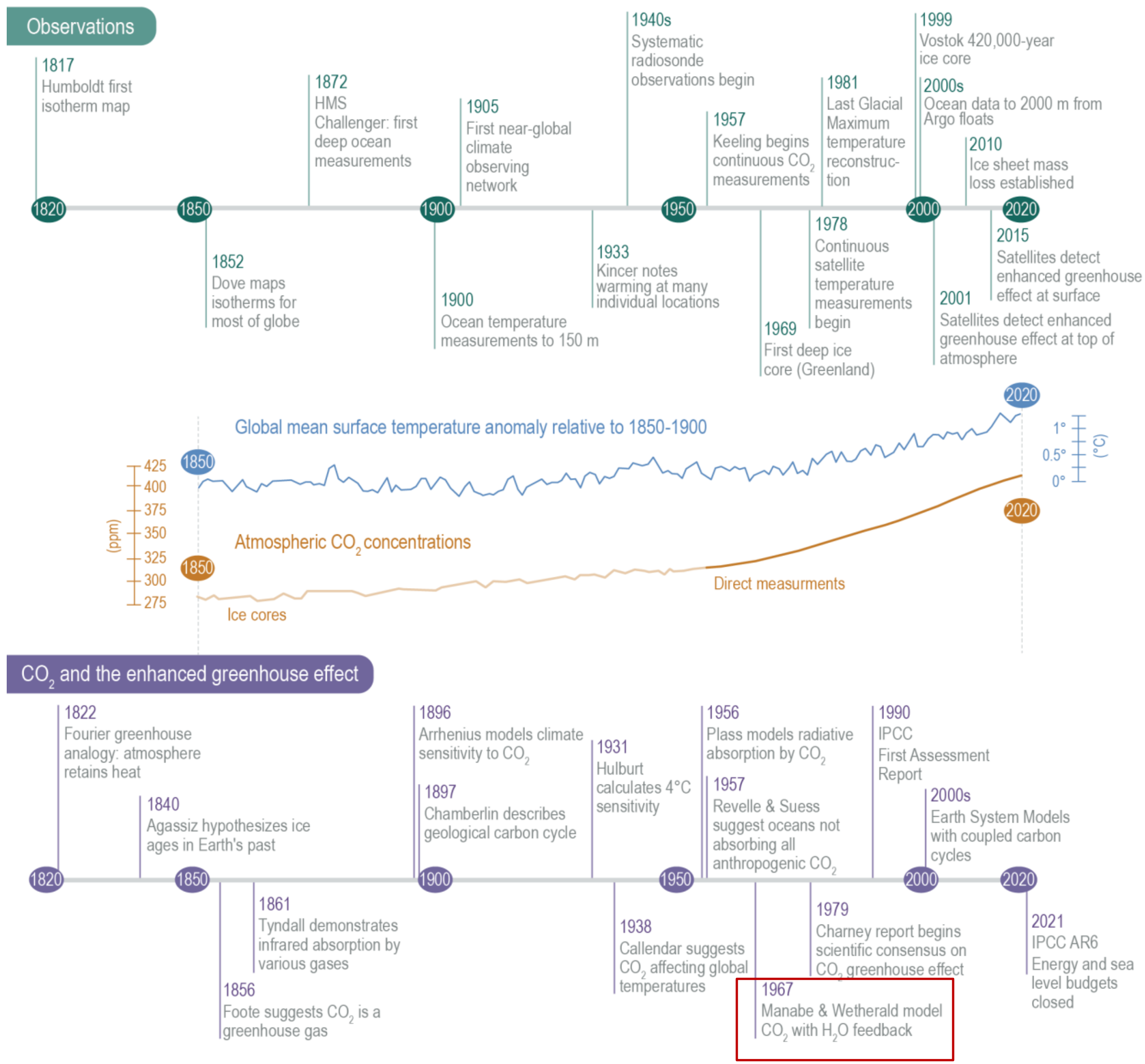
CHAPTER 8

CLIMATE CHANGE, FORCINGS AND FEEDBACKS

Climate Science Milestones



IPCC, 2021

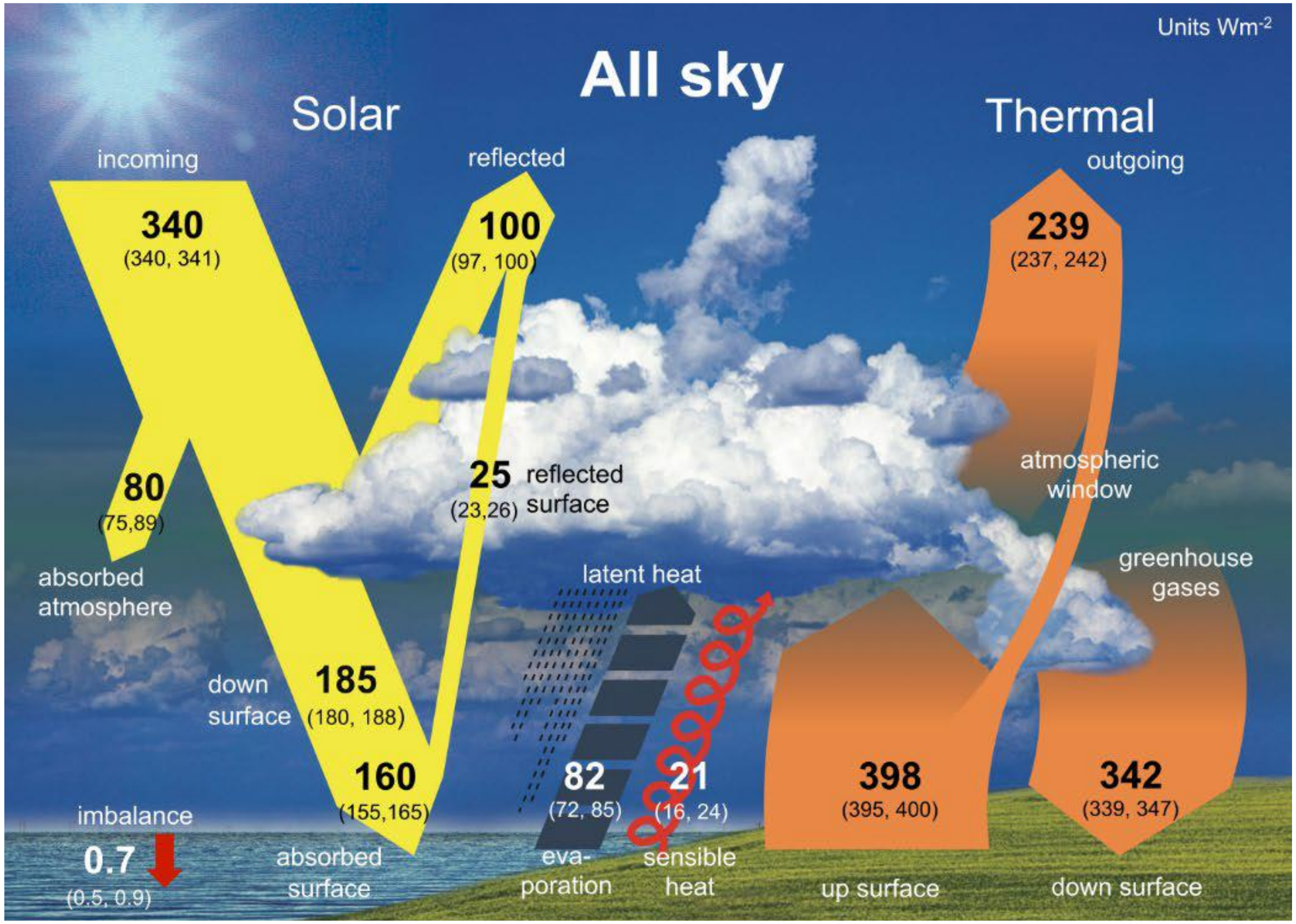
Global Warming

气候变化争议

- ✓ 有没有变暖
- ✓ 变暖是否一定与人类活动有关
- 变暖是否一定不好、有多不好
- 变暖是否会持续/加速
- 我们可否减缓/消除变暖
- 减缓还是适应
- 减缓/适应的手段
- 责任分配

In my view, the aspect of climate change we are concerned most is:
SO RAPID AND SO SEVERE ANTHROPOGENIC CLIMATE CHANGE THAT CANNOT BE ADAPTED WITHOUT ENORMOUS AND UNACCEPTABLE COSTS

