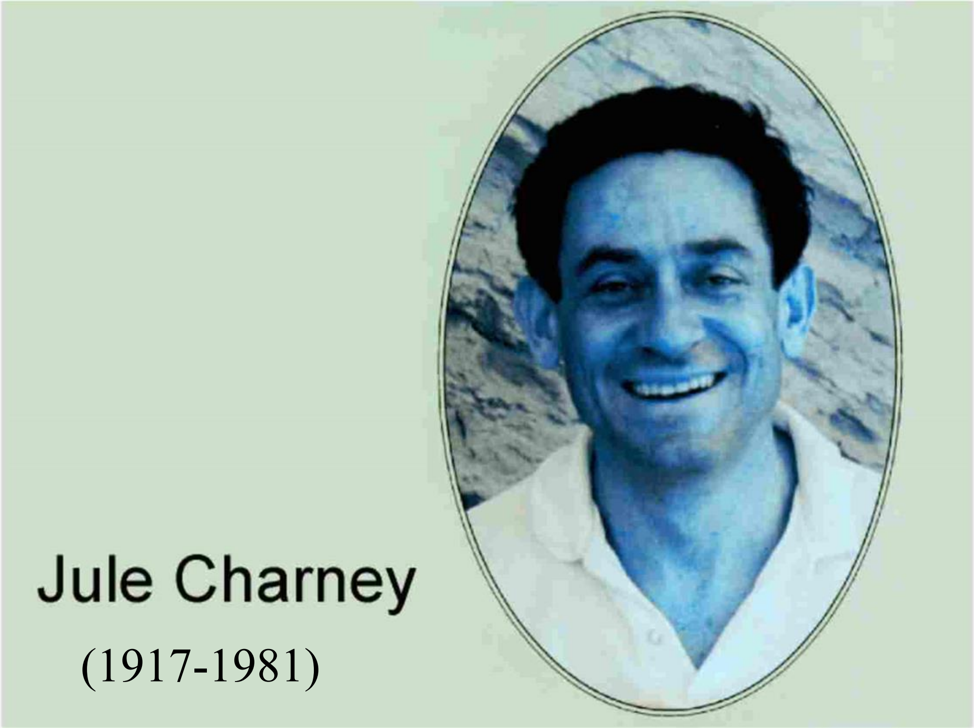
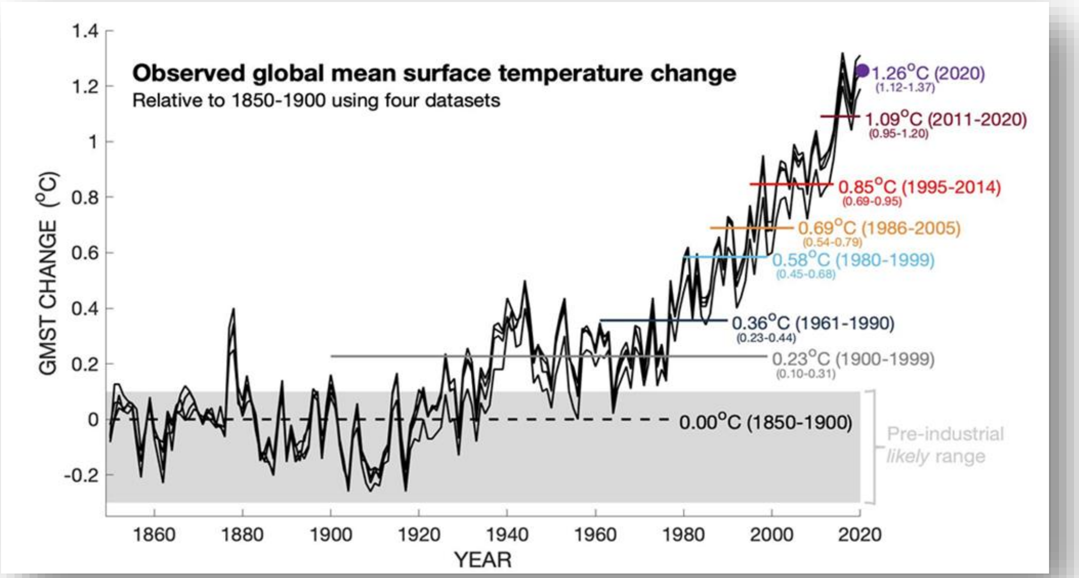
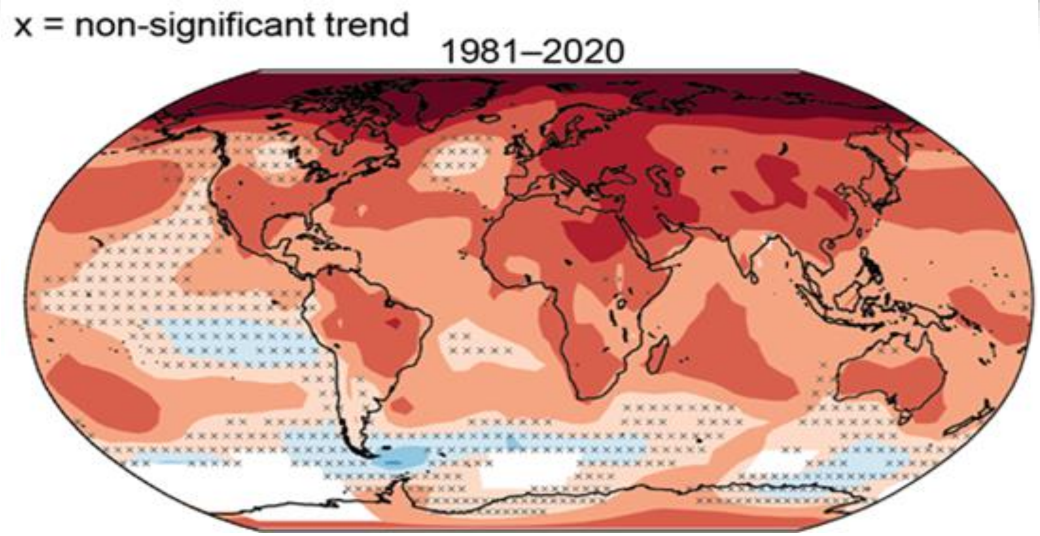
Washington, D.C. 1982

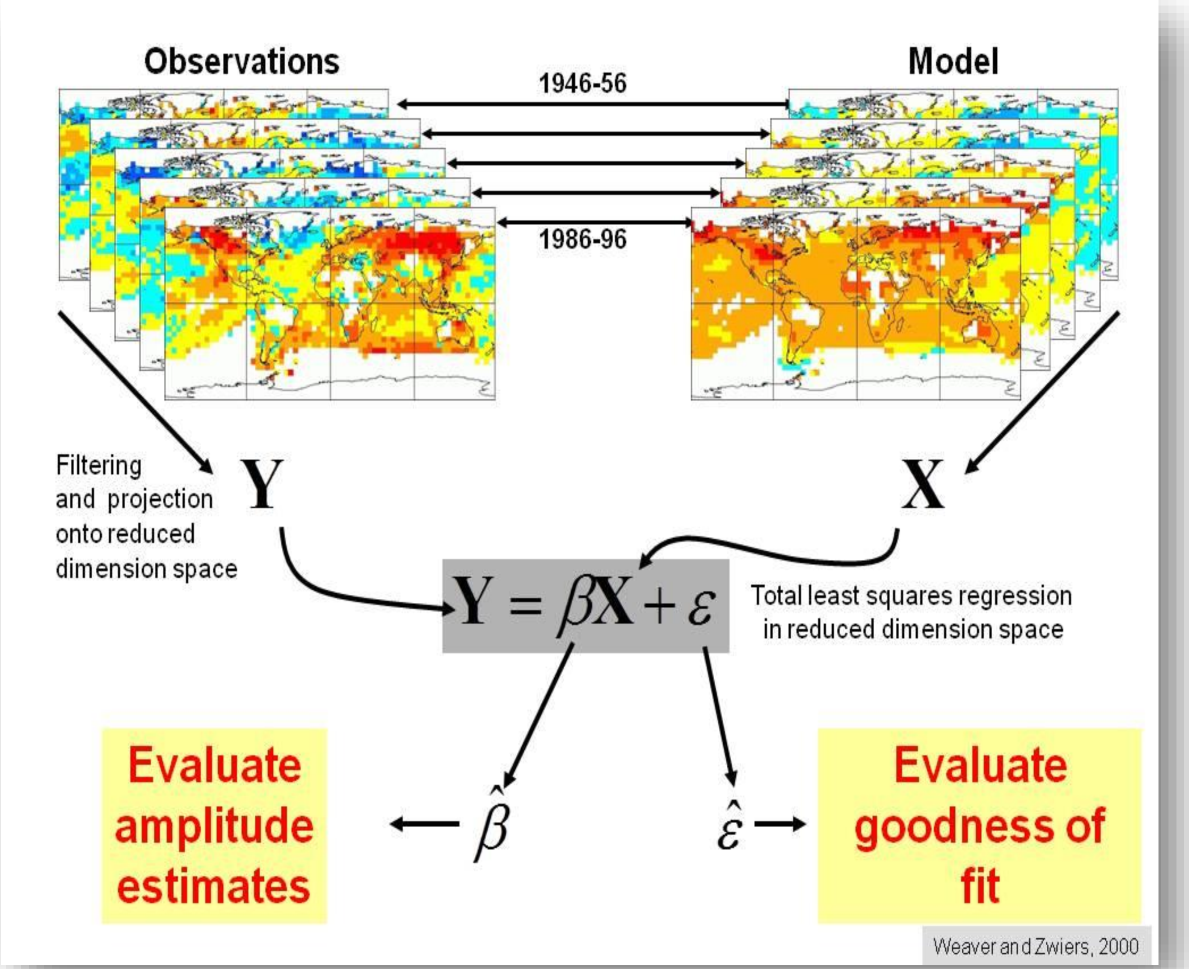


1948-1956：普林斯顿高等研究院，利用准地转近似计算行星波；在数学家、计算机之父John von Neumann领导下任理论气象组主任，证明数值预报可行

Klaus Hasselmann：从观测中寻找人类活动的指纹



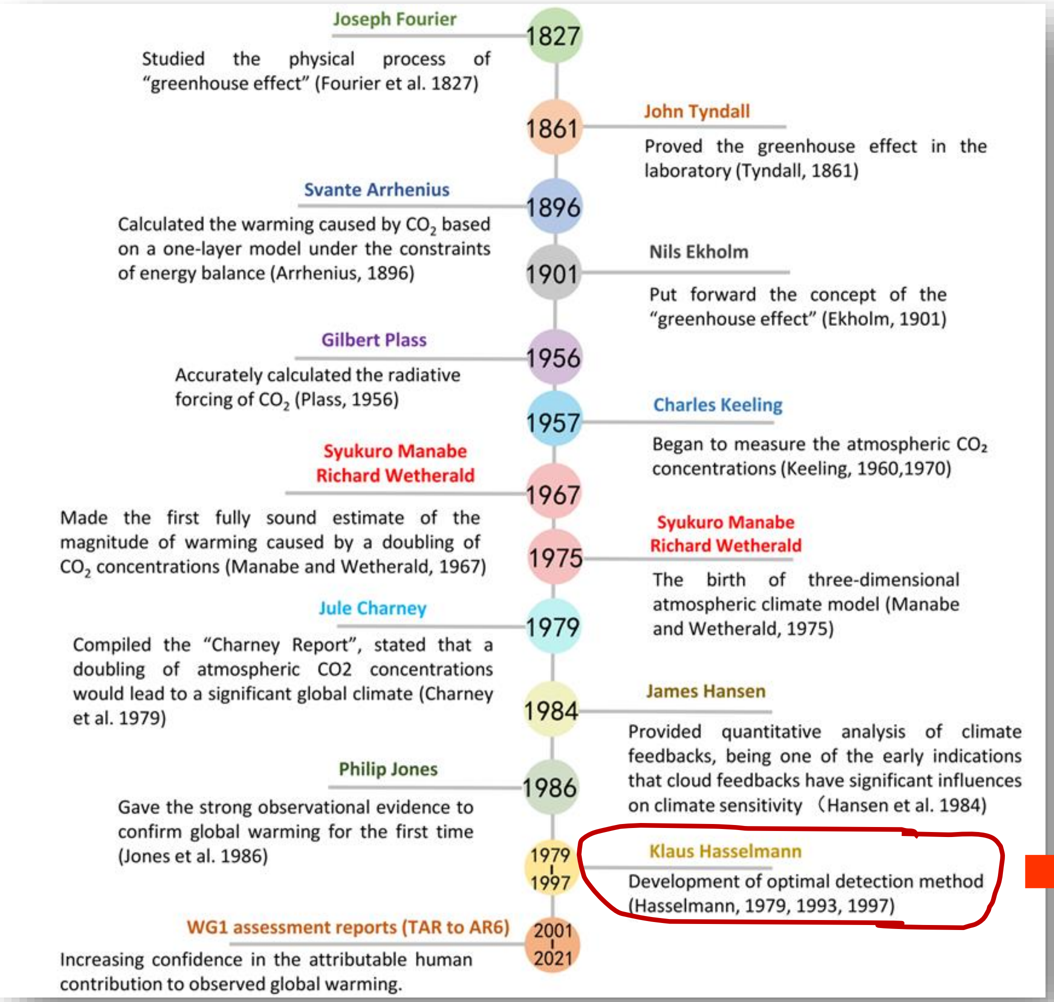




Courtesy to F. Zwiers

（IPCC AR6)

检测归因研究推动工业化以来气候变化驱动因子认知



(Zhou et al. 2021, Science China Earth Sciences)

历次IPCC第一工作组科学评估报告关于全球平均增温的检测归因结论

表 1　历次IPCC第一工作组科学评估报告关于全球平均增温的检测归因结论[a)]

IPCC评估报告	检测归因关注时段	该时段观测增温	各因子(人为外强迫、自然外强迫、自然内部变率)的定量贡献	检测归因结论
FAR及1992年补充报告(1990, 1992)	决策者摘要(SPM)中未综合给出检测归因的定量估算结果			"人类活动产生的各种排放正在使大气中的温室气体浓度显著增加, 这将使温室效应增强, 平均来说就是使地表更暖." "观测到的0.3~0.6℃度增温(过去一个世纪中)…与气候模式预测的结果总体一致, 但其量值与气候自然变率亦相仿. 所以观测到的升温可能很大程度是自然变率引起, 另一种可能是自然变率或其他人为因素已经部分抵消了由人类活动引起的更大的温室效应引起的增温. 要毫无疑义的从观测资料中检测出增强的温室效应引起的升温, 在未来十年或更长时间似乎不太可能."
SAR(1996)	SPM中未综合给出检测归因的定量估算结果			"当前出现的全球变暖不太可能全部是由自然界造成的, 人类活动已经对全球气候系统造成了***可以辨别的***影响."
TAR(2001)	SPM中未综合给出检测归因的定量估算结果			"过去50年观测到的大部分增暖***可能***归因于人类活动造成的温室气体浓度上升(66%以上的可能性)."
AR4(2007)	SPM中未综合给出检测归因的定量估算结果			"全球变暖是不争的事实, 近半个世纪以来的全球变暖***很可能***是人类活动所致(90%以上可能性)"
AR5(2013)	1951~2010	0.6~0.7℃(可能范围)	可能(>66%)范围: 人为强迫: 0.6~0.8℃; 温室气体强迫: 0.5~1.3℃; 其他人为强迫: −0.6~0.1℃; 自然外强迫: −0.1~0.1℃; 自然内部变率: −0.1~0.1℃	"***极有可能***(95%以上可能性)的是, 观测到的1951~2010年全球平均地表温度升高的一半以上是由温室气体浓度的人为增加和其他人为强迫共同导致"
AR6(2021)	1850~1900至2010~2019(与前几次评估报告相比, 归因时段延伸至工业革命以来)	0.9~1.2℃(可能范围)	可能(>66%)范围: 人为强迫: 0.8~1.3℃; 温室气体强迫: 1.0~2.0℃; 其他人为强迫: −0.8~0.0℃; 自然外强迫: −0.1~0.1℃; 自然内部变率: −0.2~0.2℃	"人类活动导致大气、海洋和陆地增暖是***毋庸置疑***的"

a) 表中检测归因的定量结果和信度均基于决策者摘要(SPM)陈述. 人类活动和全球增暖信号的不断增强, 对于归因结论信度的提高有重要作用

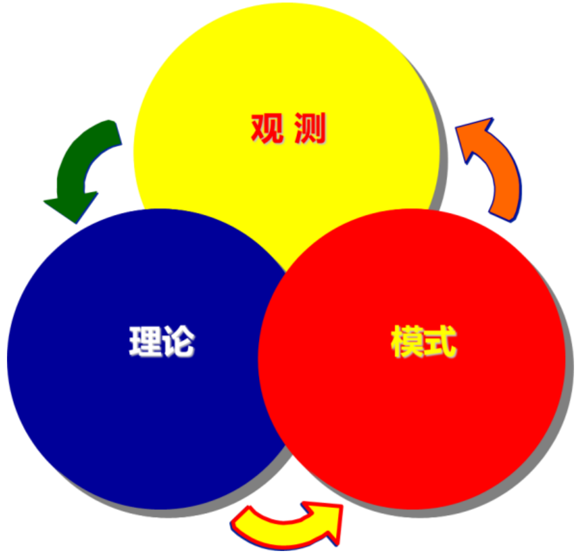
(周天军 等, 2021, 中国科学)

推动气候变化科学发展的关键环节

1. 观测事实的积累发挥了举足轻重的作用
2. 气候物理学理论的日臻完善是成果被认同的基础
3. 气候系统科学的形成为认识气候变化提供了全局视野
4. 地球系统科学的形成拓展了气候变化研究范畴
5. IPCC通过其科学评估报告，极大地推动了气候变化科学研究
6. 依托高性能计算机的发展，**数值模拟技术已经和理论研究、观测研究一道**共同成为支撑现代气候学研究的三大手段

（周天军等，2021，中国科学）

中科院创新团队国际合作伙伴计划
《气候系统模式研发及应用研究》（2004-2008）



（宇如聪，2008）

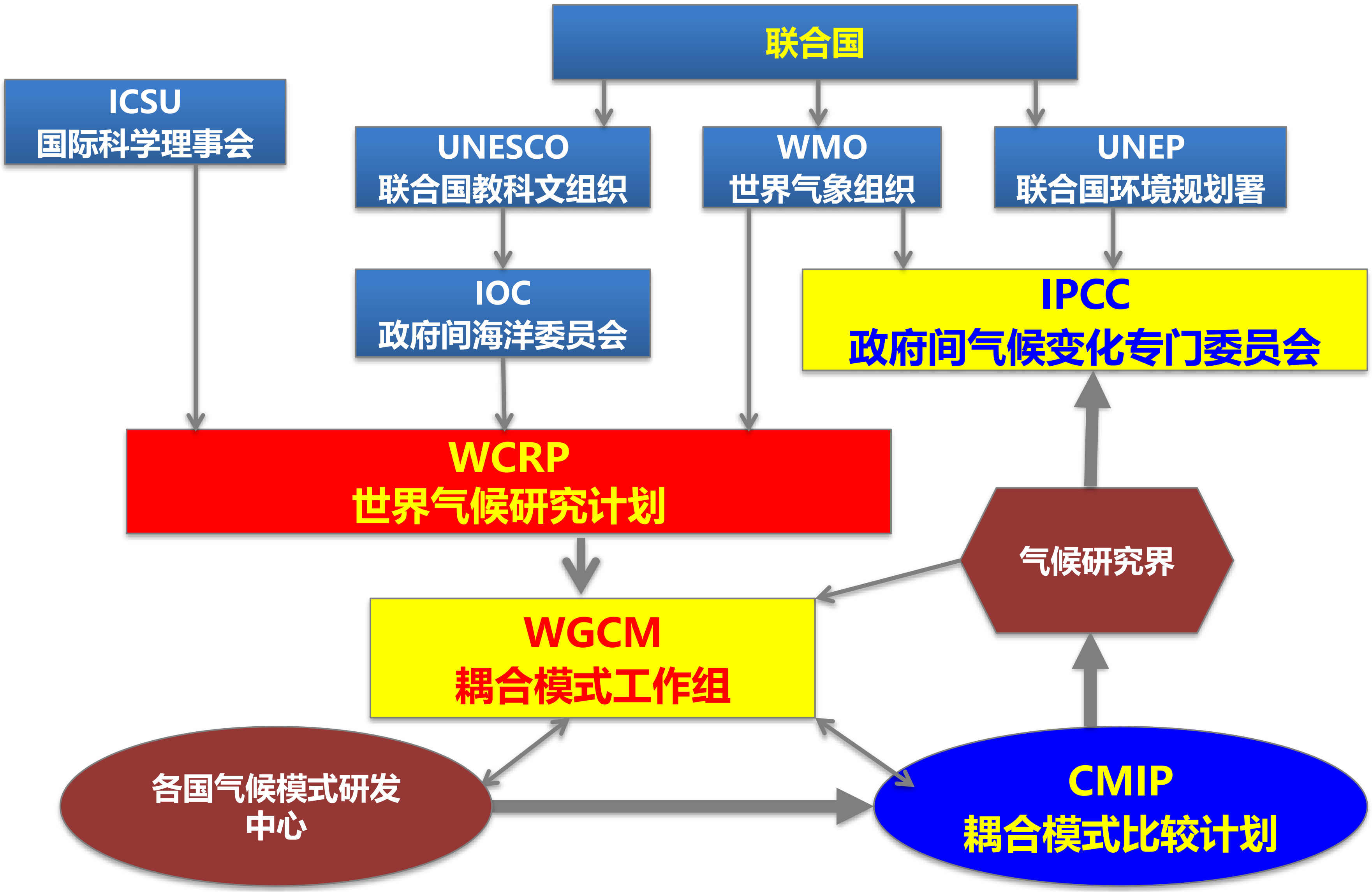
‘Great fun’: Manabe wins Nobel Prize in physics for modeling climate change

https://www.princeton.edu/news/2021/10/05/great-fun-manabe-wins-nobel-prize-physics-modeling-climate-change

提纲

- 从气候变化简史看数值模拟
- 国际耦合模式比较计划
- 对气候变化科学的推动
- 气候模式的未来

国际耦合模式比较计划(CMIP)

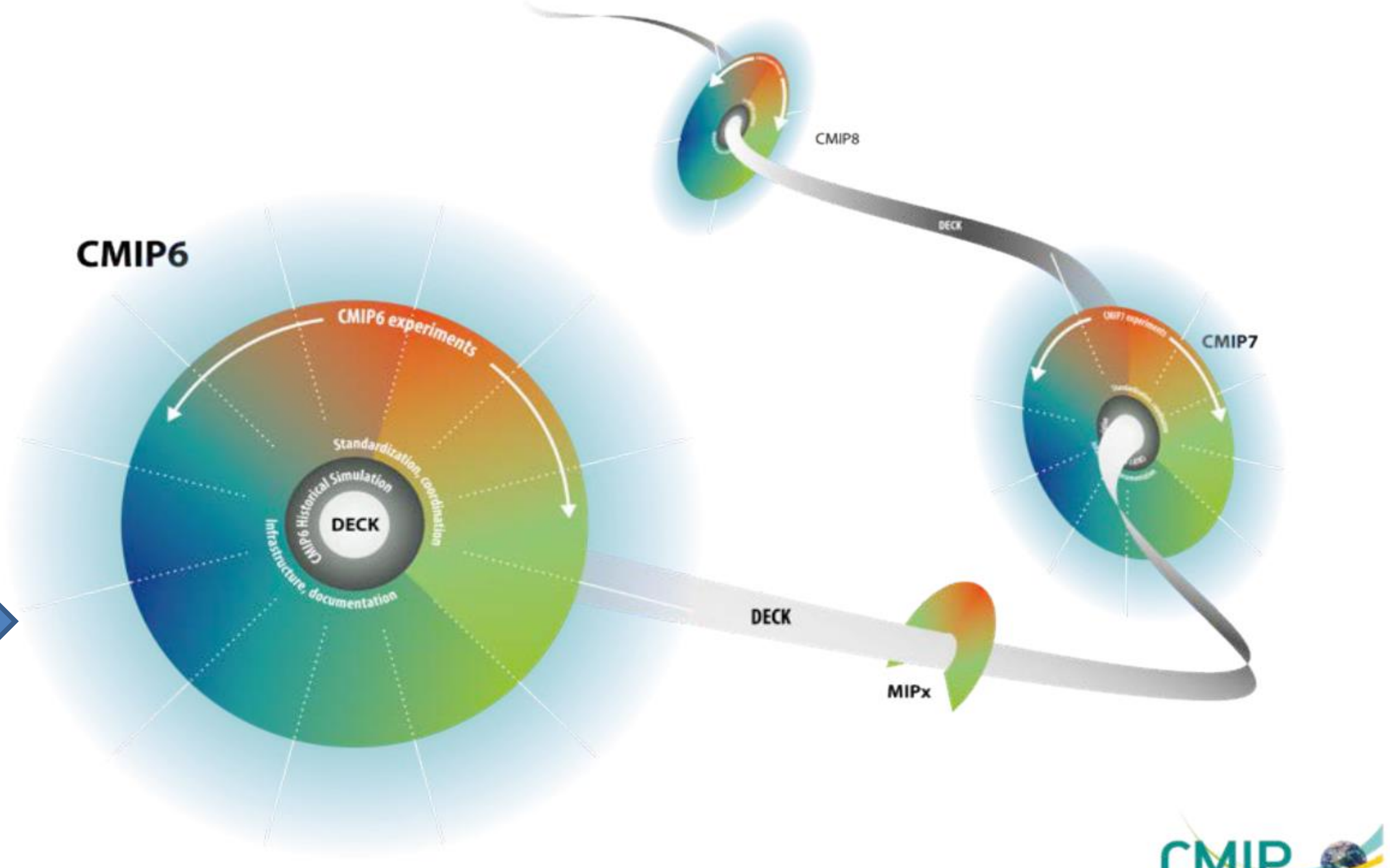


基于Taylor et al. 2012绘制

CMIP Continuity

A common suite of experiments for each phase of CMIP provides an opportunity to construct a multi-model ensemble using model output from various phases of CMIP

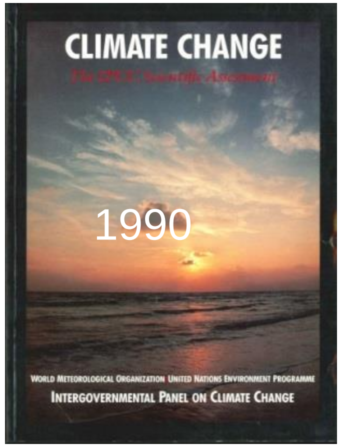
1995

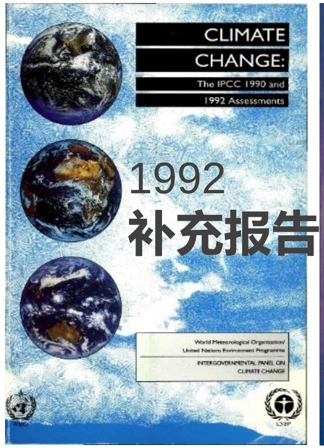


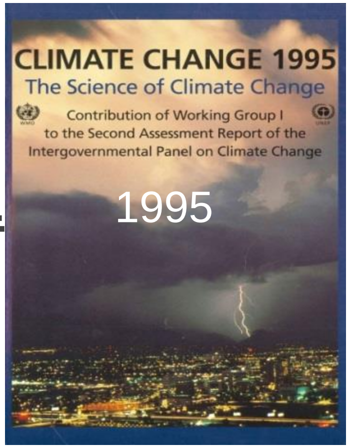
Eyring et al., CMIP6 Experimental Design and Organization, GMD, 2016

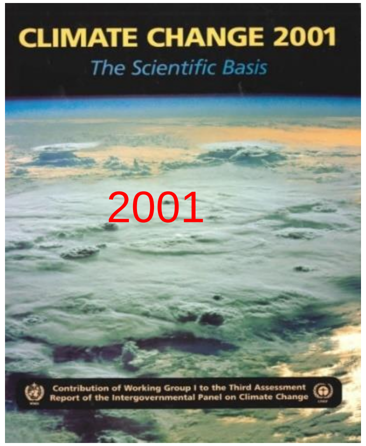
周天军等, 2014: 我国地球气候系统模式研究进展: **CMIP计划实施20年回顾**,**气象学报**, 72(5), 892-907

气候模拟和预估支撑IPCC科学评估报告的编写





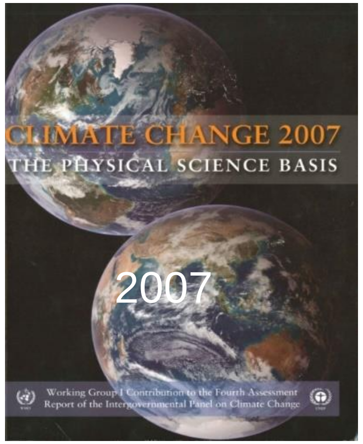


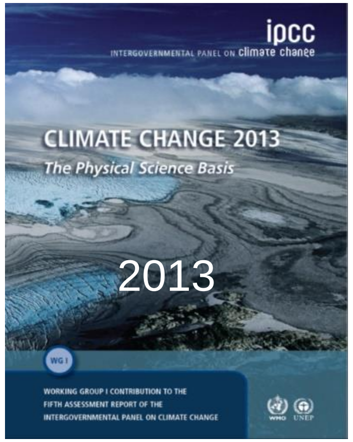


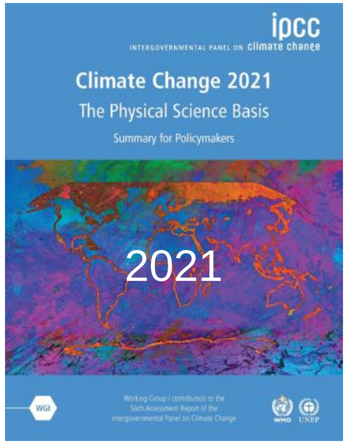
自1990年以来，与第二（WG2）、第三工作组(WG3)一道，IPCC 第一工作组（WG1）已经发布六次科学评估报告。