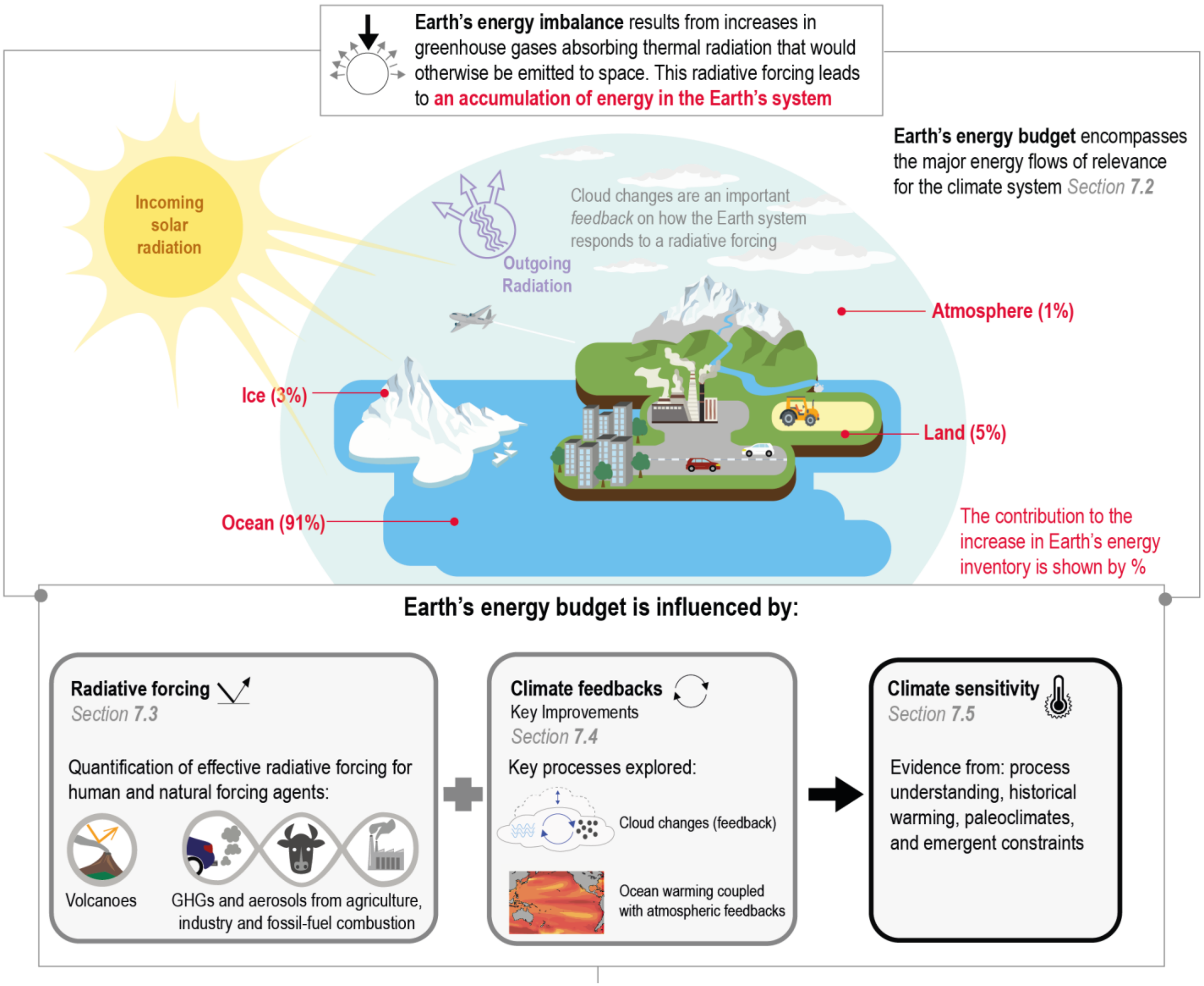
Earth Energy Balance



IPCC, 2021

- Energy balance: Atmosphere 80+(398-40)+21+82-342-(239-40), Surface 160+342-398-21-82, Earth 340-100-239
- Planetary albedo: ~29% (surface 7%, atmosphere 22%)

How Earth Energy Balance Is Affected by Human



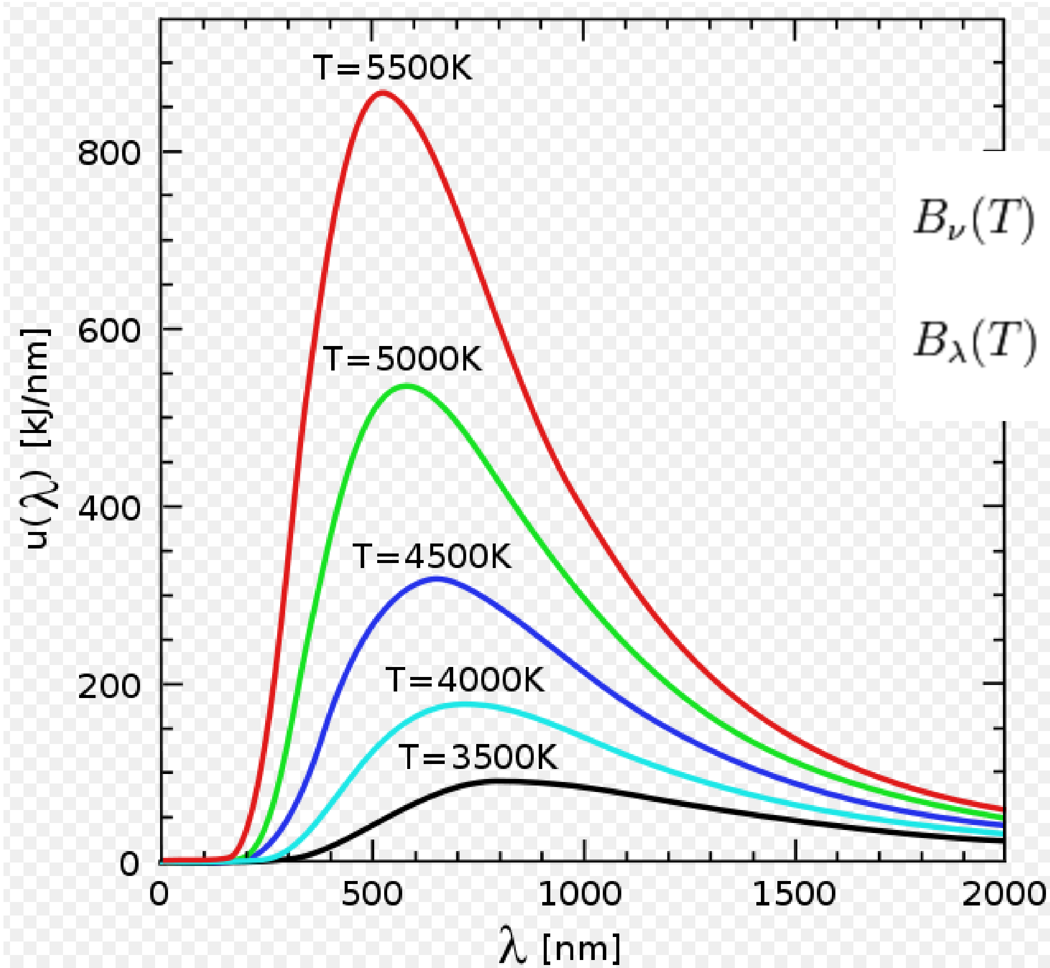
IPCC, 2021

影响气候的因子

改变地球的辐射平衡有三种最基本的方法：
1.改变入射的太阳辐射
2.改变被反射的那部分太阳辐射
3.改变地球向空间的长波辐射

- 内部变率：气候系统自身动态演化
- 自然（外部）因素：
  - 地质运动（板块运动、火山活动、陨石等）
  - 地球轨道变化（偏心率、黄赤交角、岁差）
  - 太阳活动（太阳黑子等）
- 人为强迫：
  - 长寿命温室气体：CO_2、CH_4、N_2O、halocarbons
  - O_3（与NO_x、CO、VOC相关）
  - 气溶胶：BC、OC、sulfate、nitrate、ammonium、dust
  - 植被改变
- 反馈过程：热力、动力、生态系统、碳循环等

Planck's Law for Black Body



$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_BT}}-1}, \text{or}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda k_BT}}-1}$$

Percentile	.01%	.1%	1%	10%	20%	**25.0%**	30%	40%	**41.8%**	50%	60%	**64.6%**	70%	80%	90%	99%	99.9%	99.99%
Sun λ (nm)	157	192	251	380	463	**502**	540	620	**635**	711	821	**882**	967	1188	1623	3961	8933	19620
288 K planet λ (μm)	3.16	3.85	5.03	7.62	9.29	**10.1**	10.8	12.4	**12.7**	14.3	16.5	**17.7**	19.4	23.8	32.6	79.5	179	394