2007 Nobel Peace Prize:
“for their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change”

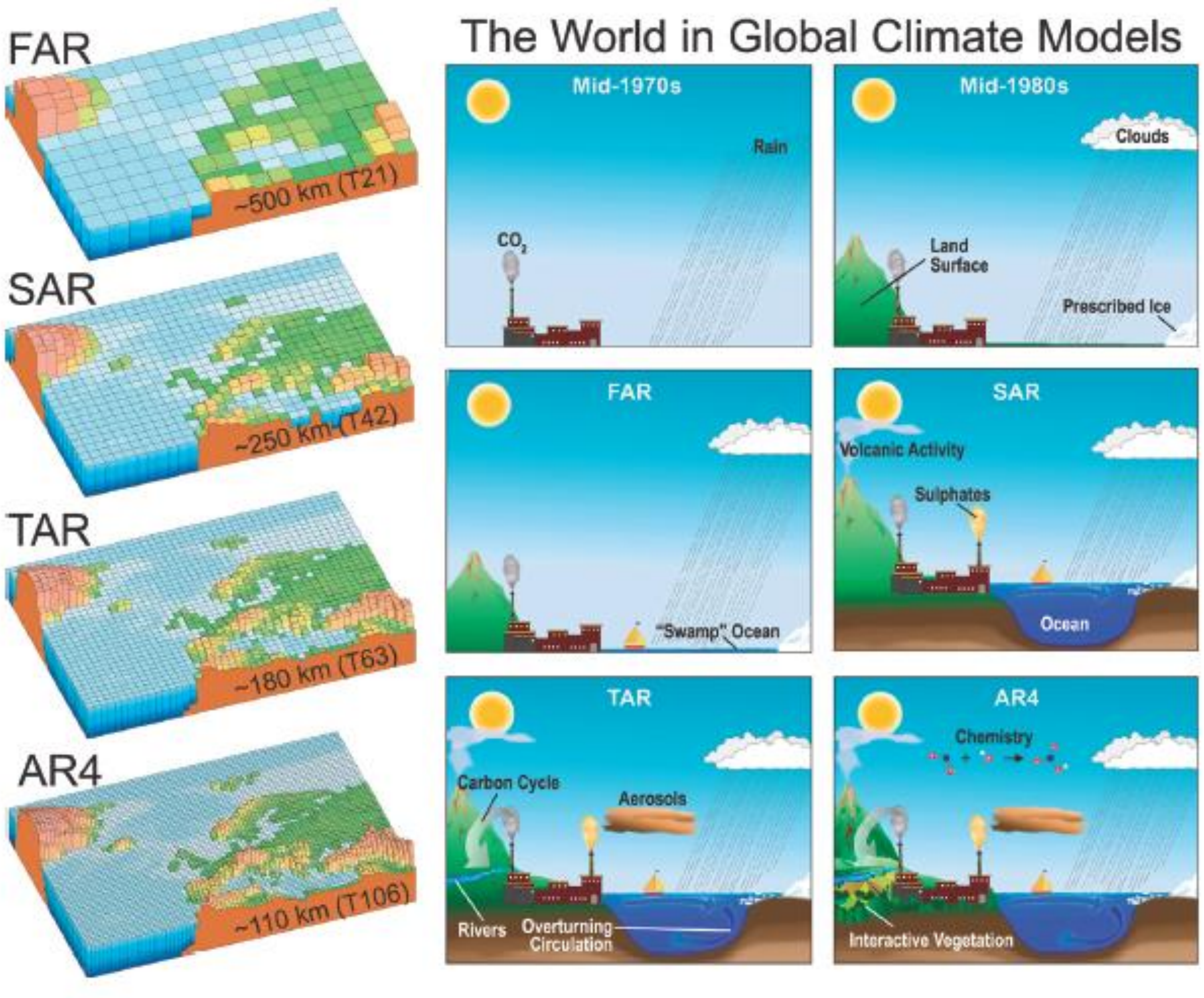
https://www.ipcc.ch/about/history/





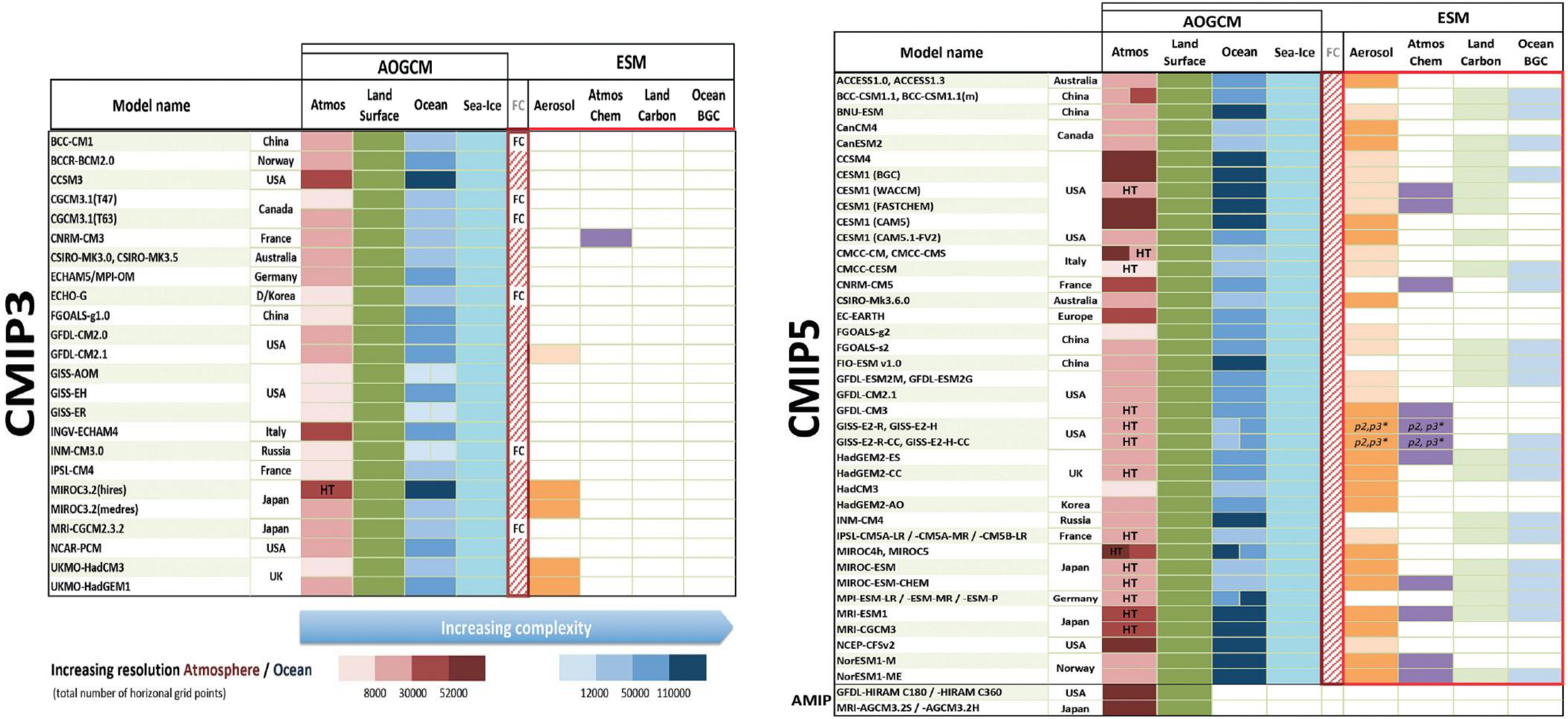


气候模式的发展态势：从第一次到第四次IPCC报告



IPCC 2007

从CMIP3到CMIP5，模式的复杂度增加、分辨率提高

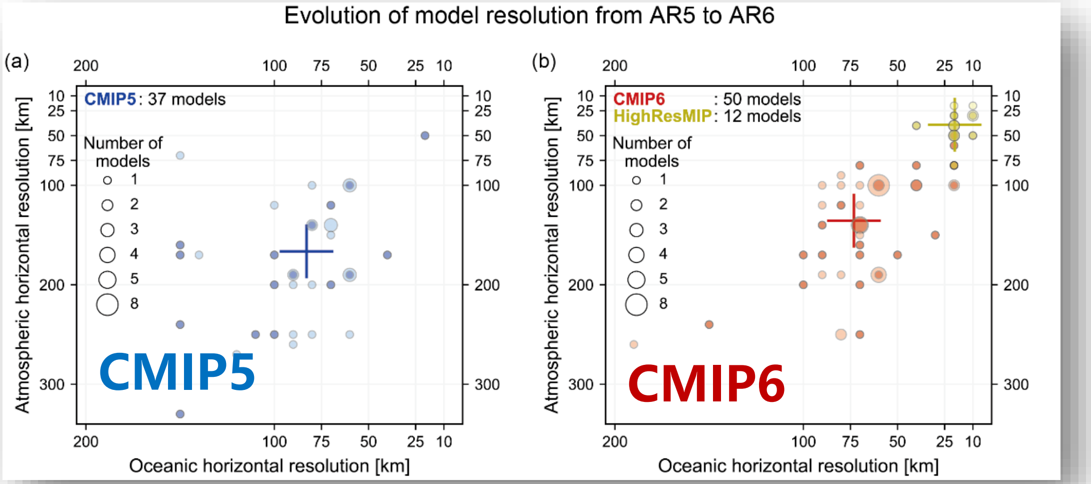


IPCC 2013

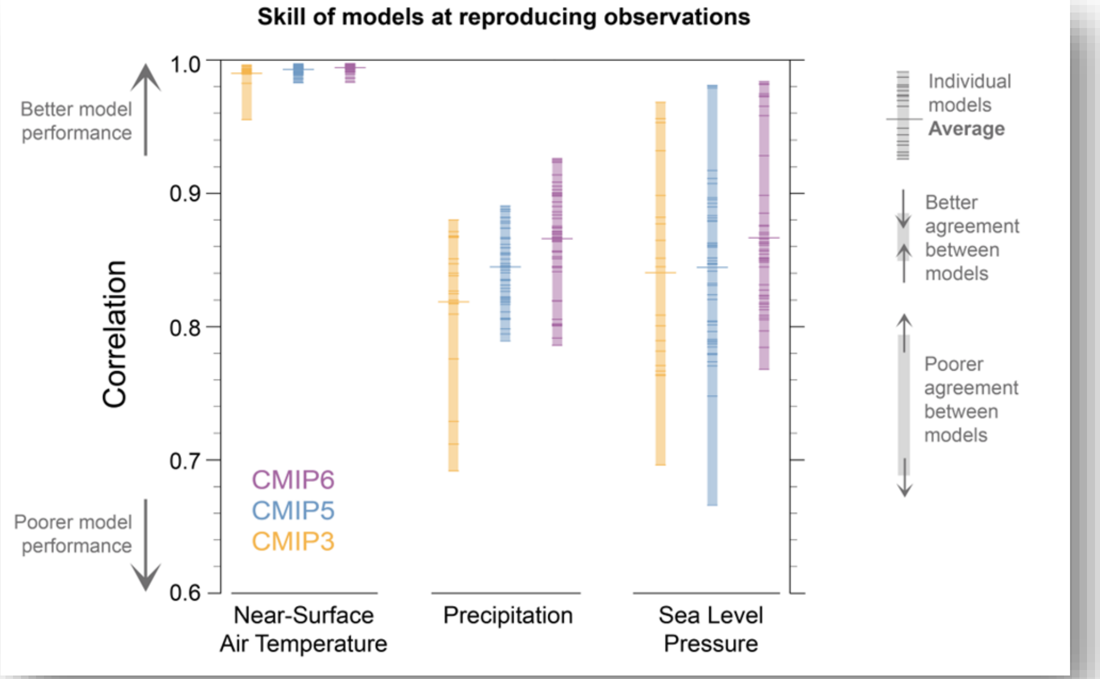
AR5到AR6分辨率的提高

用三个指标评价模式性能的提高

大气模式水平分辨率



海洋模式水平分辨率



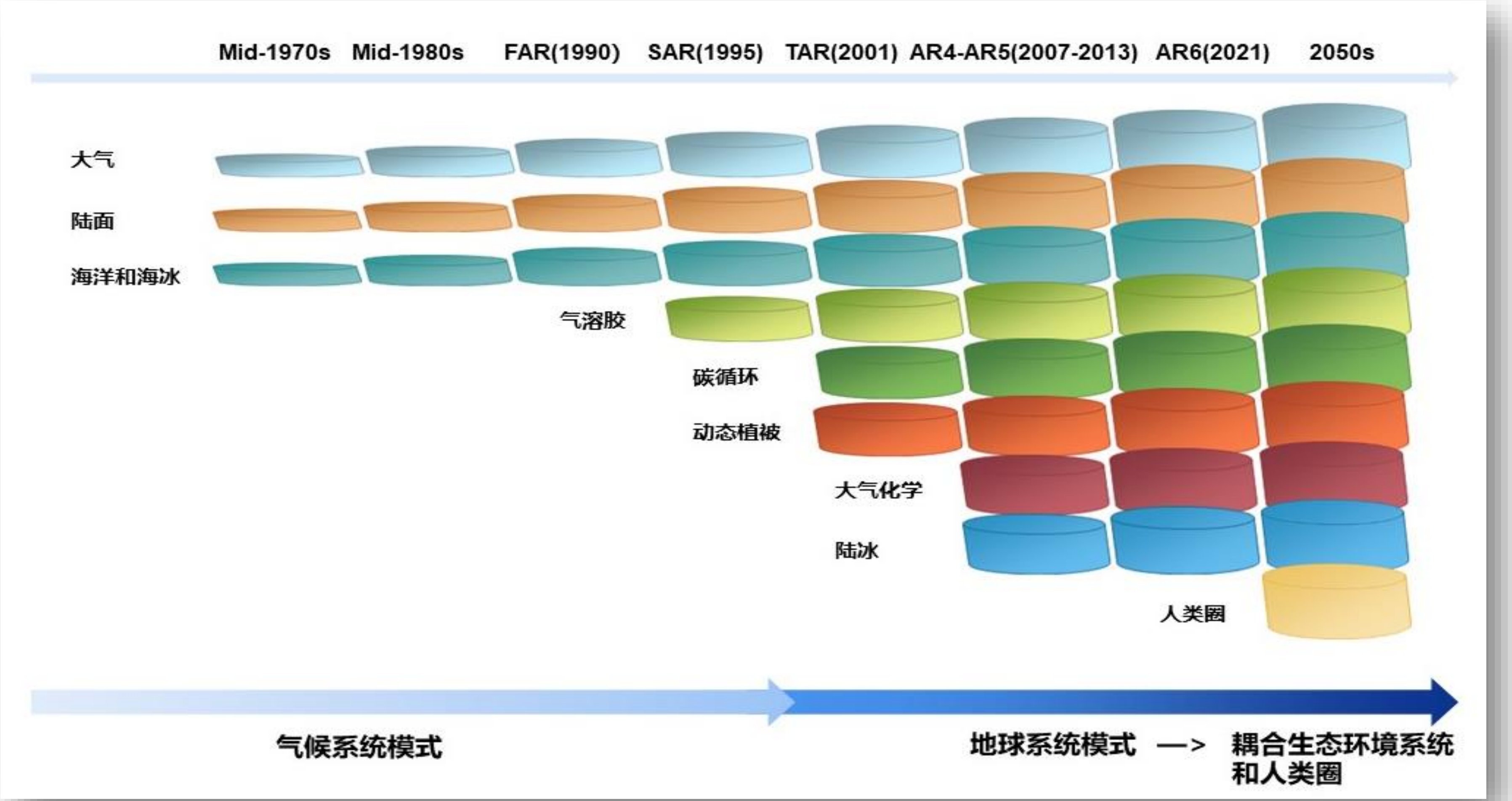
CMIP5: 37个模式

CMIP6: 60个模式

IPCC AR6 Figure 1.19

IPCC AR6 FAQ 3.3

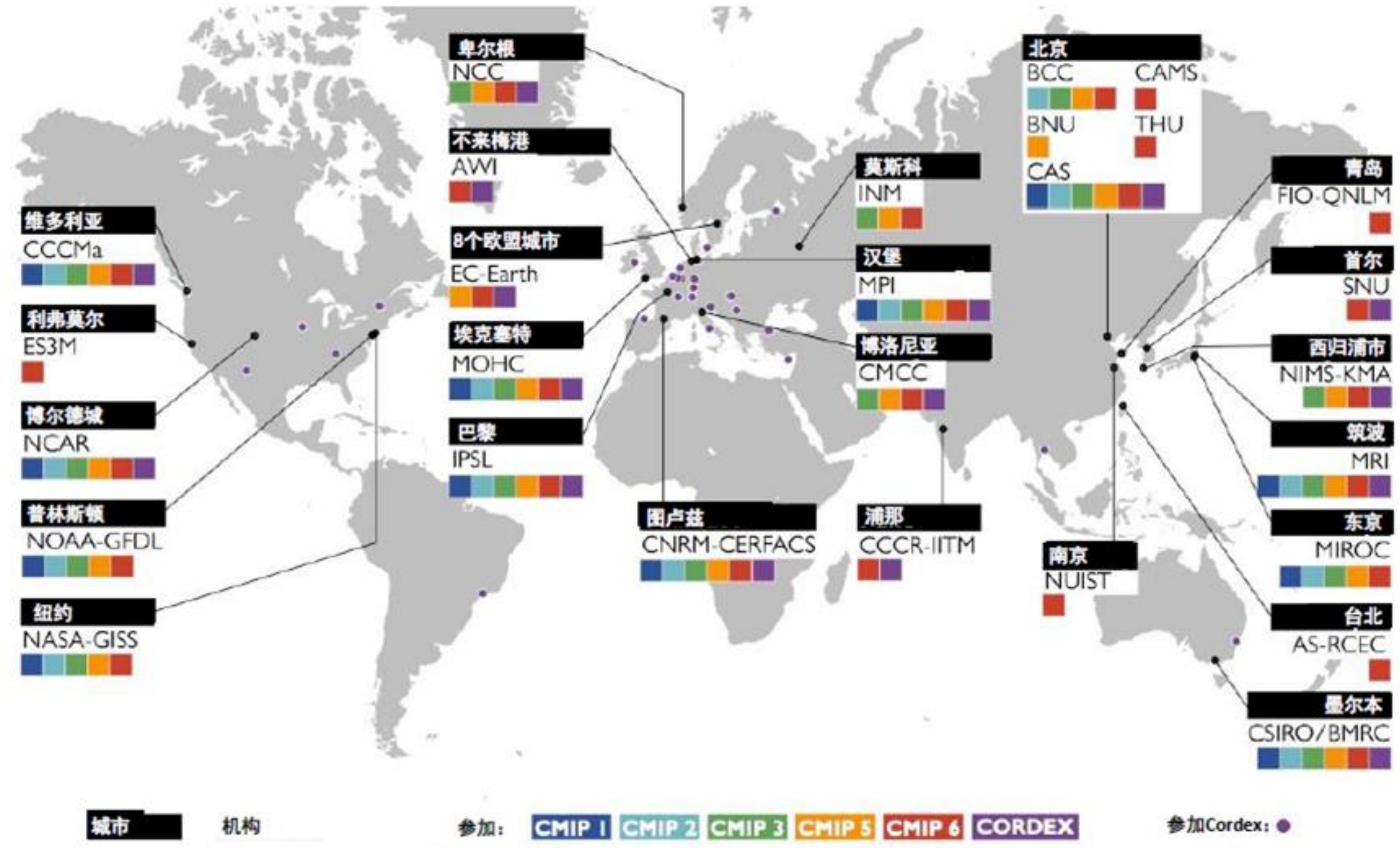
地球气候系统模式的过去、现在和未来



圆柱体高度表示模块的完善和复杂程度（经授权，在IPCC AR5的图1.13基础上基于IPCC AR6的模式信息加以修订）

周天军,张文霞, 陈德亮, 张学斌等，2022: 2021年诺贝尔物理学奖解读: 从温室效应到地球系统科学. 中国科学, 52, doi: 10.1360/SSTe-2021-0338

被IPCC AR6采用的全球地球气候系统模式



IPCC AR6最终用到来自全球28家单位的39个模式版本

(基于IPCC AR6图形修订)

周天军，张文霞，陈德亮，张学斌 等：**2021年诺贝尔物理学奖解读：从温室效应到地球系统科学**. 中国科学, 2021, 52, doi: 10.1360/SSTe-2021-0338

提纲

- ◆ 从气候变化简史看数值模拟
- ◆ 国际耦合模式比较计划
- ◆ **对气候变化科学的推动**
- ◆ 气候模式的未来

WCRP's mission....世界气候研究计划的使命

... is to facilitate analysis and prediction of Earth system variability and change for use in an increasing range of practical applications of direct relevance, benefit and value to society.

The two overarching objectives of WCRP are:

- to determine the predictability of climate气候的可预报性
- to determine the effect of human activities on climate人类活动的影响

WCRP: WORLD CLIMATE RESEARCH PROGRAMME

WMO IOC ICSU WCRP

WCRP Grand Science Challenges 七大科学挑战：应对国际社会需求和联合国SGDs

Water for Food Baskets

Regional Sea Level & Coastal Impacts

Melting Ice & Global Consequences

Near-Term Prediction

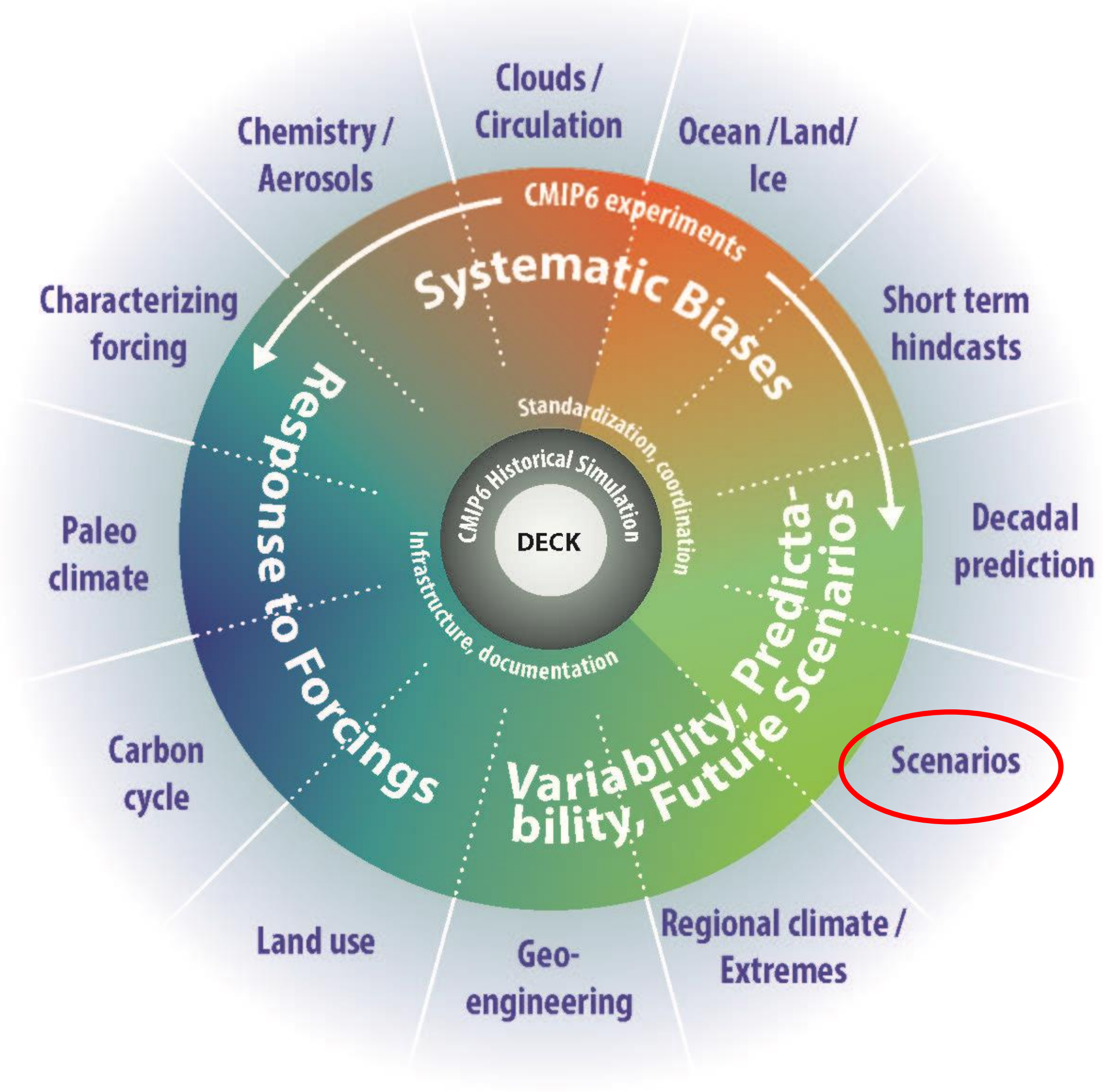
Weather & Climate Extremes

Clouds, Circulation & Climate Sensitivity

Climate & Carbon

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

CMIP6科学试验的设计原则：必须呼应WCRP七大科学挑战问题

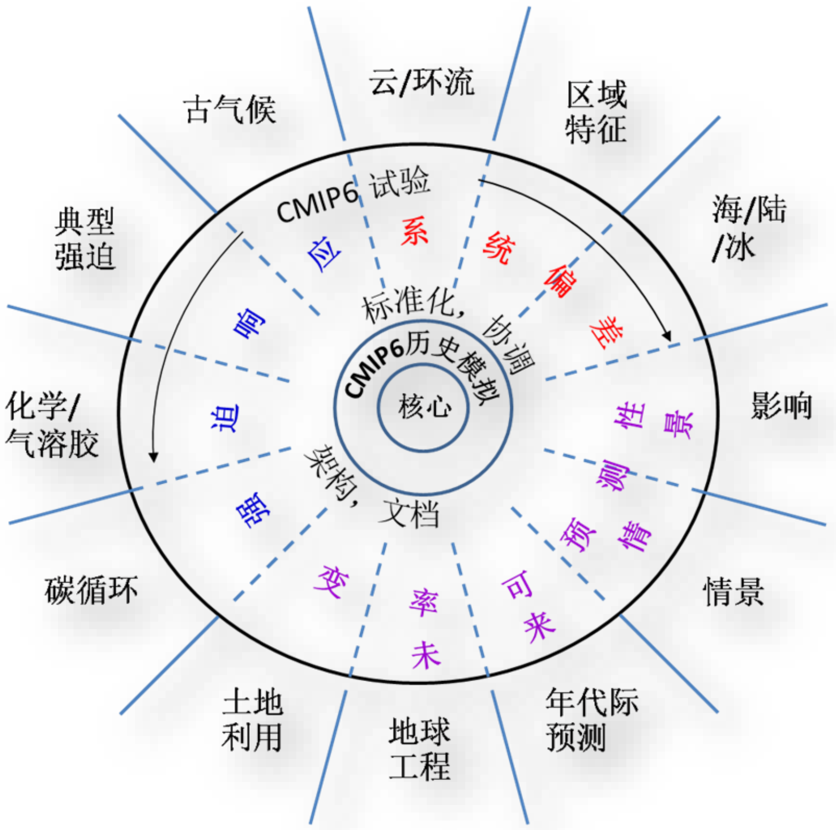


WCRP Grand Challenges:

1. Clouds, circulation and climate sensitivity,
2. Changes in cryosphere,
3. Climate extremes,
4. Regional climate information,
5. Regional sea-level rise, and
6. Water availability, plus an additional theme on “Biogeochemical forcings and feedbacks”

(Courtesy to Veronika Eyring)

CMIP6试验设计示意图



(基于CMIP6图形绘制)

- 最内环其周边黑色文字代表CMIP 核心（DECK）试验和CMIP6历史模拟的标准功能；
- 中间层列出了CMIP6子计划所解决的科学主题：

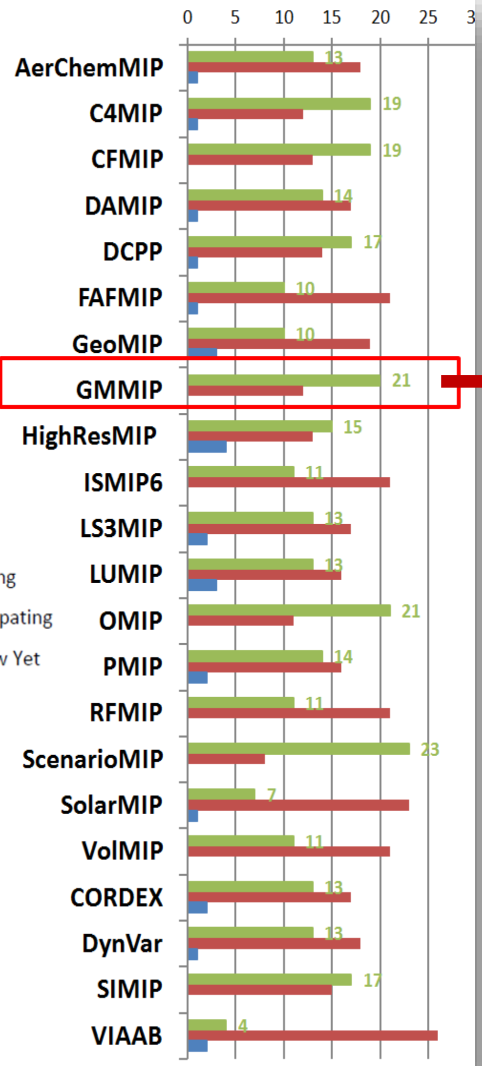
  系统偏差、强迫响应、变率可预报性、未来情景
- 最外层为子计划MIPs的主题。

周天军, 邹立维, 陈晓龙. 2019: 第六次国际耦合模式比较计划（CMIP6）评述. **气候变化研究进展**, 15(5): 445-456.