大气气体、气溶胶对辐射的吸收与散射

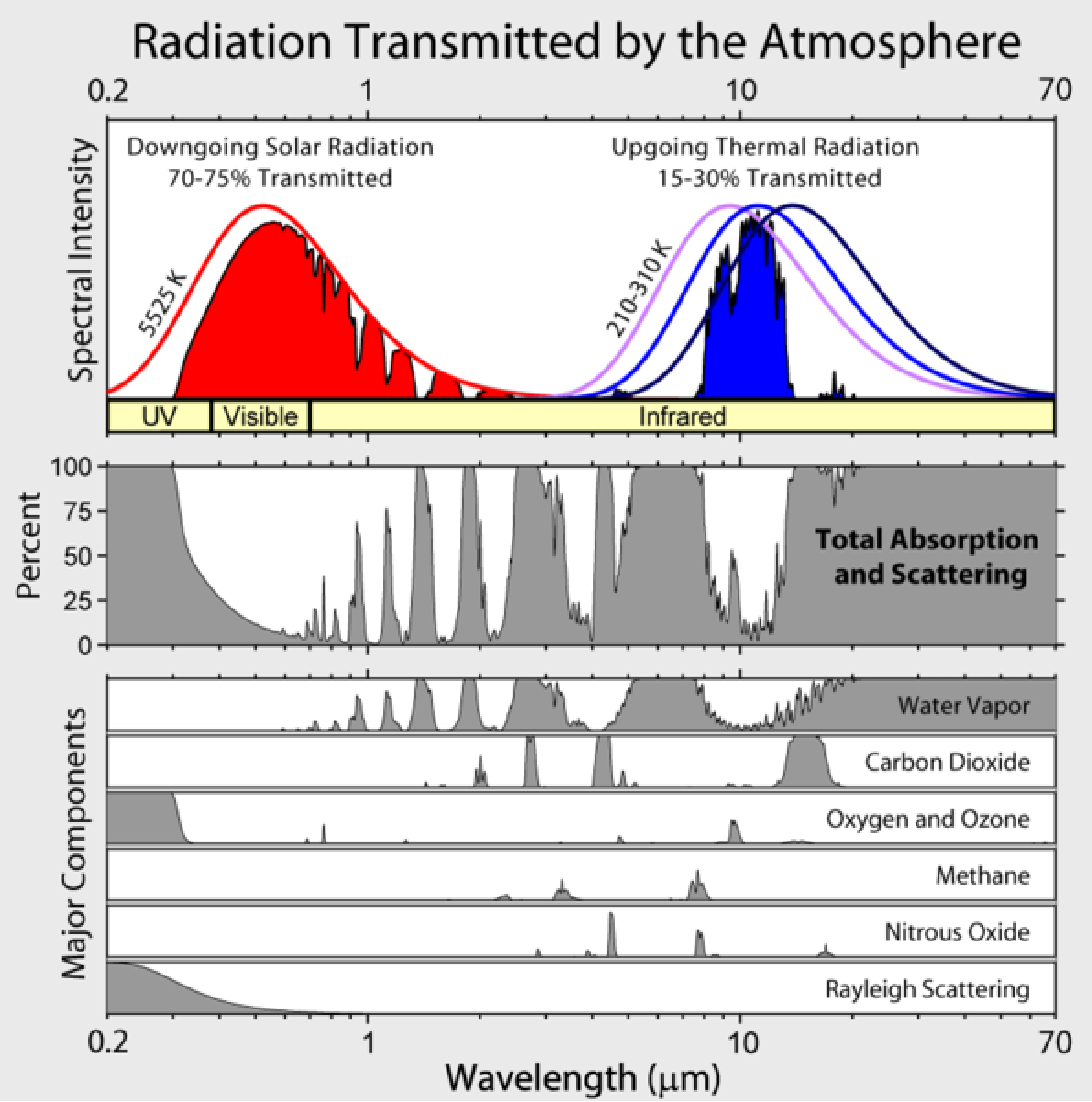
- 吸收：电子能级跃迁（UV/VIS）、原子振动（near IR）、分子转动（IR、microwave）