CMIP6框架下的模拟试验计划(MIPs)

Proposals from CMIP6-Endorsed MIPs & Model Groups' Commitments to Participate in each MIP

	Long Name of MIP (Short Name of MIP)
1	Aerosols and Chemistry Model Intercomparison Project (AerChemMIP)
2	Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP)
3	Cloud Feedback Model Intercomparison Project (CFMIP)
4	Detection and Attribution Model Intercomparison Project (DAMIP)
5	Decadal Climate Prediction Project (DCPP)
6	Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP)
7	Geoengineering Model Intercomparison Project (GeoMIP)
8	Global Monsoons Model Intercomparison Project (GMMIP)
9	High Resolution Model Intercomparison Project (HighResMIP)
10	Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6)
11	Land Surface, Snow and Soil Moisture MIP (LS3MIP)
12	Land-Use Model Intercomparison Project (LUMIP)
13	Ocean Model Intercomparison Project (OMIP)
14	Palaeoclimate Modelling Intercomparison Project (PMIP)
15	Radiative Forcing Model Intercomparison Project (RFMIP)
16	Scenario Model Intercomparison Project (ScenarioMIP)
17	Solar Model Intercomparison Project (SolarMIP)
18	Volcanic Forcings Model Intercomparison Project (VolMIP)
19	*Coordinated Regional Climate Downscaling Experiment (CORDEX)*
20	*Dynamics and Variability of the Stratosphere-Troposphere System (DynVar)*
21	*Sea-Ice Model Intercomparison Project (SIMIP)*
22	*Vulnerability, Impacts, and Adaptation Advisory Board for CMIP6 (VIA AB)*

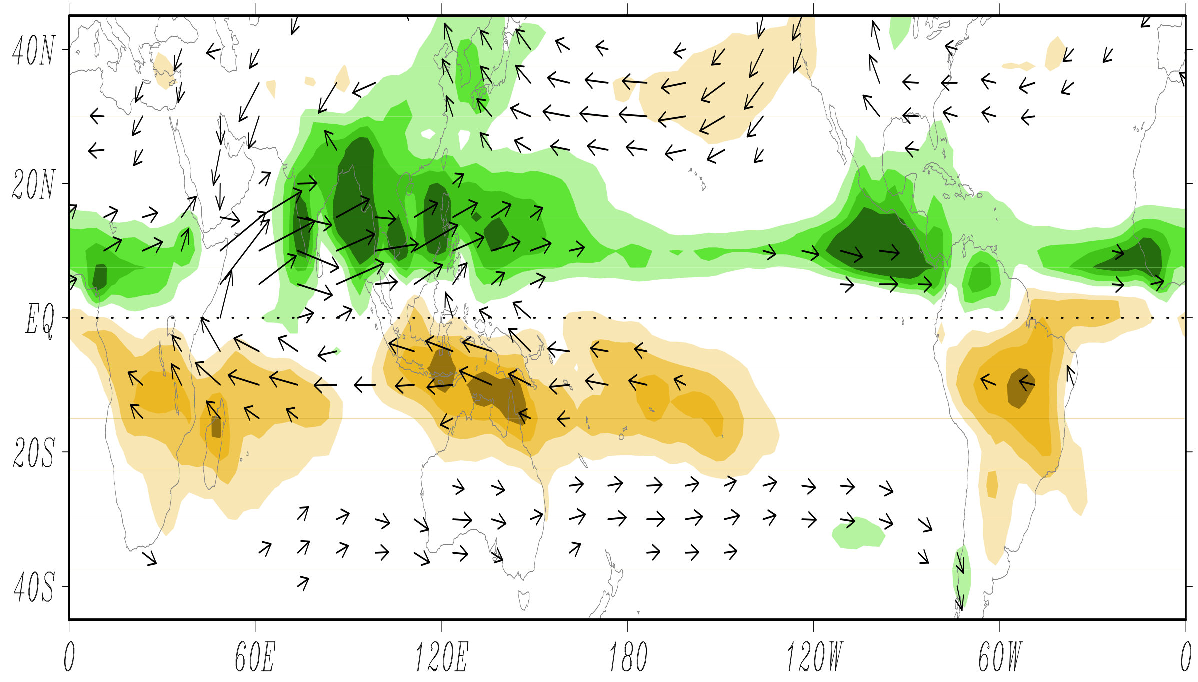


全球季风模拟比较计划

- GMMIP: Global Monsoons Modeling Inter-comparison Project
- Proposed by CLIVAR/GEWEX Monsoons Panel & CLIVAR/C20C+
- Co-chairs:
  Tianjun Zhou,
  Andy Turner,
  James Kinter III
- Secretariat:
  LASG/IAP

CMIP The World Climate Research Programme's Coupled Model Intercomparison Project

全球季风模拟比较计划GMMIP的科学目标



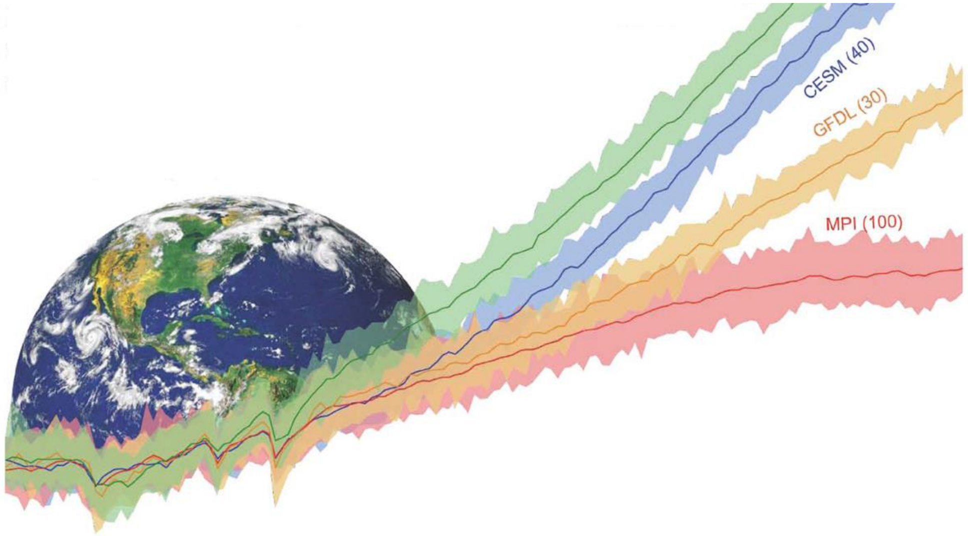
全球季风区示意图 (After Bin Wang)

针对季风变化，展示四个方面进展

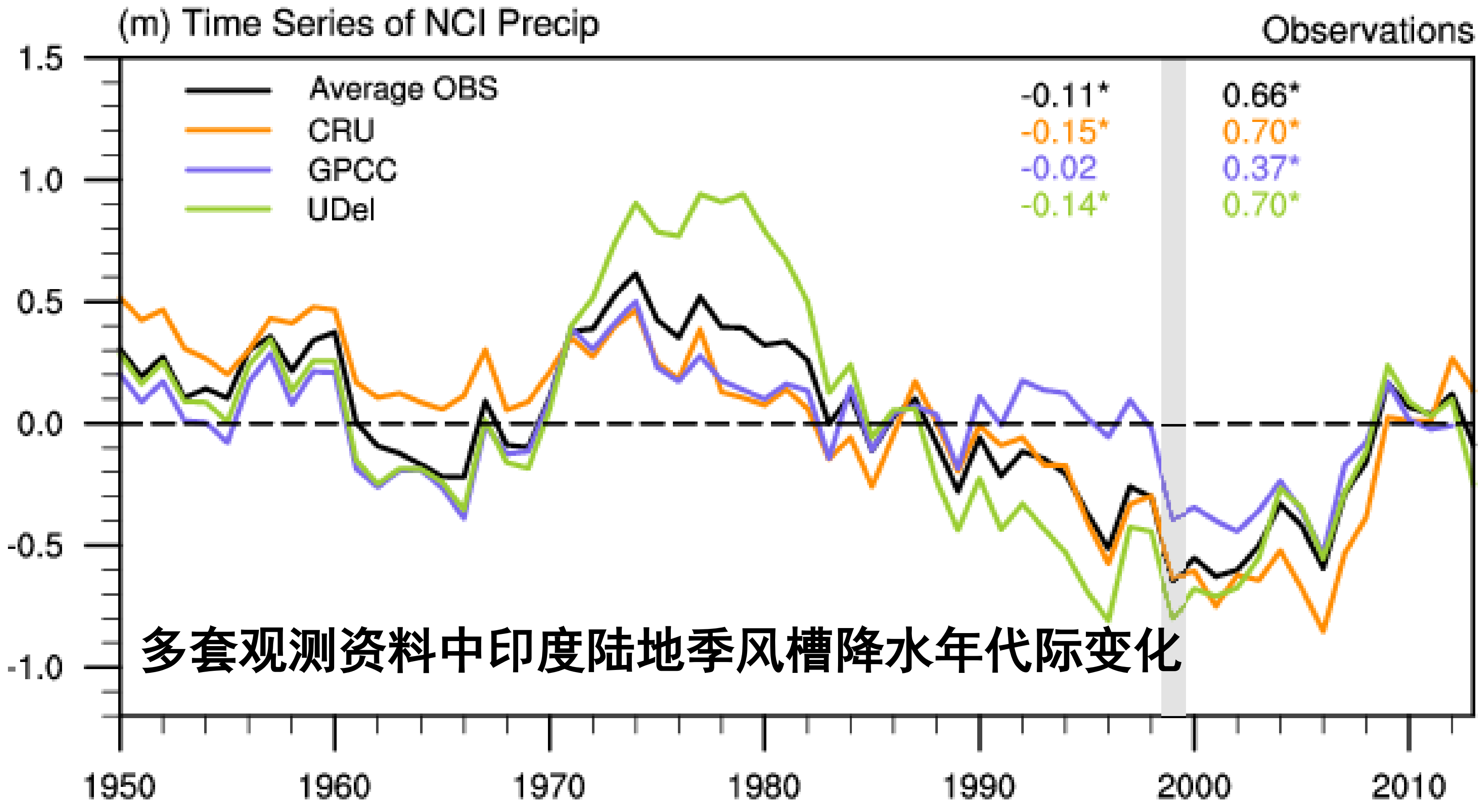
1. What are the relative contributions of internal processes and external forcings that have driven the 20th century historical evolution of global monsoons?
2. To what extent and how does the ocean-atmosphere interaction affect the interannual variability and predictability of monsoons?
3. How well can developing high-resolution models and improving model dynamics and physics help to reliably simulate monsoon precipitation and its variability and change?
4. What are the effects of Eurasian orography, in particular the Himalaya/Tibetan Plateau, on the regional/global monsoons?

Zhou, T., Turner, A. G., Kinter, J. L., et al. 2016: **GMMIP (v1.0) contribution to CMIP6: Global Monsoons Model Inter-comparison Project**, ***Geosci. Model Dev.***, 9, 3589-3604, doi:10.5194/gmd-9-3589-2016, 2016.

个例1：历史变化的机理理解



观测中近65年南亚夏季风降水的变化



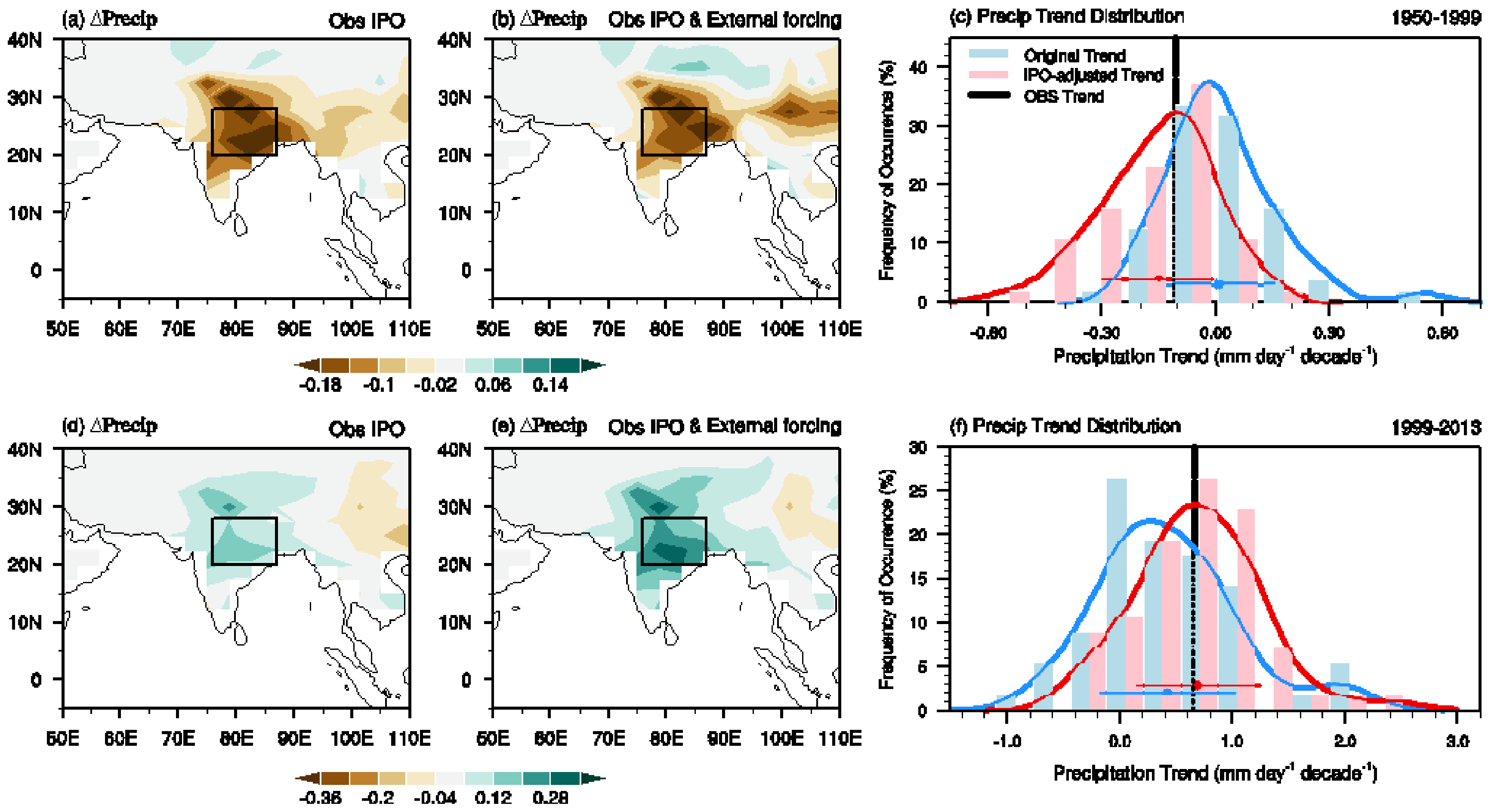
Huang, Zhou* et al. 2020 JC

外强迫和IPO贡献的定量分析

IPO | **IPO+外强迫** | **IPO+外强迫与观测相近**

1950～1999

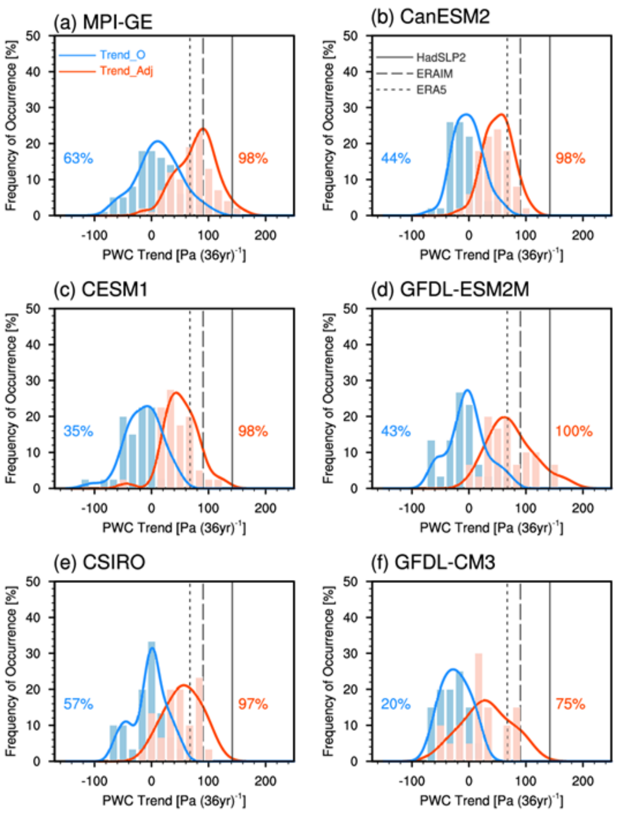
1999～2013



Huang, Zhou* et al. 2020 JC

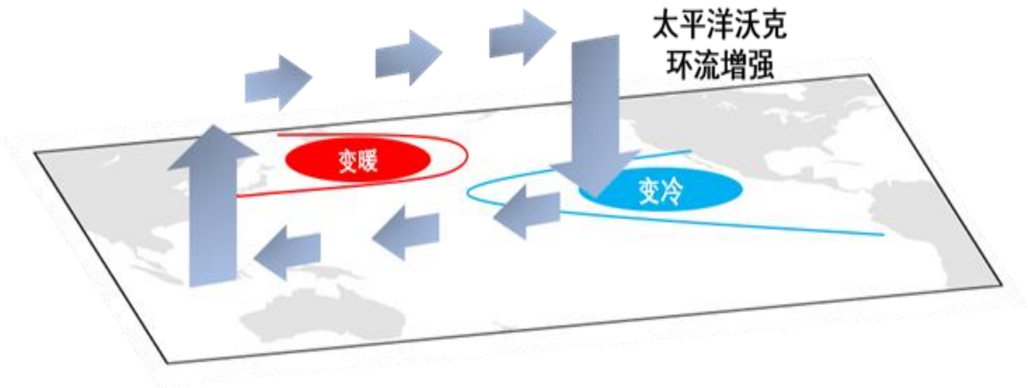
1980-2015年太平洋Walker环流为何增强?

调整前后PWC变化趋势的PDF分布



计入IPO影响后的变化

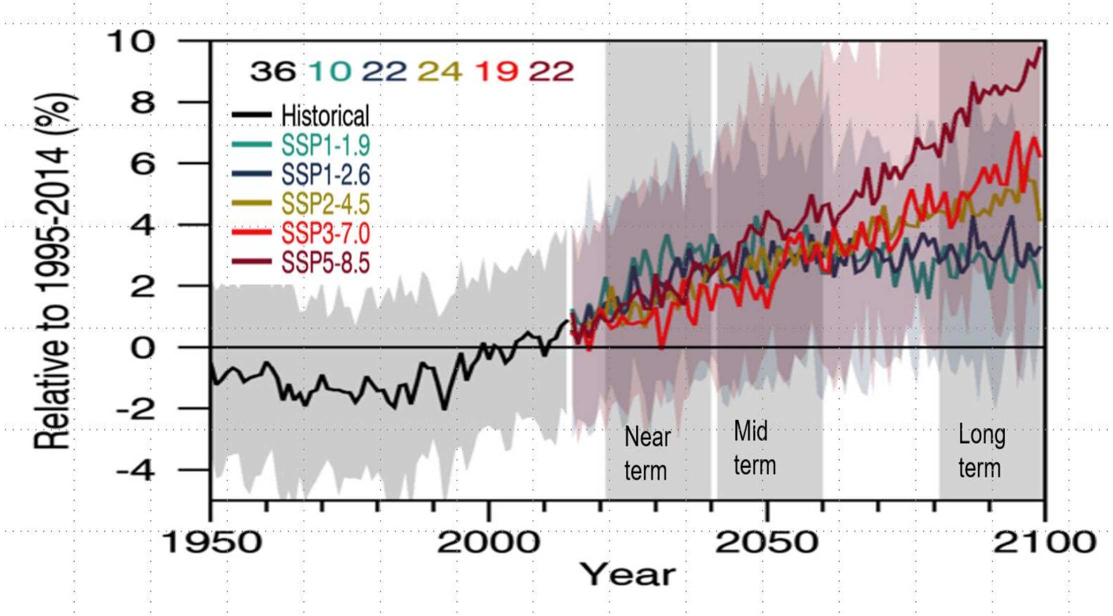
历史变化：正位相→负位相



- IPO位相的转变可以解释观测中约63%(~51-72%)的太平洋Walker环流增强
- IPO位相由正转负，使得热带东-西太平洋海温梯度增大，太平洋Walker环流增强

Wu M, Zhou T*, Li C, et al. A very likely weakening of Pacific Walker Circulation in constrained near-future projections. *Nature Communications*, 2021, 12(1): 6502.

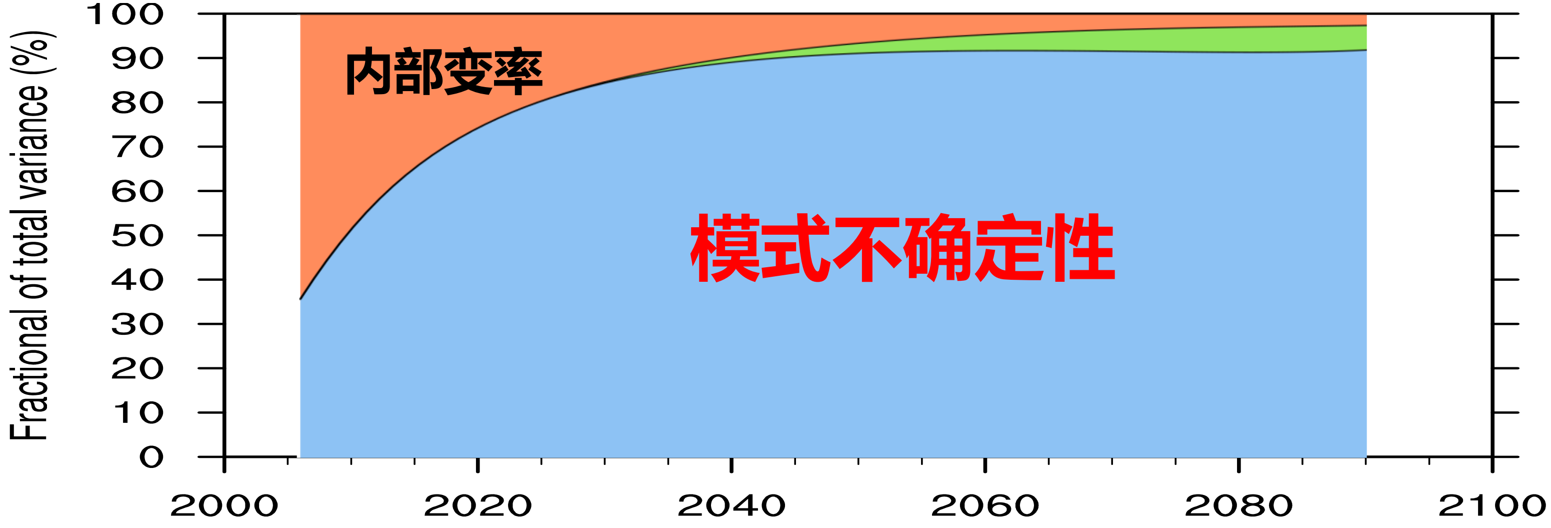
个例2：近中期气候预估的信噪比问题



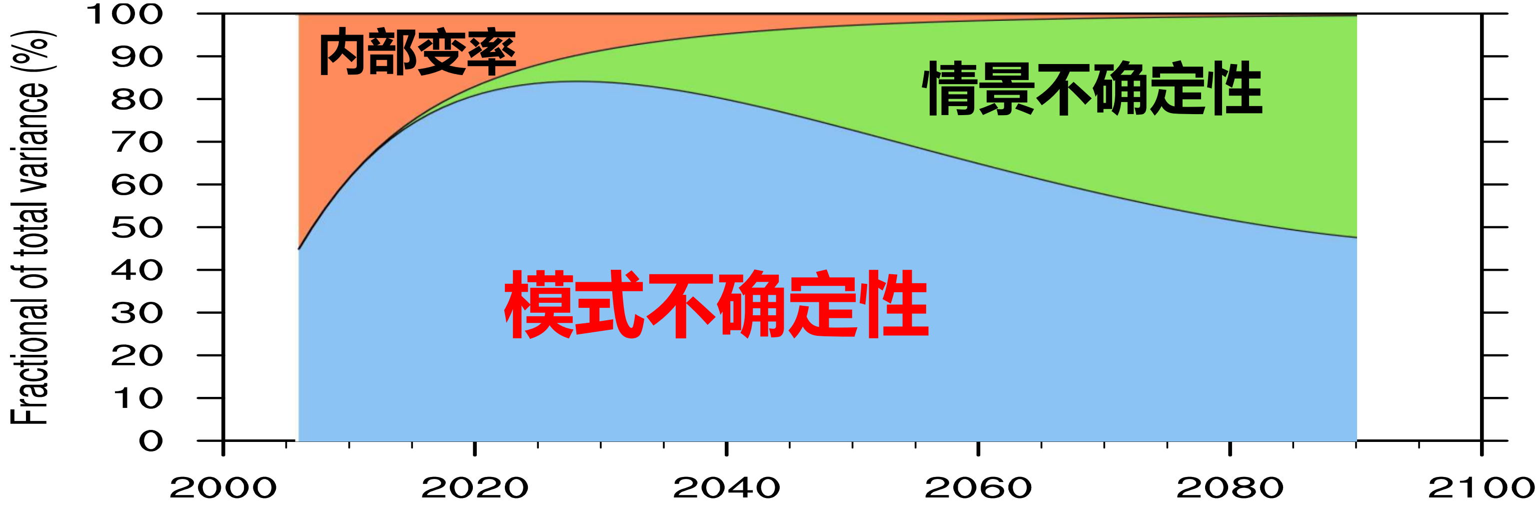
CMIP6全球陆地平均降水的预估：近期、中期、远期

IPCC AR6

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Pav



极端降水RX5day

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

年代际内部变率对南亚夏季风降水近期预估的影响

黑线：观测历史

灰色：模式历史

红线：模式多成员平均

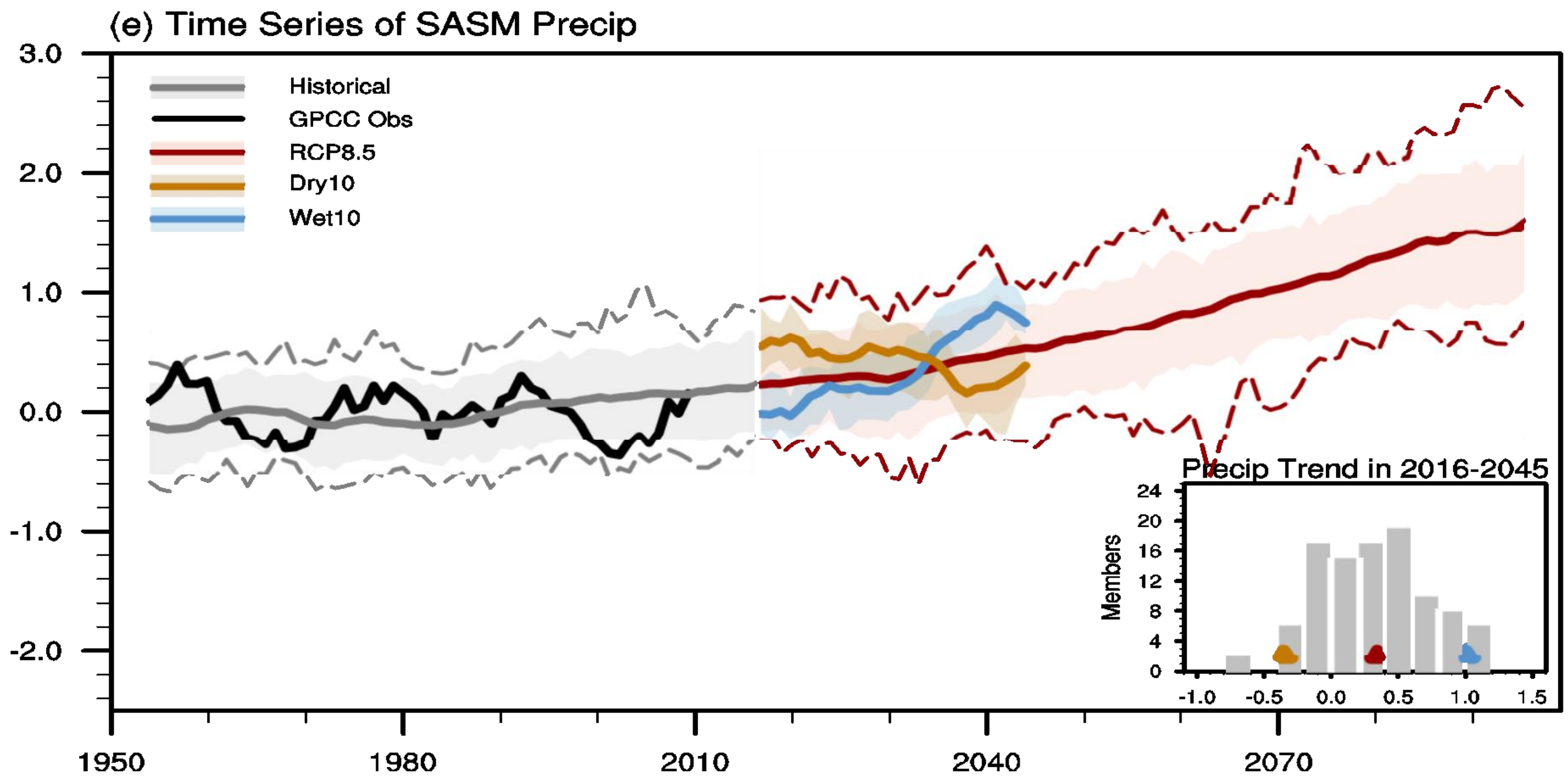
阴影：成员间不确定性

蓝线：10个最湿成员

黄线：10个最干成员

柱状图：100个成员预估

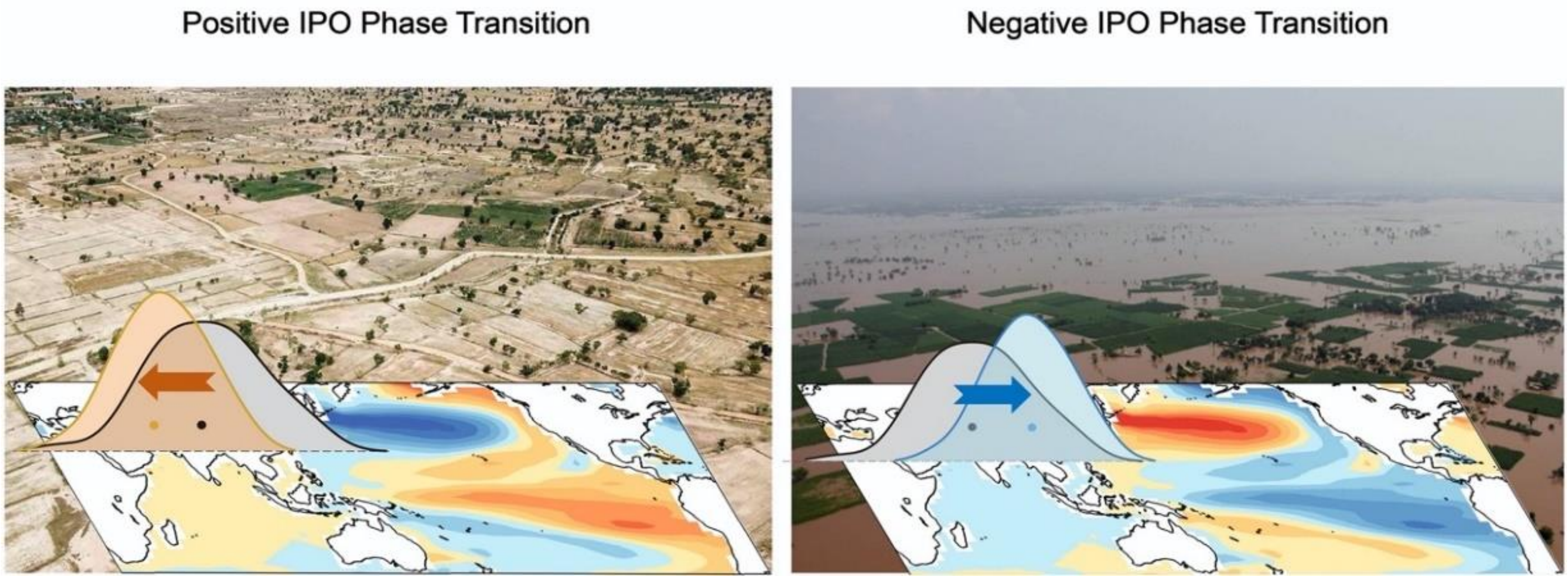
2016～2045降水趋势



RCP8.5排放情景下，内部变率可以影响近期预估南亚夏季风降水趋势的大小和符号

Huang, Zhou* et al. 2020 *Science Advances*

印度季风降雨会变多吗？这还得看太平洋“脸色”



未来15～30年，若IPO位相由负转正，则降水增加的概率将会降低，印度半岛出现极端变干（湿）的概率将会增大（减小）；若IPO位相由正转负，则情况相反。

Huang,Zhou* et al. 2020 *Science Advances*

个例3：如何解决CMIP6模式“过热”问题

Setting the agenda in research

Comment

Island communities in the Ganges–Brahmaputra delta in south Asia are at risk of flooding as a result of climate warming.

SUPRATIM BHATTACHARJEE/ZUMA WIRE

Climate simulations: recognize the ‘hot model’ problem

Zeke Hausfather, Kate Marvel, Gavin A. Schmidt, John W. Nielsen-Gammon & Mark Zelinka

The sixth and latest IPCC assessment weights climate models according to how well they reproduce other evidence. Now the rest of the community should do the same.

Computer models that project future climates are widely used for adaptation, mitigation and resilience planning. More than 50 such models were assessed and compared in the latest round of the Coupled Model Intercomparison Project, phase 6 (CMIP6), run by the World Climate Research Programme[1]. It is crucial that researchers know the best way to use those outputs to provide consistent information for climate science and policy.

We are climate modellers and analysts who develop, distribute and use these projections. We know scientists must treat them with great care. Users beware: a subset of the newest generation of models are ‘too hot’[2] and project climate warming in response to carbon dioxide emissions that might be larger than that supported by other evidence[3–7]. Some suggest that doubling atmospheric CO_2 concentrations from pre-industrial levels will result in warming above 5 °C, for example. This was not the case in previous generations of simpler models.