  特定波长、选择性吸收、组合

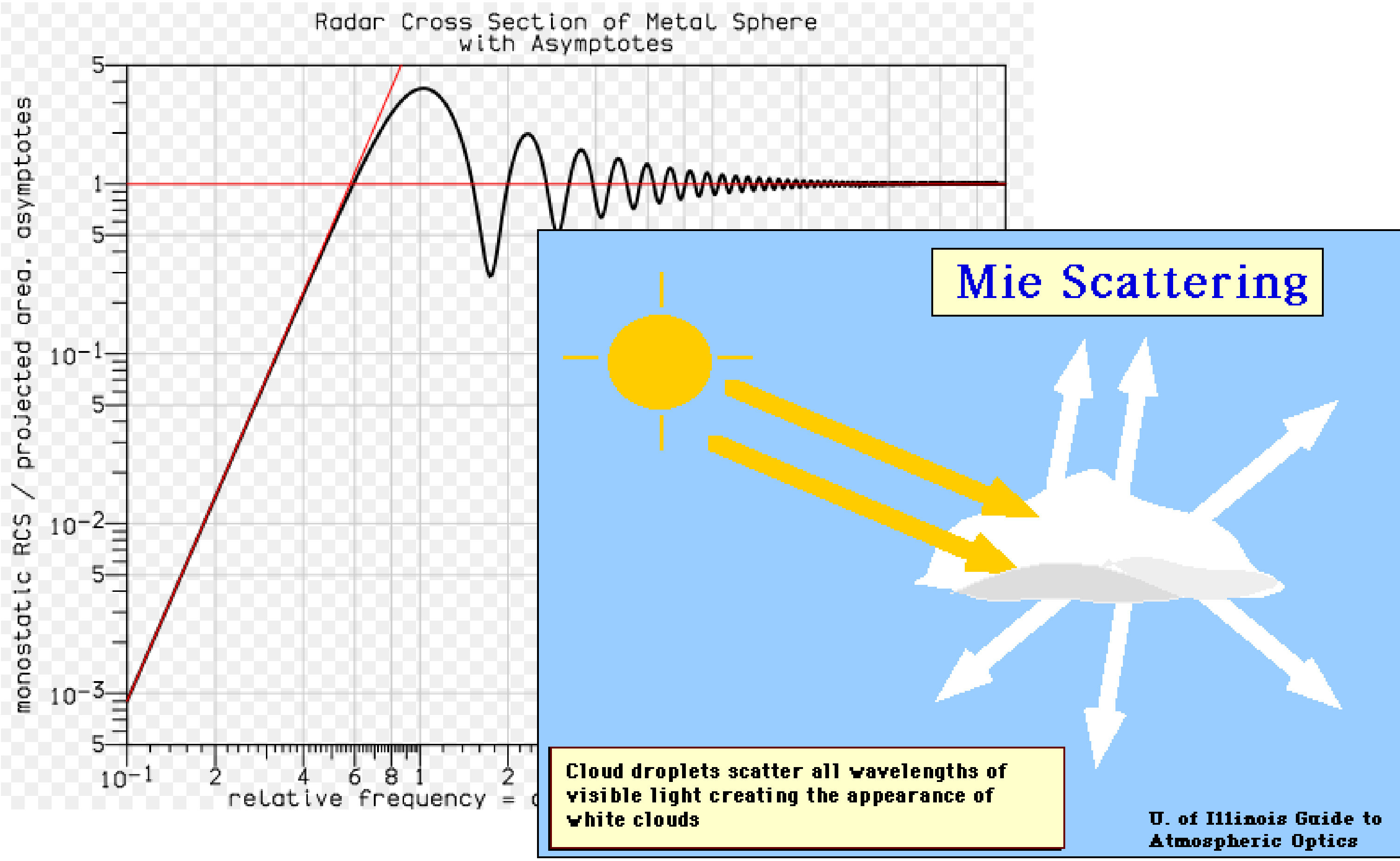
- 谱线增宽：自然增宽（可忽略）、压力增宽、多普勒增宽

- 散射：弹性散射、非弹性散射

大气气体吸收和瑞利散射



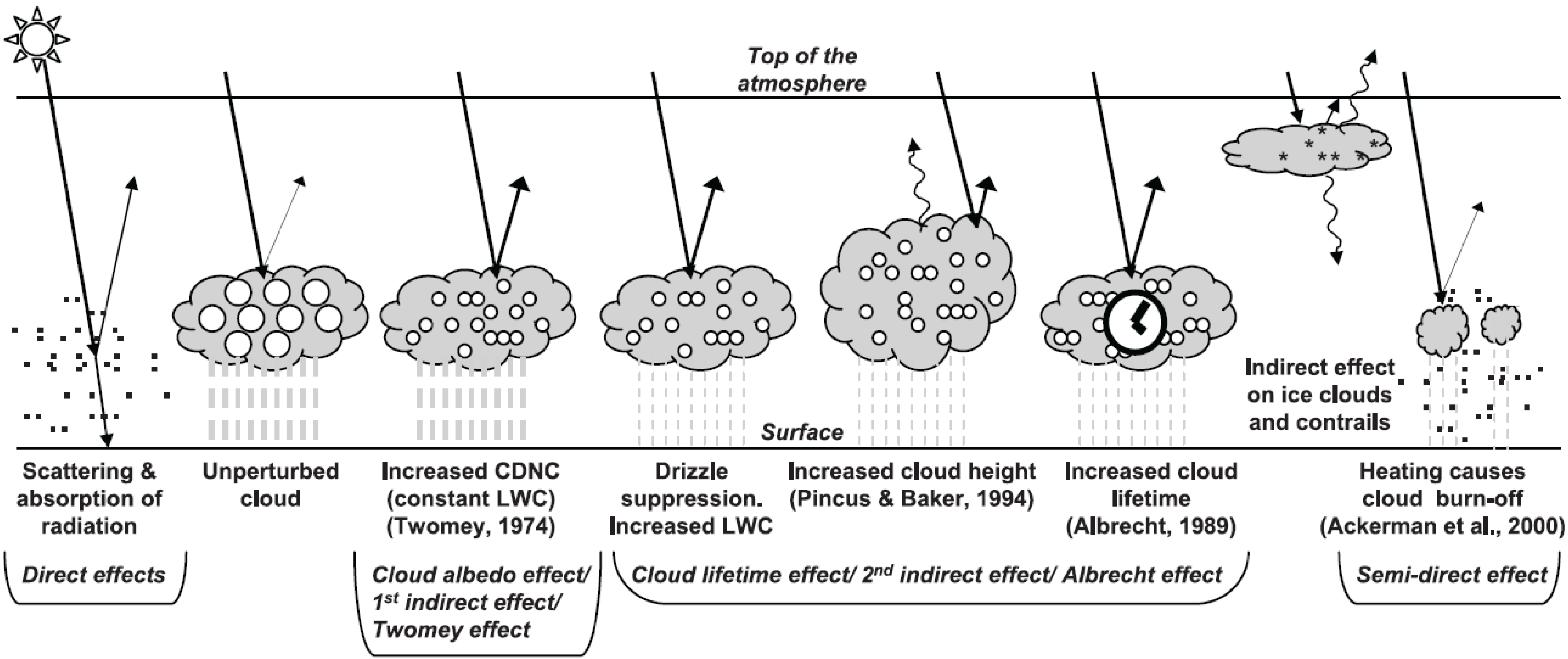
Mie Theory for Atmospheric Scattering



$\alpha = 2\pi R / \lambda$

- $\alpha < 0.1$: Rayleigh scattering (N_2, O_2)
- $0.1 < \alpha < 50$: Mie scattering (aerosols, clouds)
- $\alpha > 50$: Geometric scattering

Scattering & Absorption of SW by Aerosols



IPCC, 2007

Radiative Forcing: Terminology

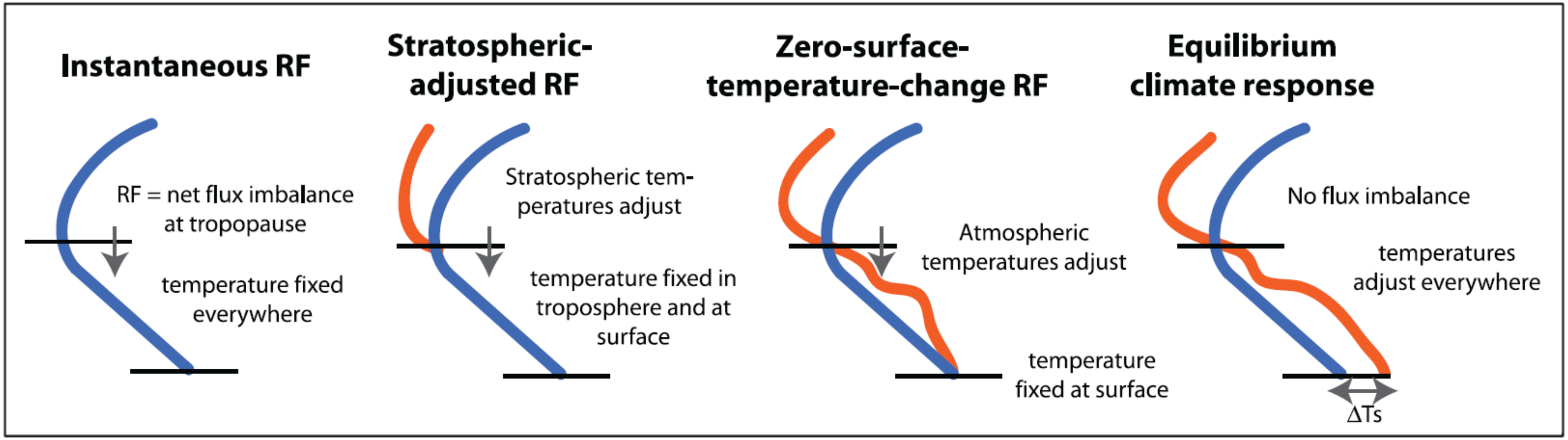
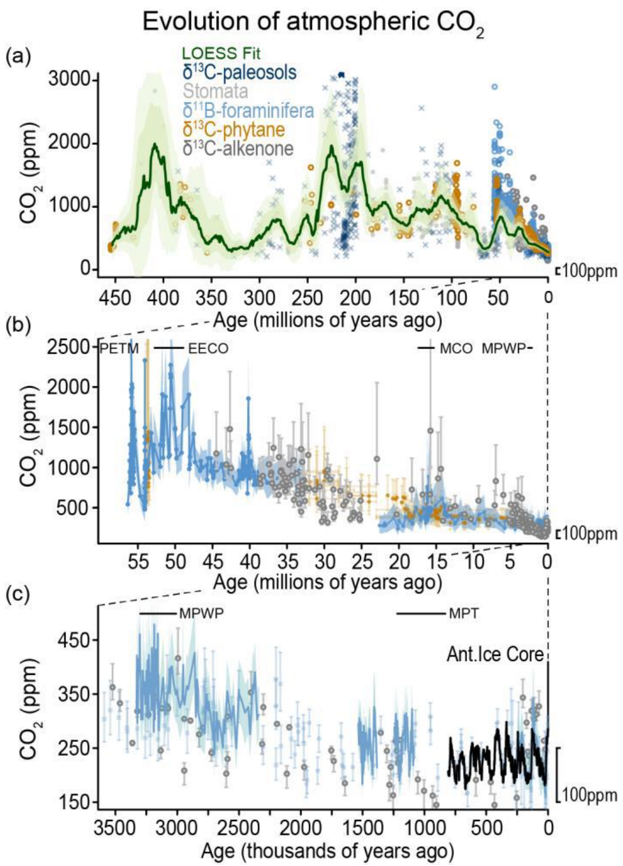


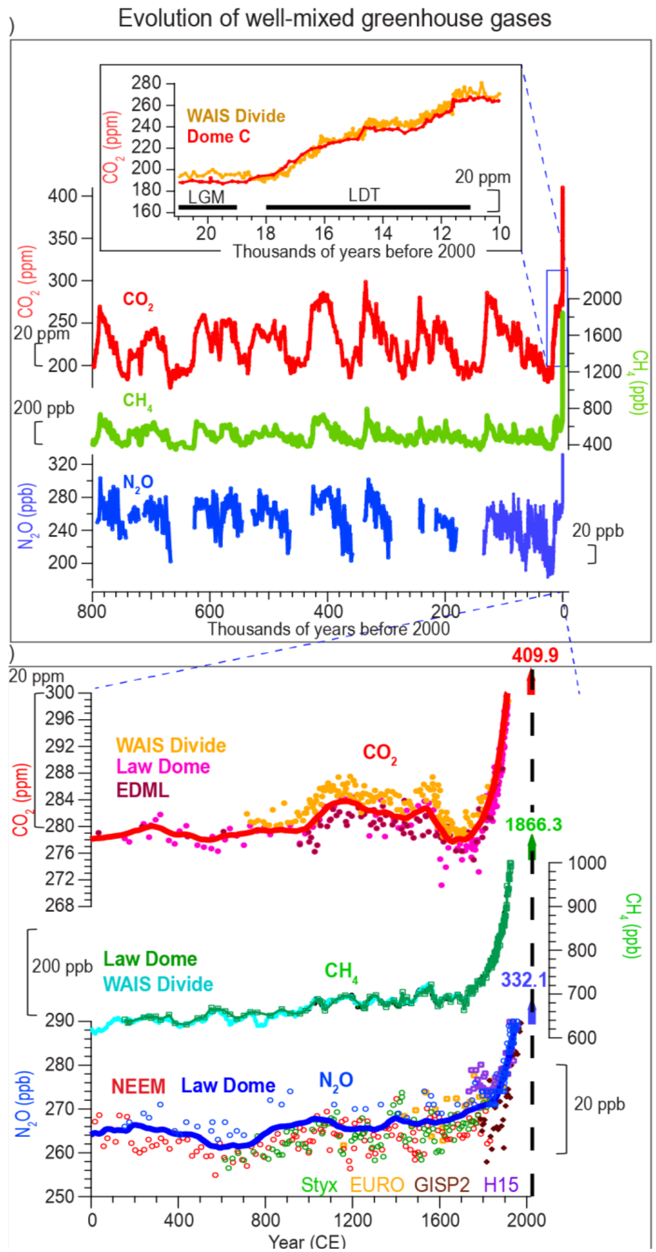
Figure 2.2. *Schematic comparing RF calculation methodologies. Radiative forcing, defined as the net flux imbalance at the tropopause, is shown by an arrow. The horizontal lines represent the surface (lower line) and tropopause (upper line). The unperturbed temperature profile is shown as the blue line and the perturbed temperature profile as the orange line. From left to right: Instantaneous RF: atmospheric temperatures are fixed everywhere; stratospheric-adjusted RF: allows stratospheric temperatures to adjust; zero-surface-temperature-change RF: allows atmospheric temperatures to adjust everywhere with surface temperatures fixed; and equilibrium climate response: allows the atmospheric and surface temperatures to adjust to reach equilibrium (no tropopause flux imbalance), giving a surface temperature change (*ΔT_s*).*