Earth is a complicated system of interconnected oceans, land, ice and atmosphere, and no computer model could ever simulate every aspect of it exactly. Models vary in their

26 | Nature | Vol 605 | 5 May 2022

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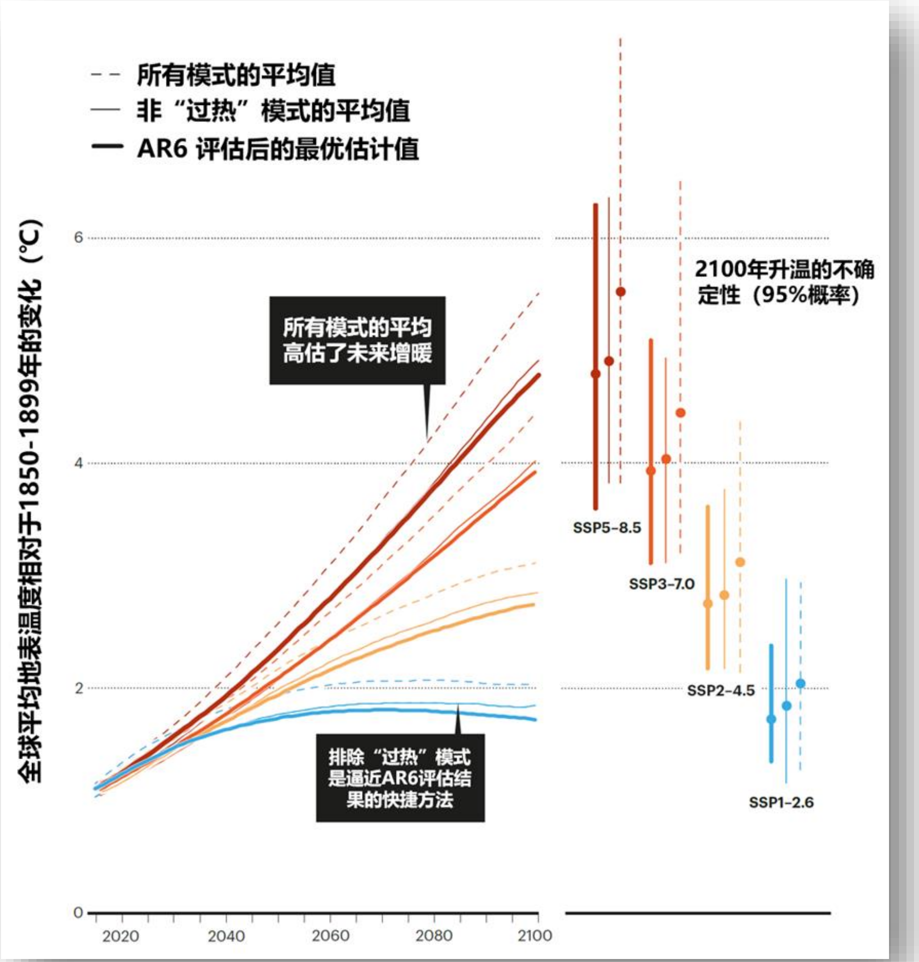
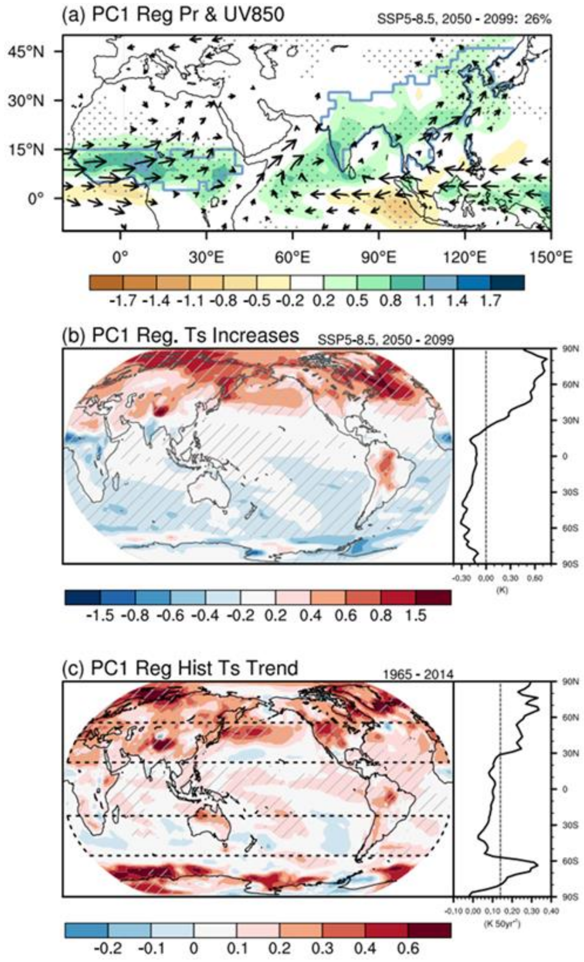
Hausfather et al. 2022 Nature

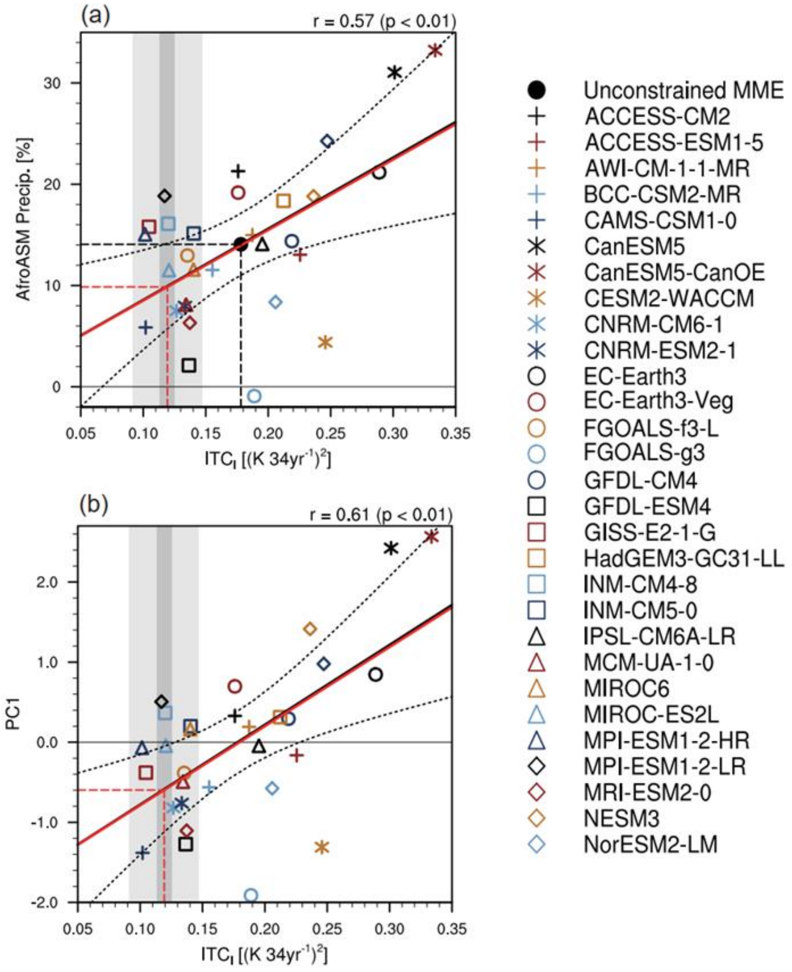


周天军，陈晓龙：气候模式过高估计了全球变暖？真相是什么？《知识分子》,2022.7.29

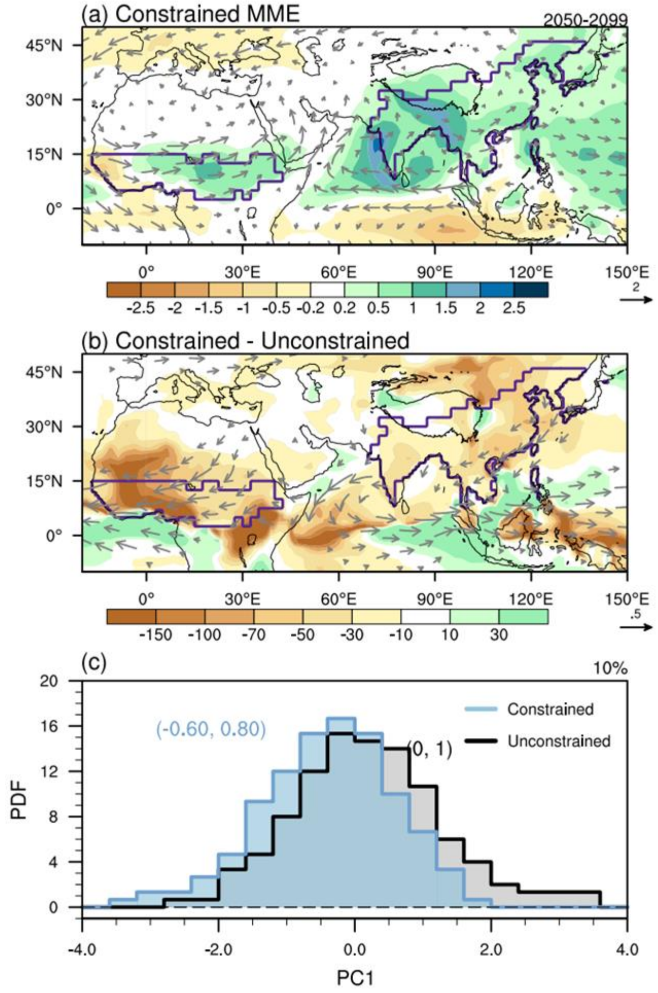
亚非季风区降水的约束预估问题



敏感度影响半球温差



利用观测约束半球温差预估



约束预估的不确定性减少

Chen, Zhou* et al. (2022) Observationally constrained projection of Afro-Asian monsoon precipitation. **Nature Communications**, DOI: 10.1038/s41467-022-30106-z

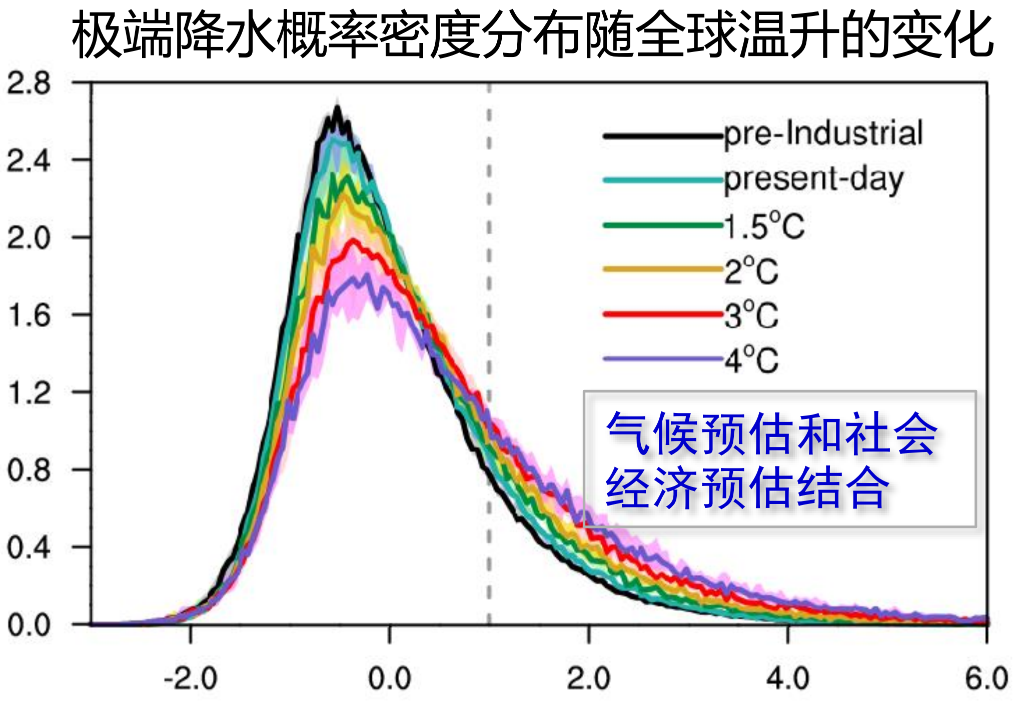
个例4：新需求--基于温升阈值的气候预估

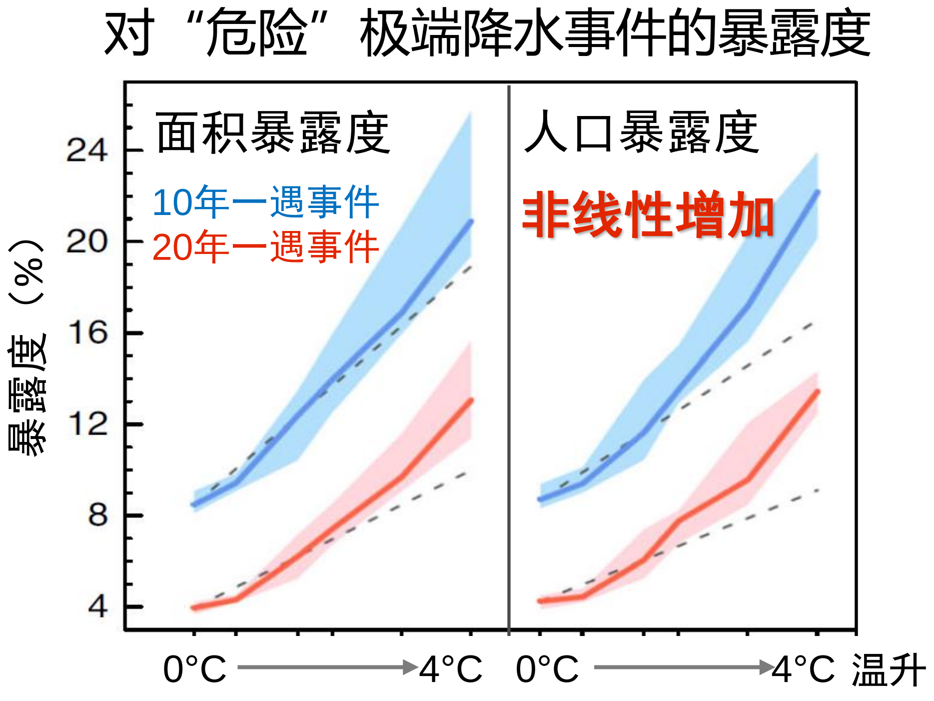
联合国气候变化框架公约**《巴黎协定》**：把全球平均气温较工业化前温升水平控制在2℃之内，并为把温升控制在1.5℃之内而努力，以降低气候变化的风险与影响。

			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]	Global increase in intensity due to warming; high latitudes (>45 °N) and monsoon regions affected most.
		South Asia	**7** [4;8]	**10** [7;14]	
海平面上升	Global sea-level rise				
		in 2100 [cm]	**40** [30;55]	**50** [35;65]	1.5 °C end-of-century rate about 30 % lower than for 2 °C reducing long-term SLR commitment.
		2081–2100 rate [mm/yr]	**4** [3;5.5]	**5.5** [4;8]	
珊瑚礁退化	Fraction of global coral reefs at risk of annual bleaching [Constant case, %]				
		2050	**90** [50;99]	**98** [86;100]	Only limiting warming to 1.5 °C may leave window open for some ecosystem adaptation.
		2100	**70** [14;98]	**99** [85;100]	
粮食产量降低	Changes in local crop yields over global and tropical present day agricultural areas including the effects of CO_2-fertilization [%]				
	Wheat	Global	**2** [-6;17]	**0** [-8;21]	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.
		Tropics	**-9** [-25;12]	**-16** [-42;14]	
	Maize	Global	**-1** [-26;8]	**-6** [-38;2]	
		Tropics	**-3** [-16;2]	**-6** [-19;2]	
	Soy	Global	**7** [-3;28]	**1** [-12;34]	
		Tropics	**6** [-3;23]	**7** [-5;27]	
	Rice	Global	**7** [-17;24]	**7** [-14;27]	
		Tropics	**6** [0;20]	**6** [0;24]	

(Schleussner et al. 2016)

量化季风区极端降水的影响：随全球温升非线性增加

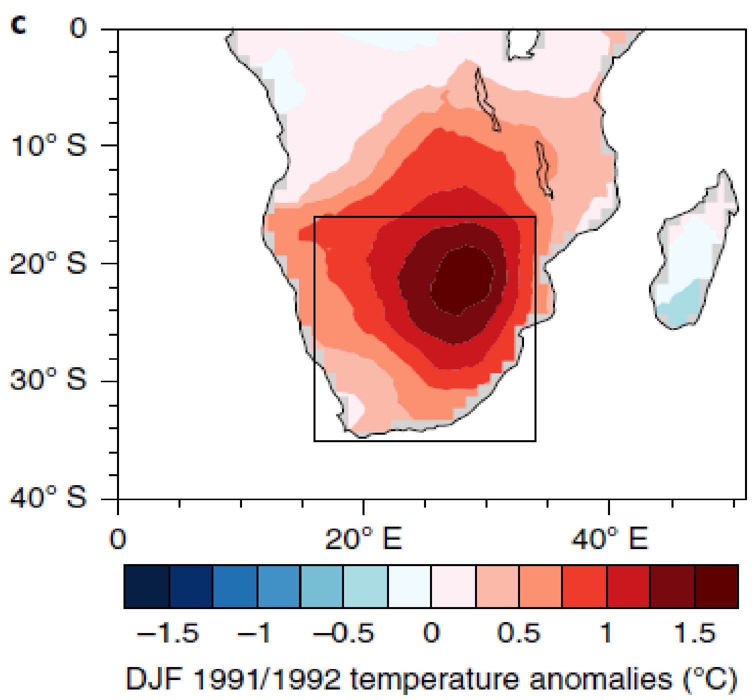


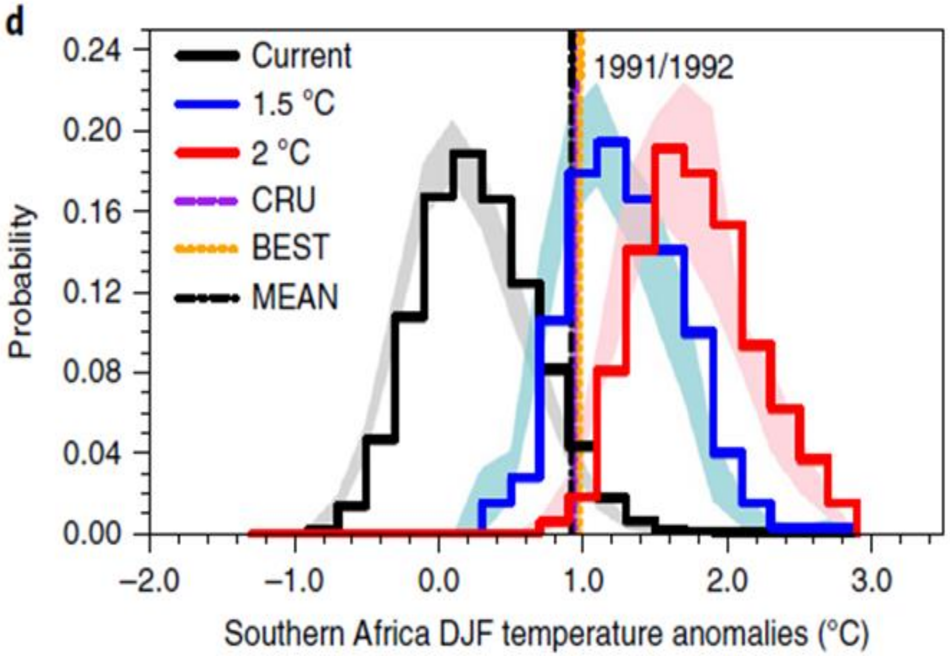


◆ **若将全球温升控制在《巴黎协定》提出的1.5°C，较之2°C温升，可以将“危险”极端降水事件带来的影响减少20-40%**

Zhang W., T. Zhou* et al. 2018: Reduced exposure to extreme precipitation by 0.5°C less warming for global land monsoon regions . ***Nature Communications***, 9. 3153 (2018) doi:10.1038/s41467-018-05633-3.