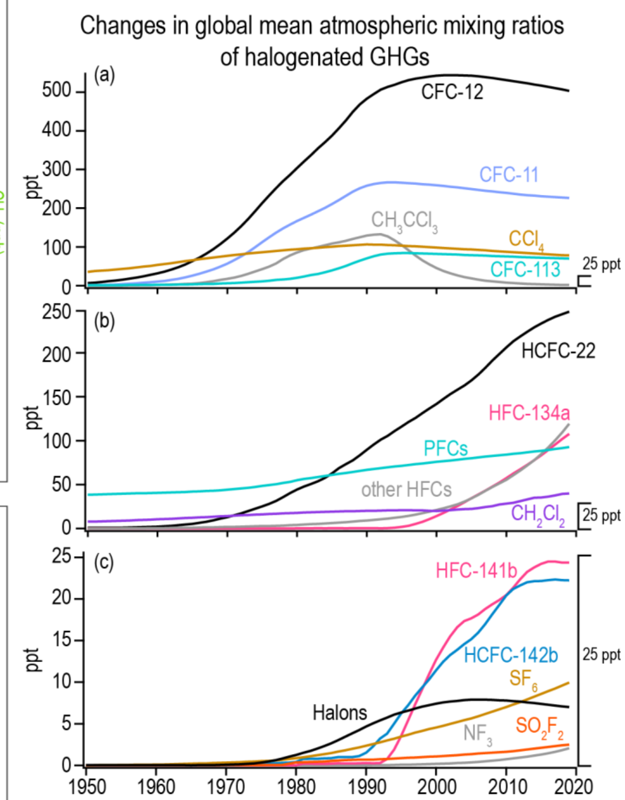
IPCC, 2007

Trends in Long-lived GHGs Concentrations

[CO_2] in 2022: 417 ppm

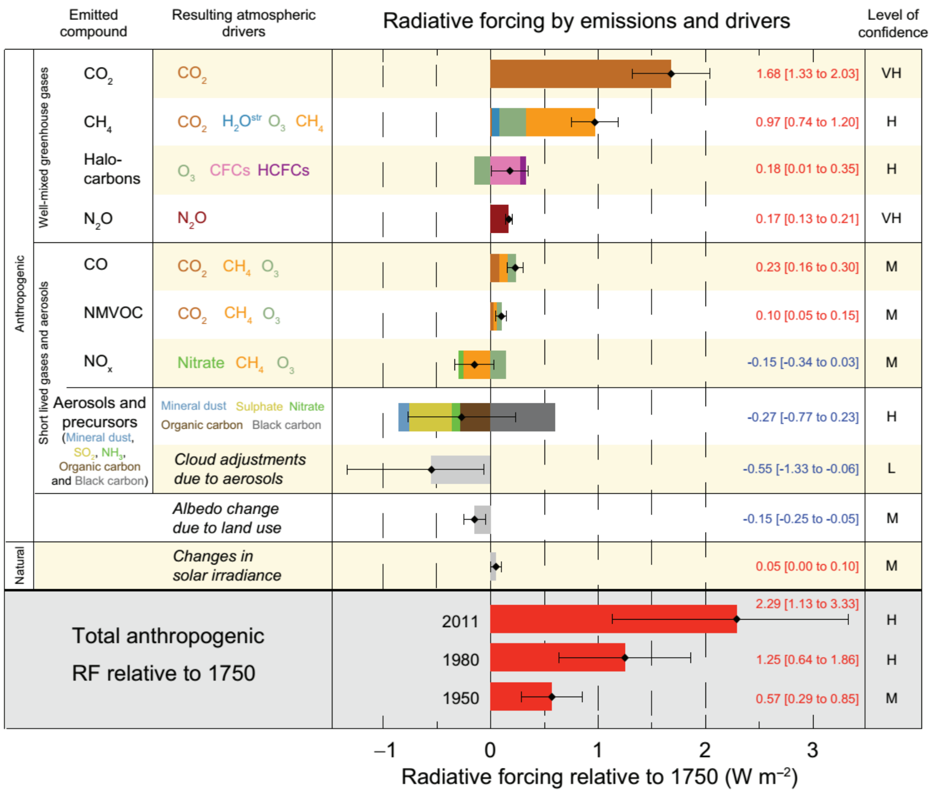






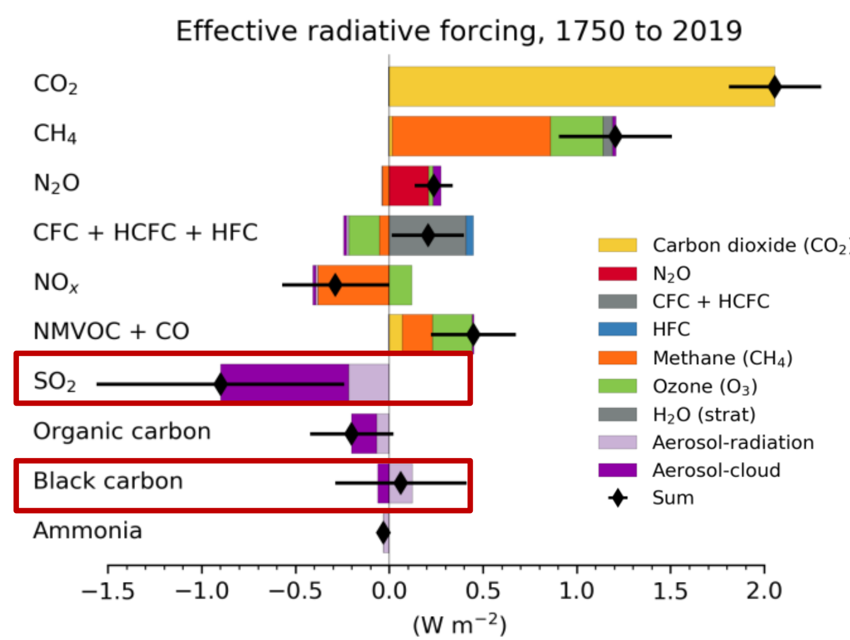
IPCC, 2021

(Effective) Radiative Forcing

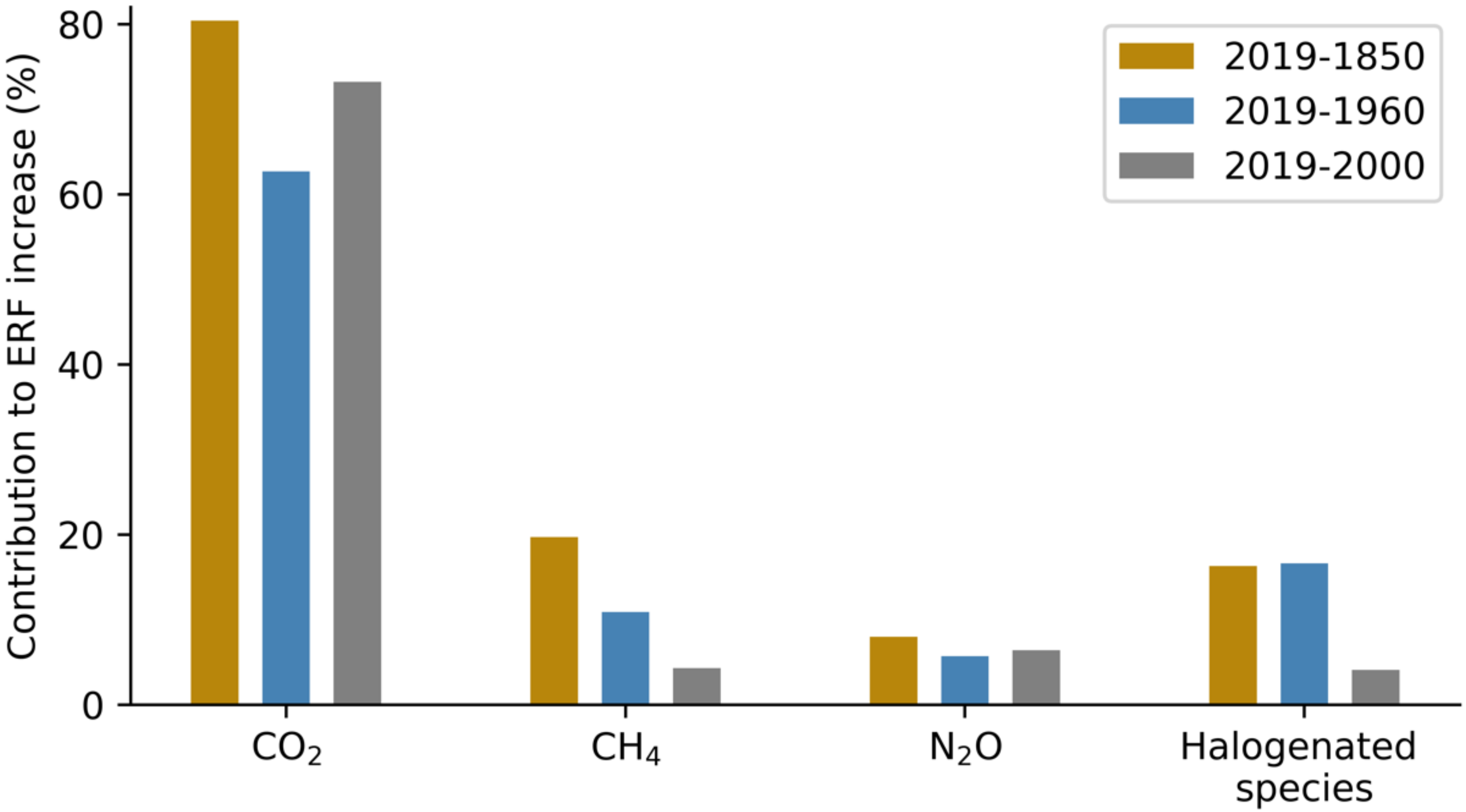


IPCC, 2013

IPCC, 2021

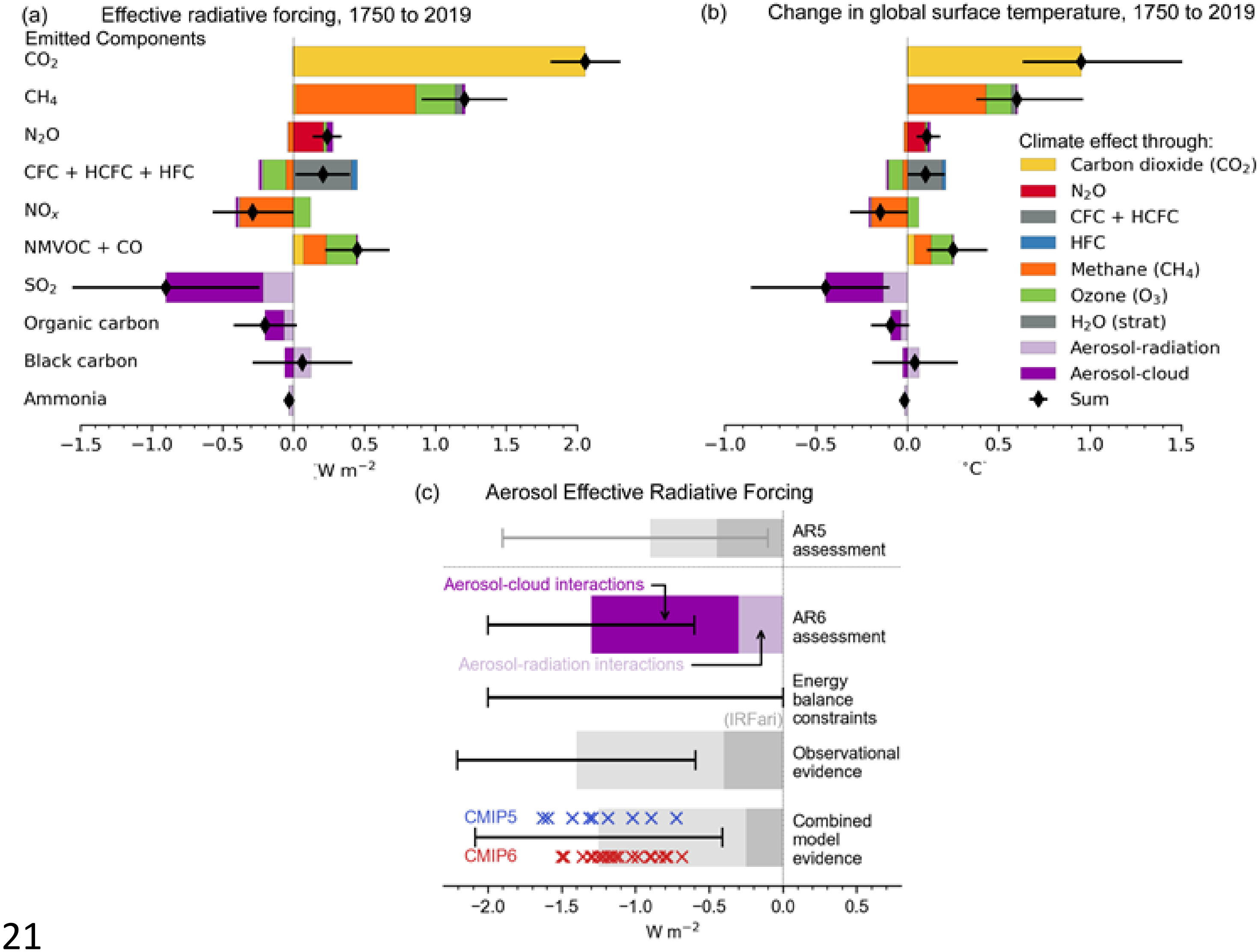


Contributions of Long-lived GHGs to Total ERF



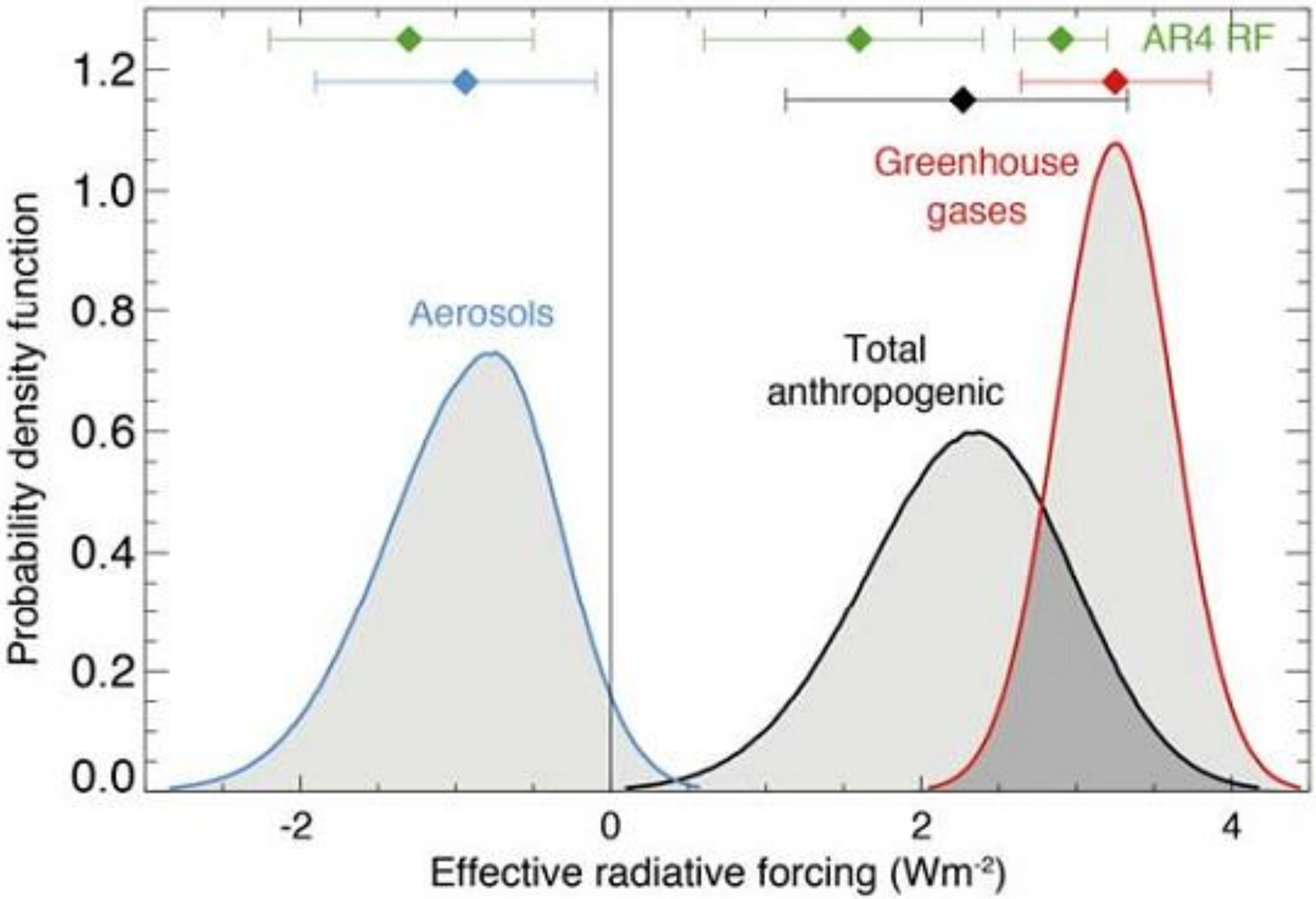
IPCC, 2013

Effective Radiative Forcing



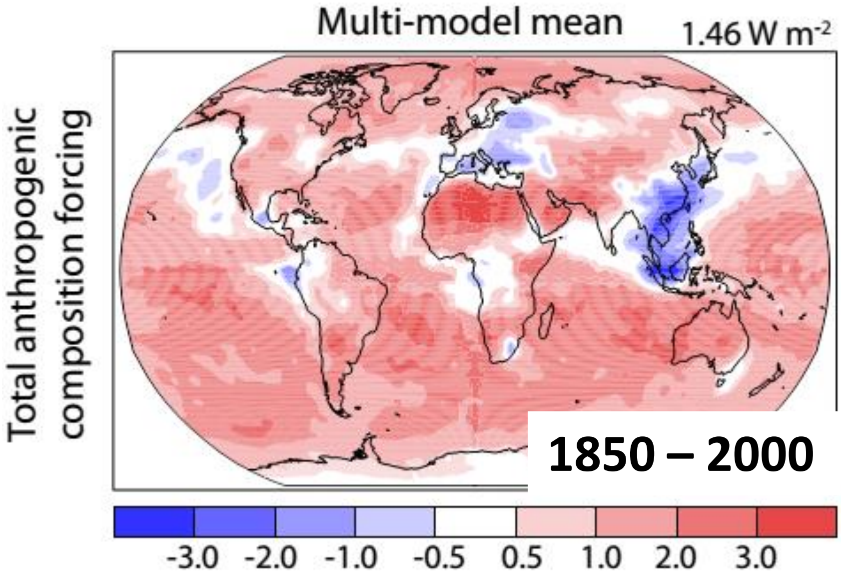
IPCC, 2021

Effective Radiative Forcing

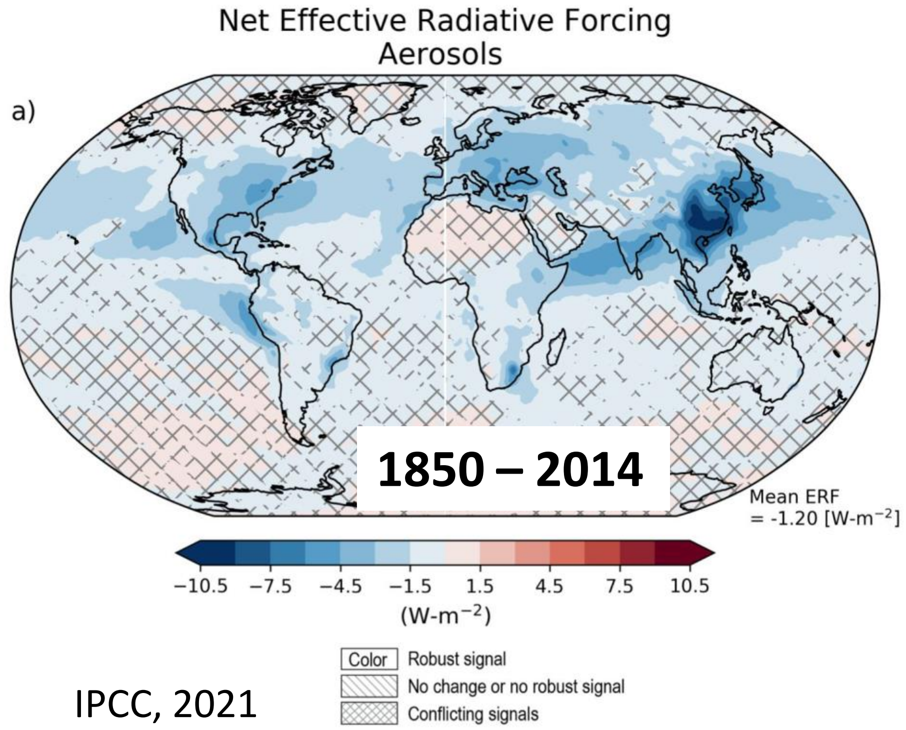