1991/92 Record-breaking Southern Africa drought: 破纪录事件的发生风险





- 1991/92 DJF extreme high temperature over southern Africa
- 1.5^{o}C: 74% (70%-78%)
- 2.0^{o}C: 98% (97%-100%)

观测破纪录事件的发生概率:

74% vs 98%

Nangombe S., T. Zhou*, W. Zhang et al. 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

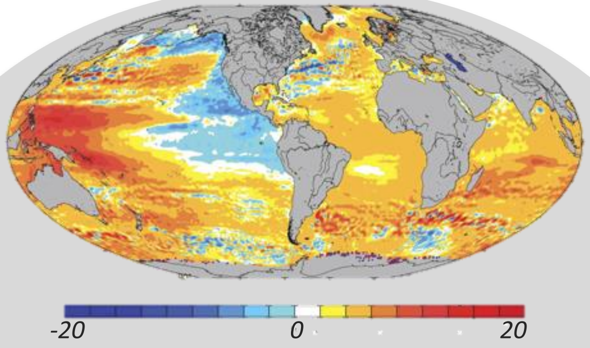
提纲

- ◆ 从气候变化简史看数值模拟
- ◆ 国际耦合模式比较计划
- ◆ 对气候变化科学的推动
- ◆ 气候模式的未来

WG Working Groups WCRP 模拟、预报、预测工作组

Numerical Experiments

WGNE

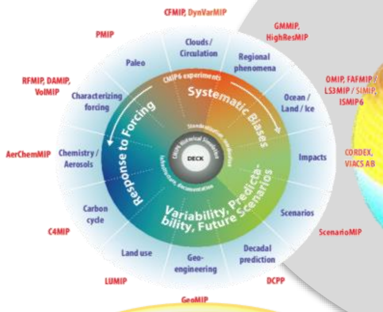


Regional Climate

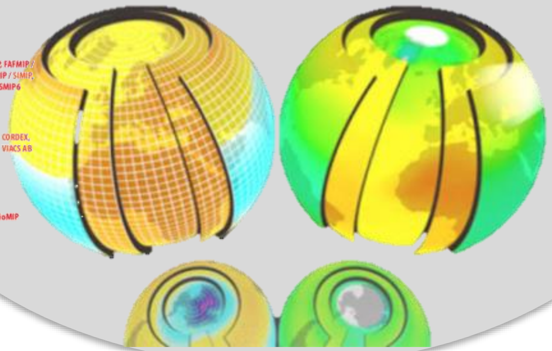
WGRC

WGCM耦合模拟

Coupled modeling

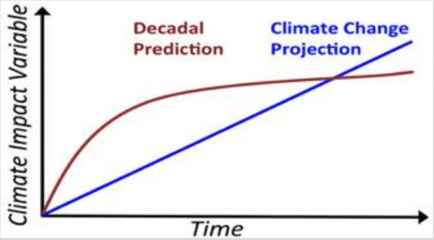


CMIP



WGSIP

Subseasonal to Interdecadal Prediction



WORLD METEOROLOGICAL ORGANIZATION
United Nations Educational, Scientific and Cultural Organization
Intergovernmental Oceanographic Commission
International Science Council
WCRP
World Climate Research Programme

Pan-WCRP modelling Meeting: Met Office, Exeter, Oct 9th-13th, 2017

Pan-WCRP modelling Meeting: Met Office, Exeter, Oct 9th-13th, 2017

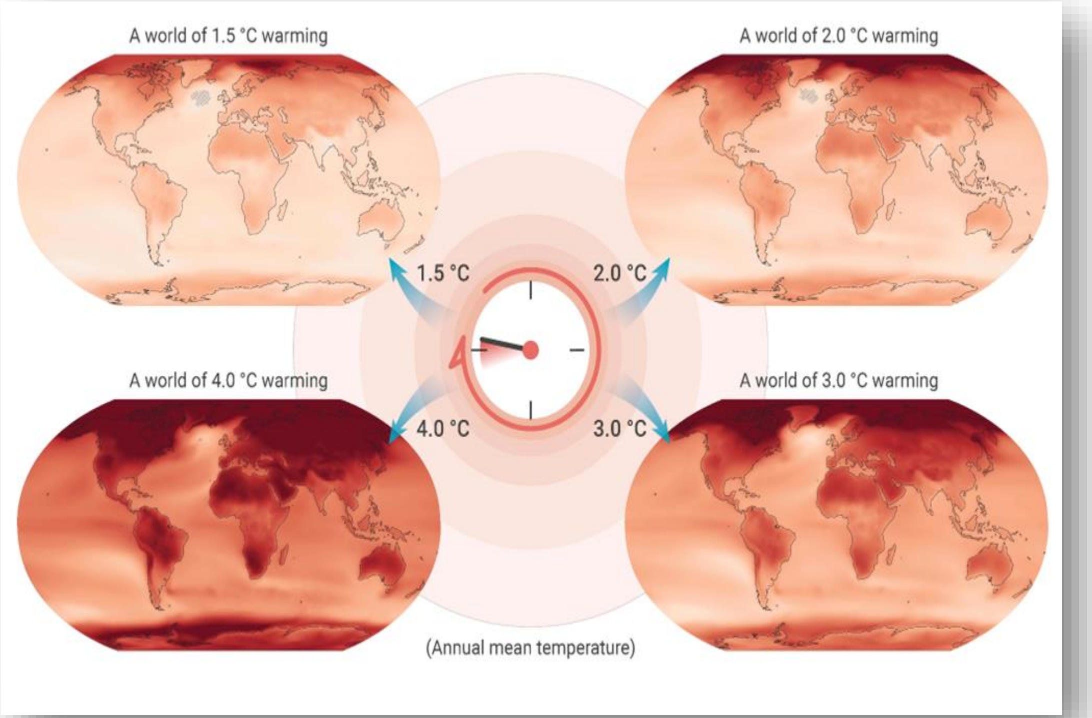
1. Modelling the Regional Climate – Regional and high-resolution global models
Session Organizers: Bill Gutowski & Julio Bacmeister
2. Earth System Modelling in WCRP – Needs from the physical system and opportunities for collaboration
Session Organizers: Pierre Friedlingstein & Gerhard Krinner (co-chair CliC)
3. Modelling infrastructure, data standards and protocols
Session Organizers: V. Balaji and Karl Taylor
4. New observations and the use of models for designing/developing observing systems
Session Organizers: Carla Cardinali (ECMWF) & Duane Waliser
5. Diagnostics, Metrics and Evaluation
Session Organizers: Peter Gleckler & Marion Mittermaier
6. Towards seamless weather and climate predictions
Session Organizers: Frederic Vitard & Keith Williams
7. Linking Models to User Communities
Session Organizers: Andrew Robertson & Daniela Jacob
8. Multi-model synthesis and associated uncertainties
Session Organizers: Paco Doblas-Reyes & Greg Flato

WHO IOC ICSU WCRP World Climate Research Programme

泛WCRP数值模拟大会

1. 模拟区域气候：全球和区域**高分辨率模式**
2. **地球系统模拟**：与物理气候模式的合作
3. 模拟架构、资料标准和协议
4. **新观测**、模式支持观测系统的设计和发展
5. 诊断、标准和评估
6. 天气、气候的**无缝隙预报**
7. 链接模式和用户的桥梁
8. 多模式与**不确定性**

应对气候变化需要精准预报预估

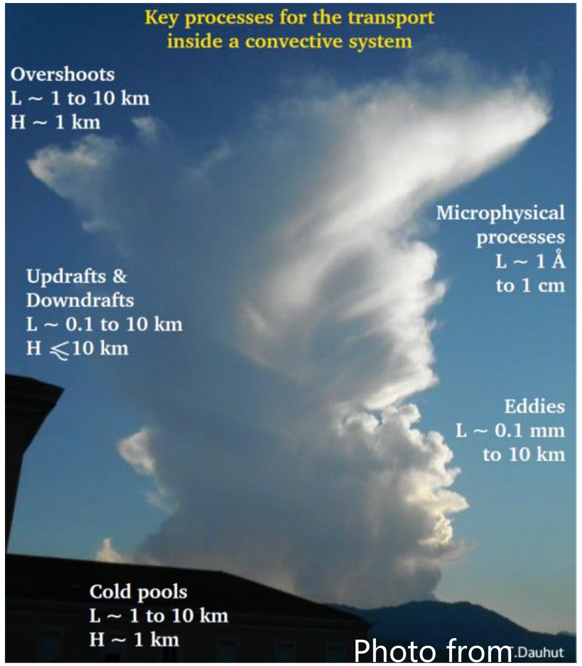


极端事件的模拟和预报是难题

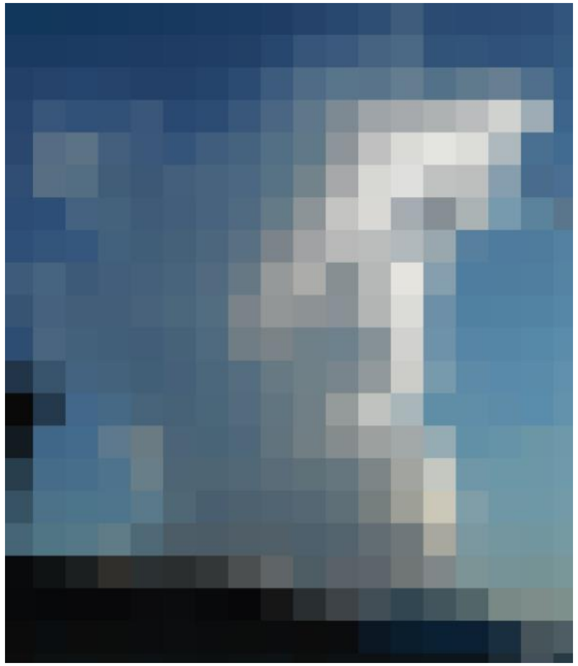
Zhou T. 2021 New physical science behind climate change: What does IPCC AR6 tell us? The Innovation 2(4), 100173

气候模拟的未来之路：风暴解析模拟（对流分辨CPM）

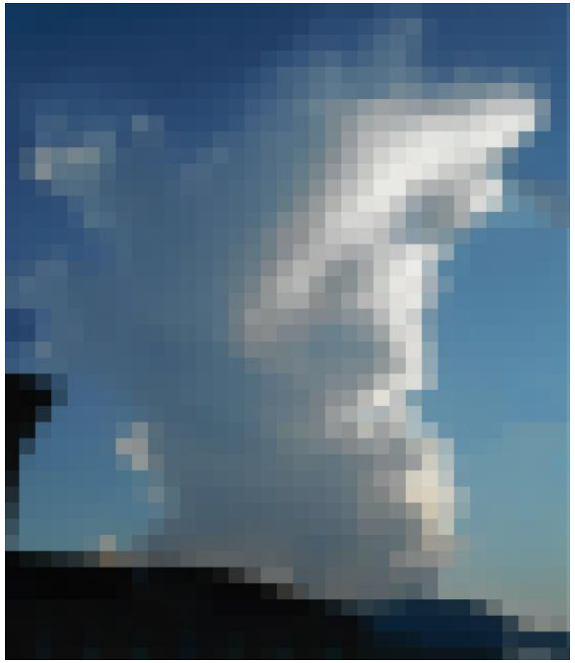
真实的对流云发展



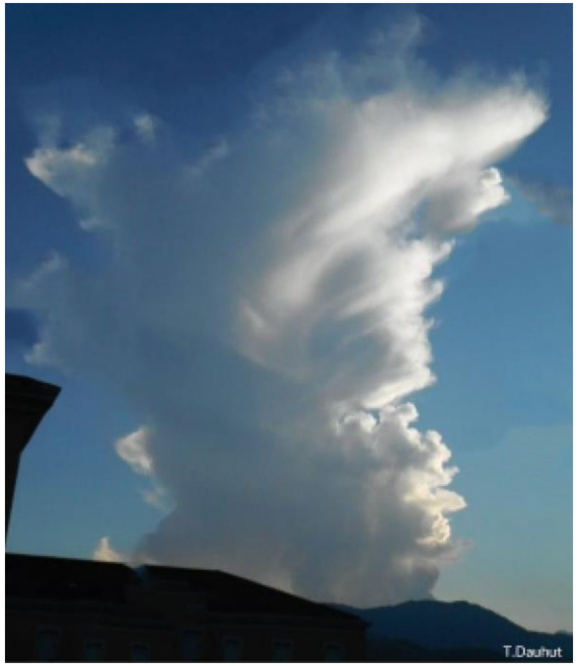
水平分辨率50km的模式



25km模式



4km模式（对流可分辨尺度）



致谢：李普曦博士

联合国气候变化大会COP26 气候行动简报：《下一代气候模式：实现向净零排放和气候适应的跨越》

THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 1

Next generation climate models:
a step change for net zero and climate adaptation

In brief

Climate models are fundamental to understanding climate change and anticipating its risks. They provide the basis for predicting impacts, guiding adaptation decisions and setting mitigation targets. Society now needs more detailed and precise information to enable robust decision-making in the face of rapidly amplifying climate change and for achieving its goal of net zero by 2050.

Existing technological potential and scientific capability can be harnessed through a new level of international cooperation and investment in next-generation super-computing and Earth system science. This step-change transformation could deliver the robust science required to support greater ambition in mitigation and adaptation in the coming decades.

INSIGHTS

- An international next-generation climate modelling centre, based on an exascale computing and data facility, can bring about the step-change that is now possible in modelling capacity to support the technology roadmap to net zero and investment in climate adaptation.
- A dedicated facility, of unprecedented scale, with a role similar to that of CERN in particle physics, would overcome the scientific and technical barriers of delivering timely, detailed, consistent and actionable climate predictions for the coming century, building on the construction of Earth system models that has been one of the great scientific achievements of the last 50 years.
- Recent studies have shown that a new generation of high-resolution models can revolutionise the quality of information available for mitigation and adaptation, from global climate and regional climate impacts, to risks of unprecedented extreme weather and dangerous climate change.
- Through partnership and collaboration with such a new global facility, national climate modelling and services around the world will be propelled to a new level of capability, to the benefit of the citizens of their countries, and indeed, the world.
- To ensure uptake and use of the latest predictions, the facility can also contain a dedicated operational data service that will embrace the latest digital technologies in data analytics and informatics, such as Artificial Intelligence (AI), machine learning and advanced visualisation.
- Ongoing evolution can be driven by an 'Incubator' to stimulate new ideas for next generation modelling, an 'Open Data Lab' to foster public-private partnership on cutting-edge digital solutions based on the Data Cloud and Application Programming Interfaces (APIs), alongside an academy to train developers and users of climate model information.

THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | CONTRIBUTORS

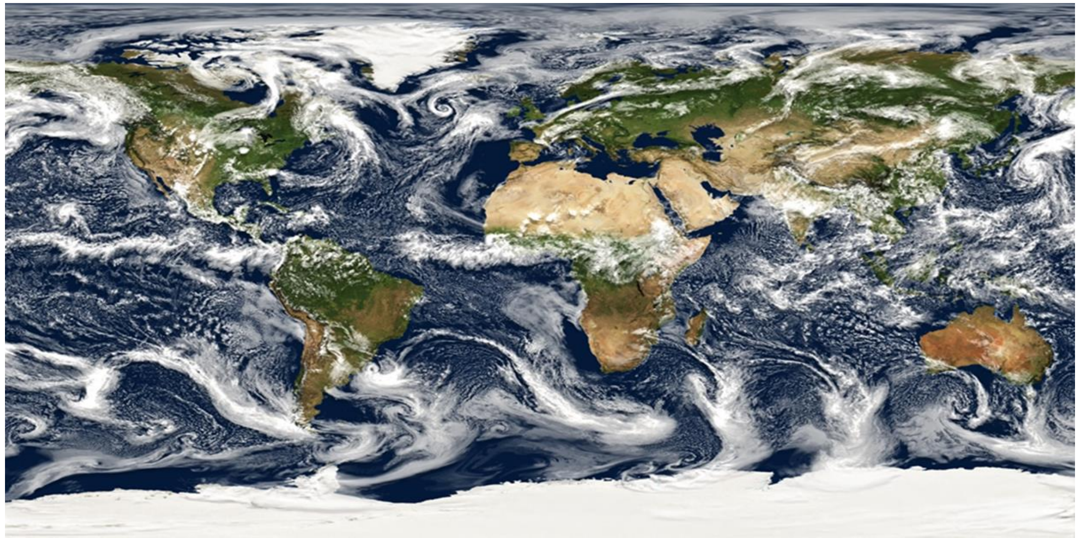
Contributors to climate change:
science and solutions briefing series

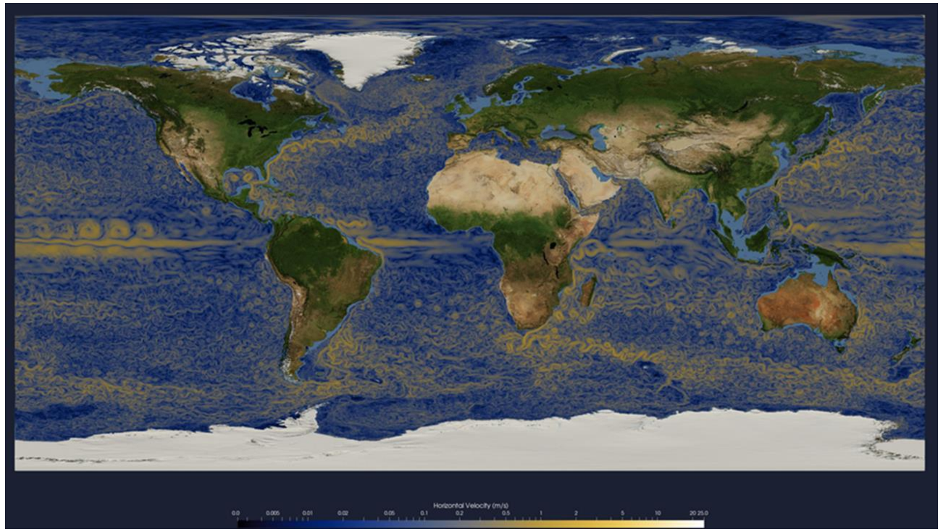
Briefing 1 | Next generation climate models: building strong foundations for climate action

Contributors
Dame Julia Slingo DBE FRS, University of Bristol, UK (lead)
Dr Peter Bauer, European Centre for Medium-Range Weather Forecasts, UK
Professor Sandrine Bony, CNRS Laboratoire de Météorologie Dynamique, France
Dr Gregory Flato, Environment Canada, Canada
Professor Gabi Hegerl FRS, University of Edinburgh, UK
Professor Jens Hesselbjerg Christensen, University of Copenhagen, Denmark
Professor James Hurrell, Colorado State University, USA
Professor Christian Jakob, Monash University, Australia
Dr Vladimir Kattsov, Voeikov Main Geophysical Observatory, Russia
Professor Masahide Kimoto, National Institute for Environmental Studies, Japan
Professor Jochem Marotzke, Max Planck Institute for Meteorology, Germany
Dr Raghavan Krishnan, Indian Institute of Tropical Meteorology, India
Professor Ted Shepherd FRS, University of Reading, UK
Professor Graeme Stephens FRS, California Institute of Technology, USA
Professor Bjorn Stevens, Max Planck Institute for Meteorology, Germany
Professor Thomas Stocker, University of Bern, Switzerland
Professor Rowan Sutton, University of Reading, UK
Professor Tianjun Zhou, Chinese Academy of Sciences, China
Peer reviewers
Professor Jason Smerdon, Columbia University, USA
Professor Inez Fung ForMemRS, University of California Berkeley, USA