IPCC, 2013

Radiative Forcing: Spatial Distribution

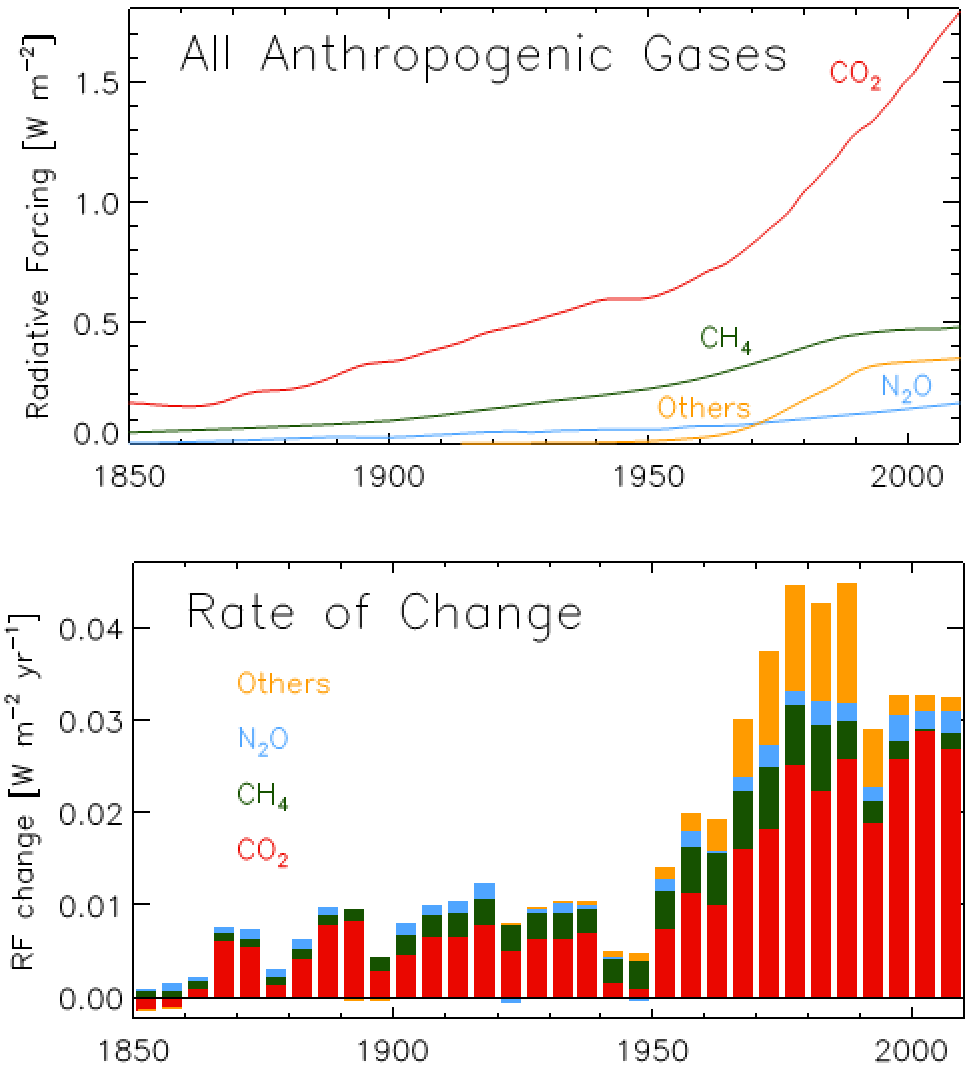


IPCC, 2013



IPCC, 2021

Trends in Long-lived GHG Radiative Forcing

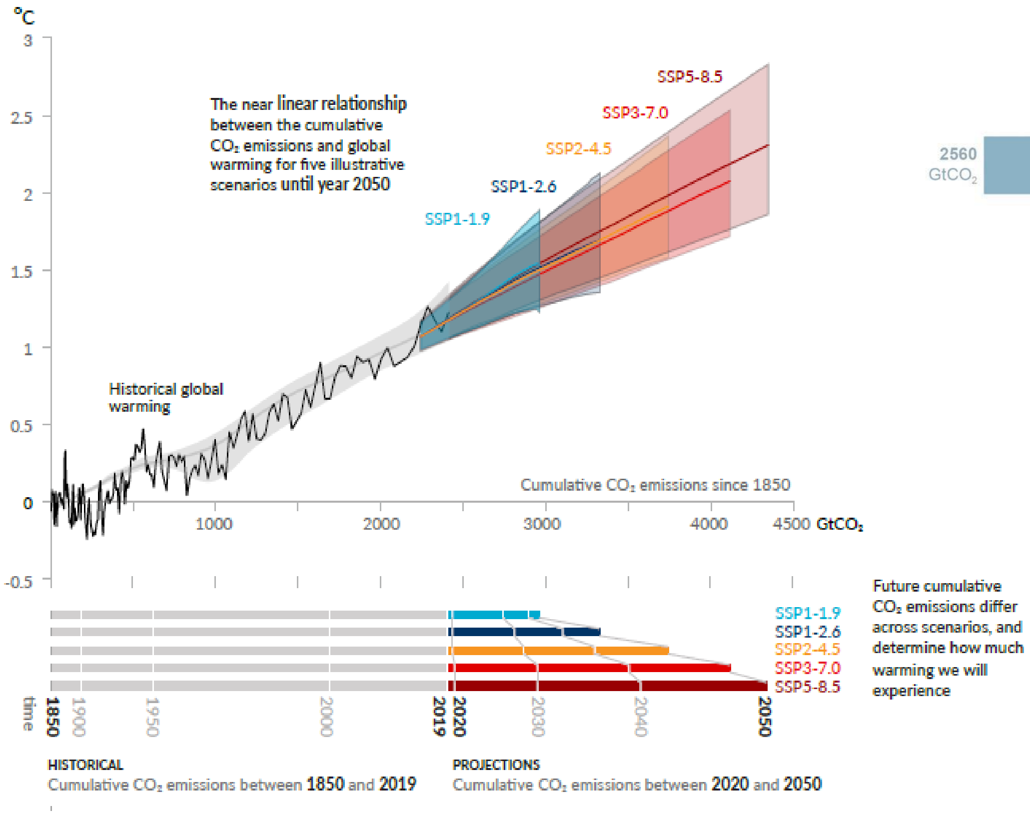


IPCC, 2013

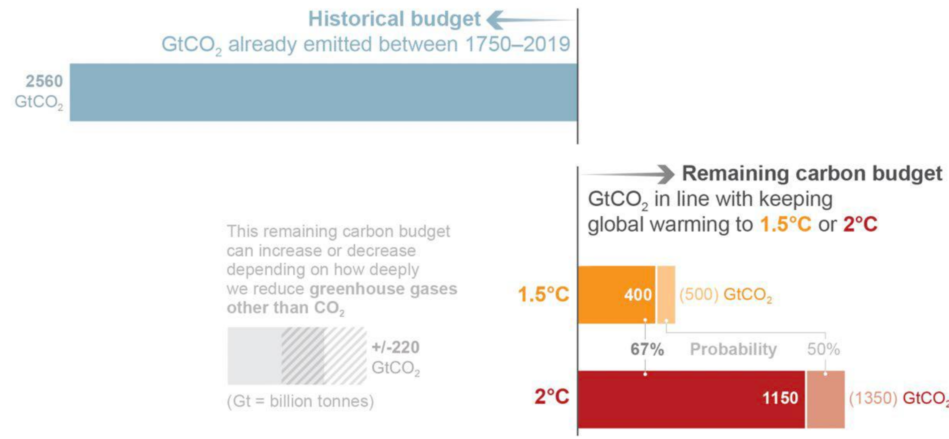
Cumulative CO_2 Emissions and Warming