由皇家学会Julia Slingo 教授牵头、来自全球的20位气候模拟专家合作，历时近一年研讨撰写完成，在COP26大会发布

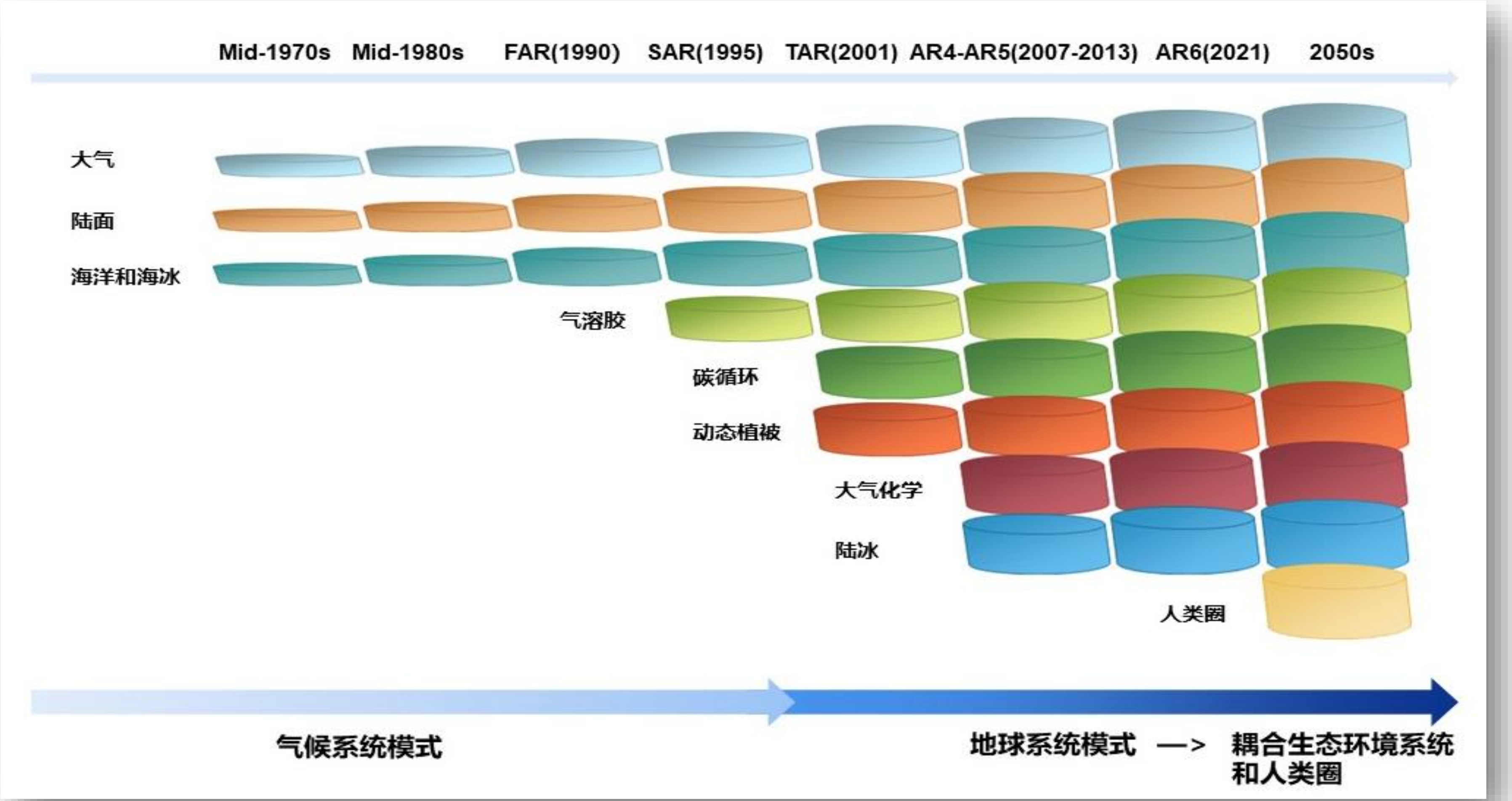
实现全球风暴解析和海洋涡旋解析的模拟和预测、预估





Julia Slingo et al. 2021

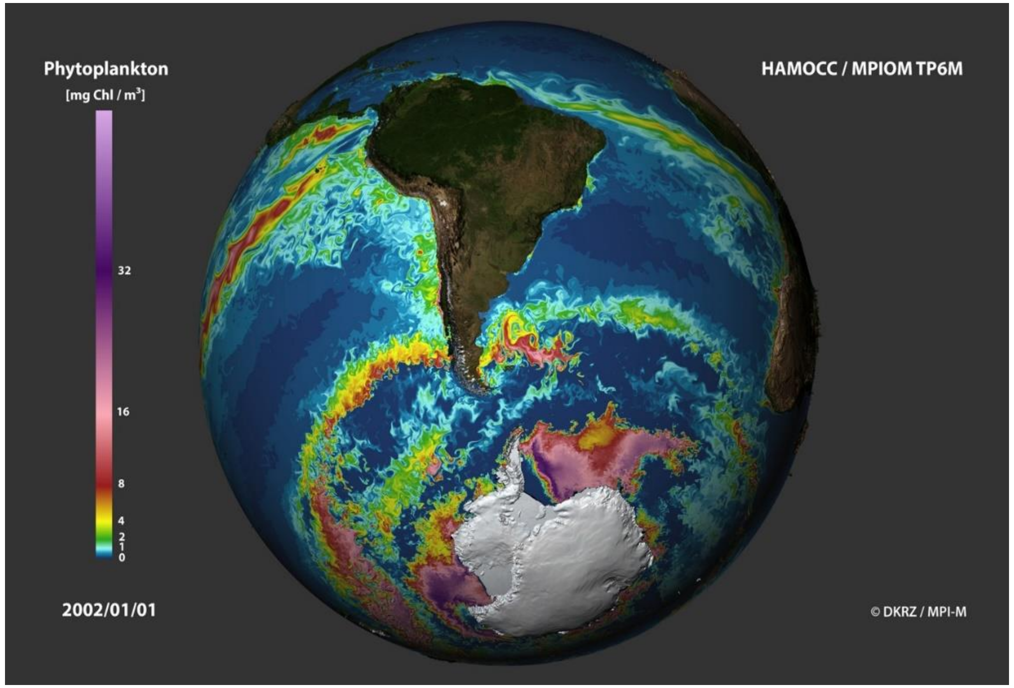
地球气候系统模式的过去、现在和未来

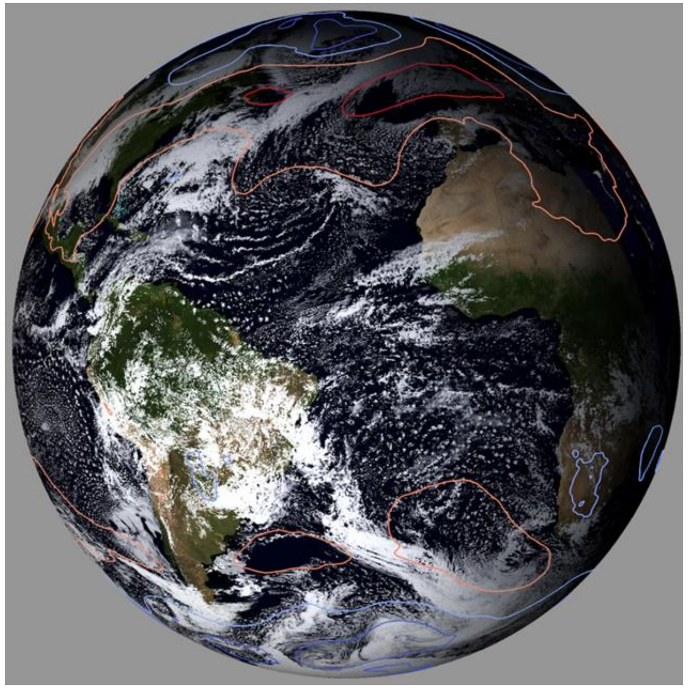


未来的**地球系统模式**将在**物理气候系统**基础上耦合**生态环境系统和人类圈**

周天军,张文霞, 陈德亮, 张学斌等，2022: 2021年诺贝尔物理学奖解读: 从温室效应到地球系统科学. 中国科学, 52, doi: 10.1360/SSTe-2021-0338

风暴解析模式与E级超算





MPI HAMOCC模拟的叶绿素

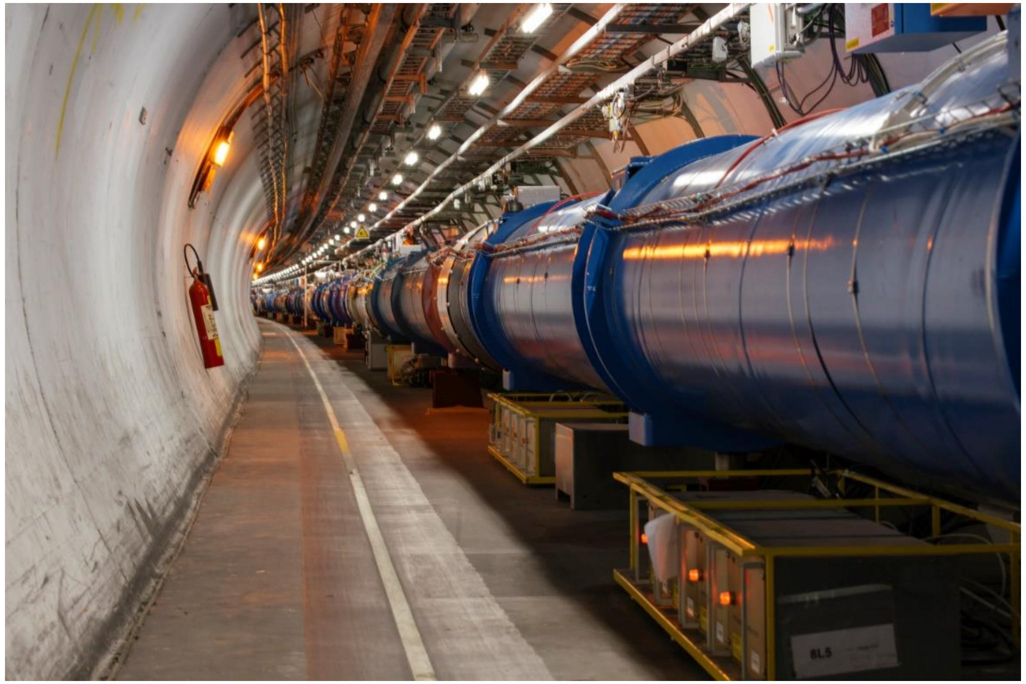
(Courtesy to Chao Li)

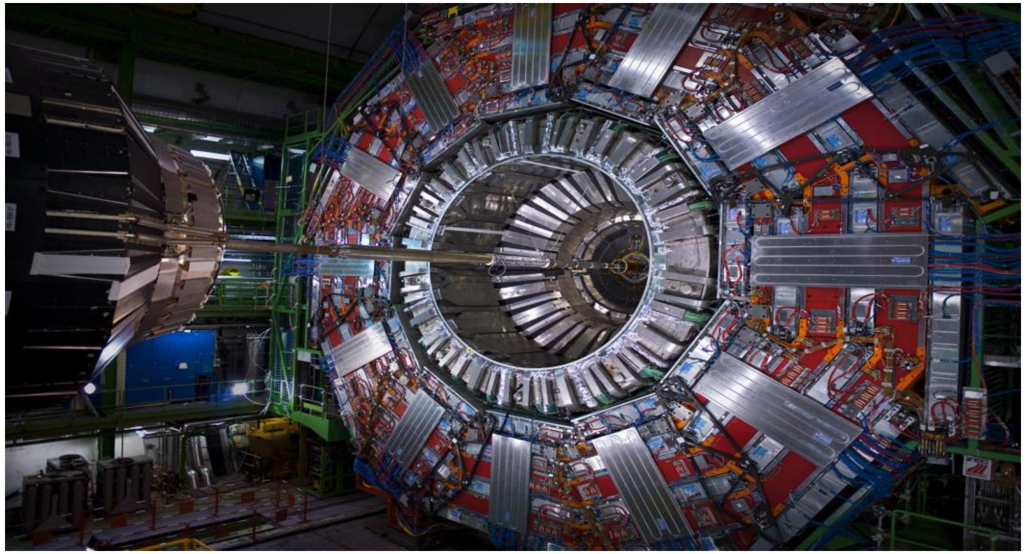
CMA GRIST 公里尺度模拟的2020-01-22云和气压

(致谢：李建)

- **实现物理气候系统和自然环境系统的公里尺度耦合模拟，需要百亿亿次（E级）超算的突破**
- **模式研发、运行、数据存储所需要的财力支持是巨大的**

欧洲核子中心CERN：国际气候治理合作的参考范式?





The European Organization for Nuclear Research, known as CERN, is a European research organization that operates the largest particle physics laboratory in the world. Established in 1954, the organization is based in a northwest suburb of Geneva on the Franco–Swiss border and has 23 member states. Israel is the only non-European country granted full membership. CERN is an official United Nations Observer.

Check for updates

editorial

For the greatest benefit to humankind

How has computational science been recognized throughout Nobel history?

On 5 October 2021, the Royal Swedish Academy of Sciences announced that the 2021 Nobel Prize in Physics will be awarded to three scientists for their "groundbreaking contributions to our understanding of complex physical systems". One half of the prize will go to Syukuro Manabe and Klaus Hasselmann for the development of physical models that enabled the simulation of global climate and the prediction of global warming; the other half will be awarded to Giorgio Parisi for the mathematical modeling of complex disordered systems.

The computational science community has certainly been thrilled with this news as it reiterates the essential role of computational science in helping to address the most critical challenges in our society, such as climate change. The mathematical and physical models developed by the three aforementioned researchers formed the foundation to investigate complex systems. The climate model, first proposed by Manabe in the 1960s by considering the interaction of radiation and vertical mass transportation, successfully predicted the correlation between the carbon dioxide content in the atmosphere and the Earth's surface temperature. Hasselmann's stochastic climate model distinguished reliable climate patterns from chaotic weather, and further differentiated the influence of human activities from that of natural effects on the climate. From a much broader perspective of complex systems, Parisi introduced the idea of 'replica trick' as a new way to mathematically interpret and predict the statistical behavior of disordered systems. This technique is widely used nowadays in various disciplines, including physics, materials science, neuroscience, and machine learning.

This isn't the first time that the contributions of the computational science community have been recognized throughout Nobel history. As a matter of fact, the community has been responsible for many advances in computer code and platforms[1] that have indirectly supported many of the awarded scientific discoveries. To name a few, in the 1960s, Martinus Veltman, who shared the 1999 Nobel Prize in Physics with Gerardus 't Hooft, employed the assembly programming language to manipulate algebraic operations that made it possible to solve complex quantum field theory equations[2], which contributed to better explaining the quantum structure of electroweak interactions in physics. Around the same time, Manabe and colleagues, with the help of Fortran code and digital computers, were able to simulate our climate system. Saul Perlmutter, one of the researchers who shared the 2011 Nobel Prize in Physics, pioneered the use of supercomputers to analyze and validate observational imaging data in cosmology, which contributed to the discovery that the expansion of the Universe is accelerating.

But computational science contributions have not only implicitly helped accelerate scientific discoveries: they have also been explicitly honored with Nobel prizes in the past. Some of these contributions are represented by important mathematical and physical models that not only help us to more accurately understand the laws of nature, but that also allow for the computation of different scientific phenomena that were otherwise hard or impossible to simulate. The climate models developed by Manabe and Hasselmann, for instance, fit this category. Another example is the Marcus theory, proposed by Rudolph A. Marcus, who received the 1992 Nobel Prize in Chemistry. In the mid-1950s, Marcus developed a mathematical model to explain the rate of electron transfer reactions between two chemical species, such as inorganic molecules and biomolecules (for instance, proteins). With many extensions and refinements for specific problems, the main contribution of the Marcus theory was to mathematically model the electron jumping process together with molecular structural change. This theory enabled the accurate computation of redox reactions in important scientific problems — including photosynthesis, enzyme reactions, and corrosion — and was successfully linked with experimental observations. Another notable example is the 1982 Nobel Prize in Physics, which was awarded to Kenneth G. Wilson for his work on phase transitions. Wilson proposed a model based on the renormalization group theory to describe the physics of multi-scale fluctuations, which made numerically computing crucial quantities during phase transition practical at the time. Wilson's finding about the key role of the dimensionality of the order parameter to describe phase transition still inspires new research today that leverages new computing algorithms and the increasing availability of data[3].

In addition to mathematical models, computational methods have also been explicitly recognized in the past. A clear example of such recognition is the 1998 Nobel Prize in Chemistry, which was shared between Walter Kohn and John Pople. Kohn laid the foundation for the density functional theory in 1954 and demonstrated that the ground state properties of a many-electron system can be described by the ground state electron density in space; in practice, this approximation made quantum chemistry calculations more computationally feasible. Pople is well-known for his pioneering work in developing the first version of Gaussian, and later for his contributions to Q-Chem, which are two of the most widely used computational chemistry tools to date. More recently, in 2013, the Nobel Prize in Chemistry again underscored the importance of computational methods, this time related to the development of the hybrid QM/MM (quantum mechanics/molecular mechanics) approach for modeling chemical reactions. The ingenious idea treats key elements that are responsible for these reactions with quantum chemistry theory (which allows for more accurate results), while the remainder is described with classical mechanics (which makes the approach more computationally efficient). Among its many important applications to different fields, the QM/MM approach stimulated fruitful research in computational structural biology[4,5].

It is worth mentioning that our list of computational science contributions related to Nobel prizes is far from being exhaustive. In addition, for the sake of this Editorial, we focused on the physics and chemistry prizes only. Nevertheless, the contributions highlighted here demonstrate that mathematical and computational methods have become exceptionally relevant in science: in many cases, they have become an essential tool to the most exciting and important scientific discoveries of our society.

What's next? Certainly, this will not be the last time that computational science is recognized by a Nobel prize. Looking ahead, as new computing algorithms and

Nature Computational Science

为了人类的最大利益：

从诺奖的历史看超级计算

1. Syukuro Manabe & Klaus Hasselmann, 2021 Nobel Prize in Physics
2. Martinus Veltman, 1999 Nobel Prize in Physics
3. Saul Perlmutter, 2011 Nobel Prize in Physics
4. Rudolph A. Marcus, 1992 Nobel Prize in chemistry
5. Kenneth G. Wilson, 1982 Nobel Prize in Physics
6. Walter Kohn, 1998 Nobel Prize in Chemistry


数值模拟推动气候变化科学
谢谢！