Every tonne of CO_2 emissions adds to global warming

Global surface temperature increase since 1850-1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)

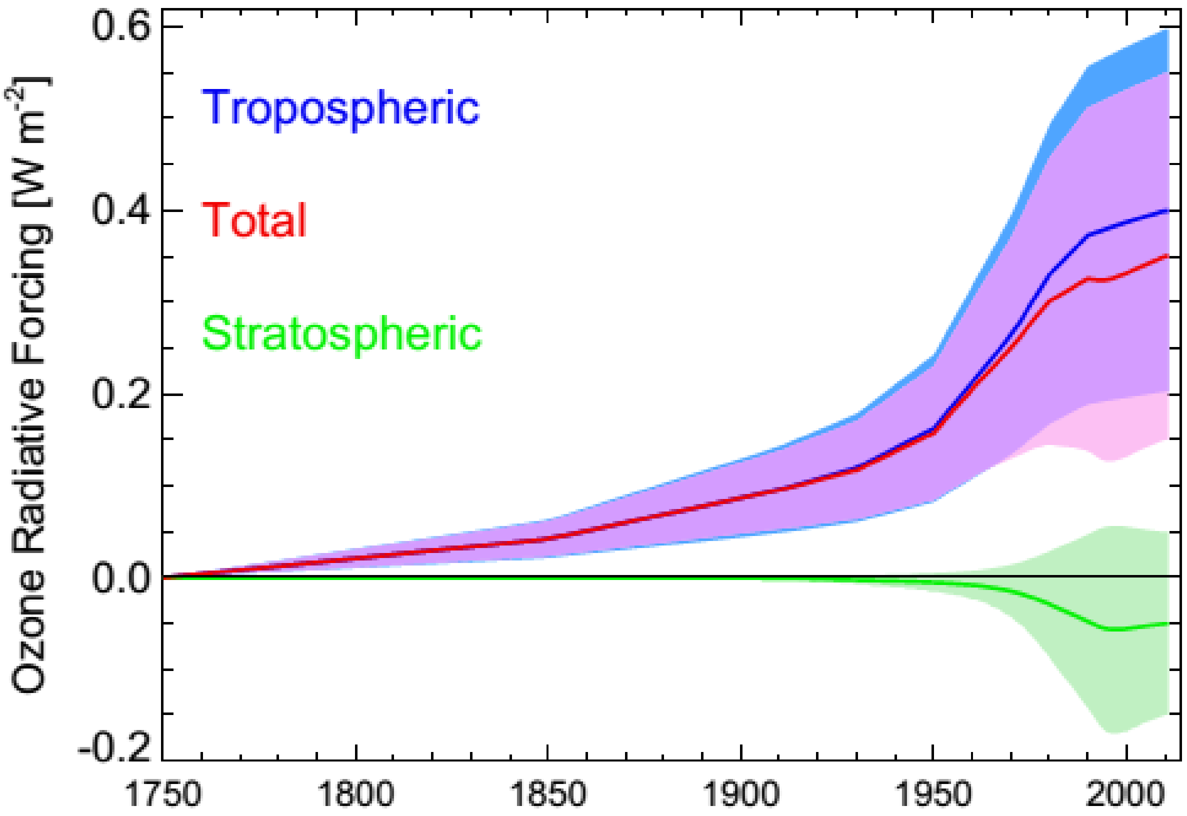


Carbon budget



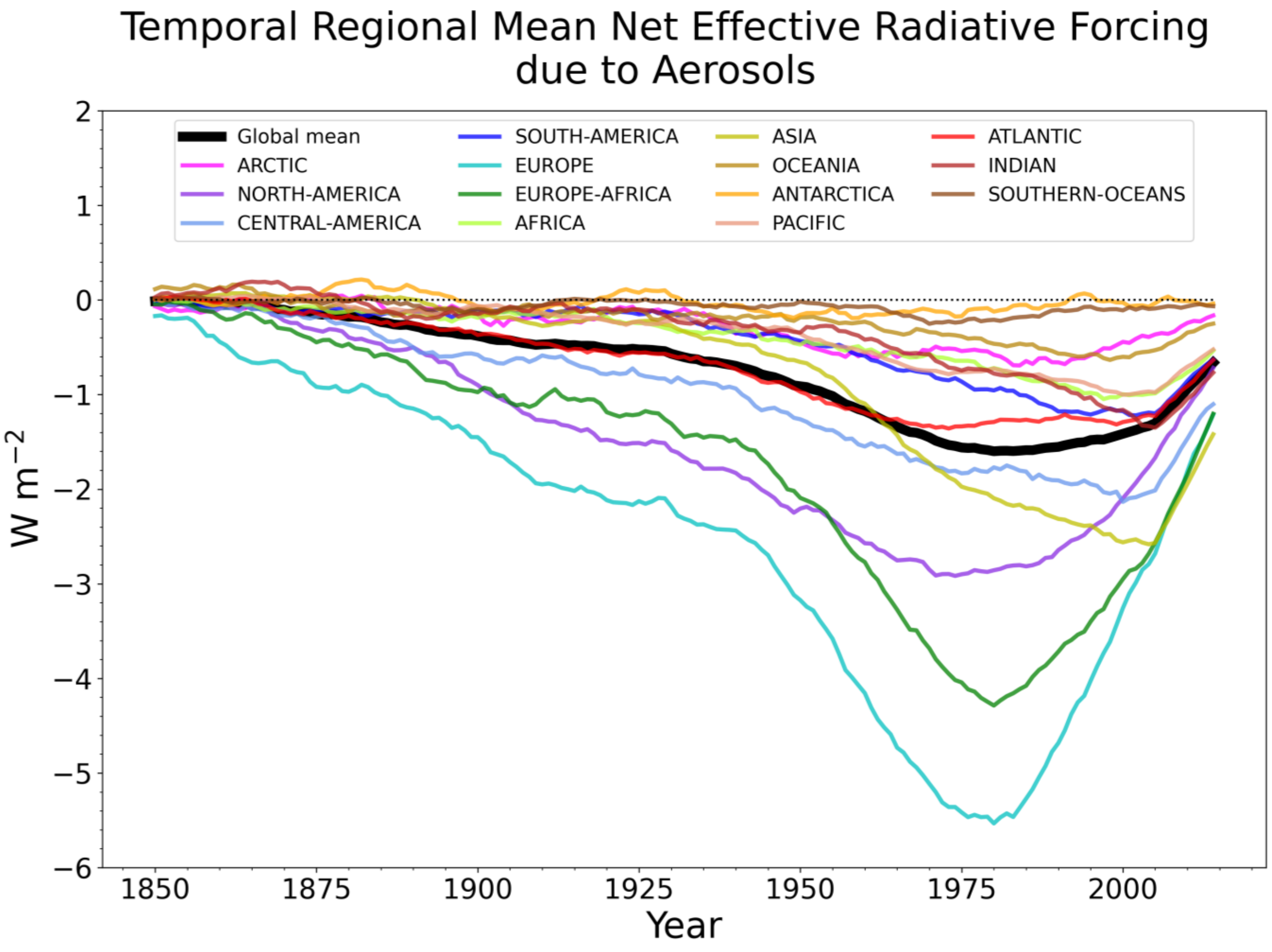
IPCC, 2021

Ozone Radiative Forcing



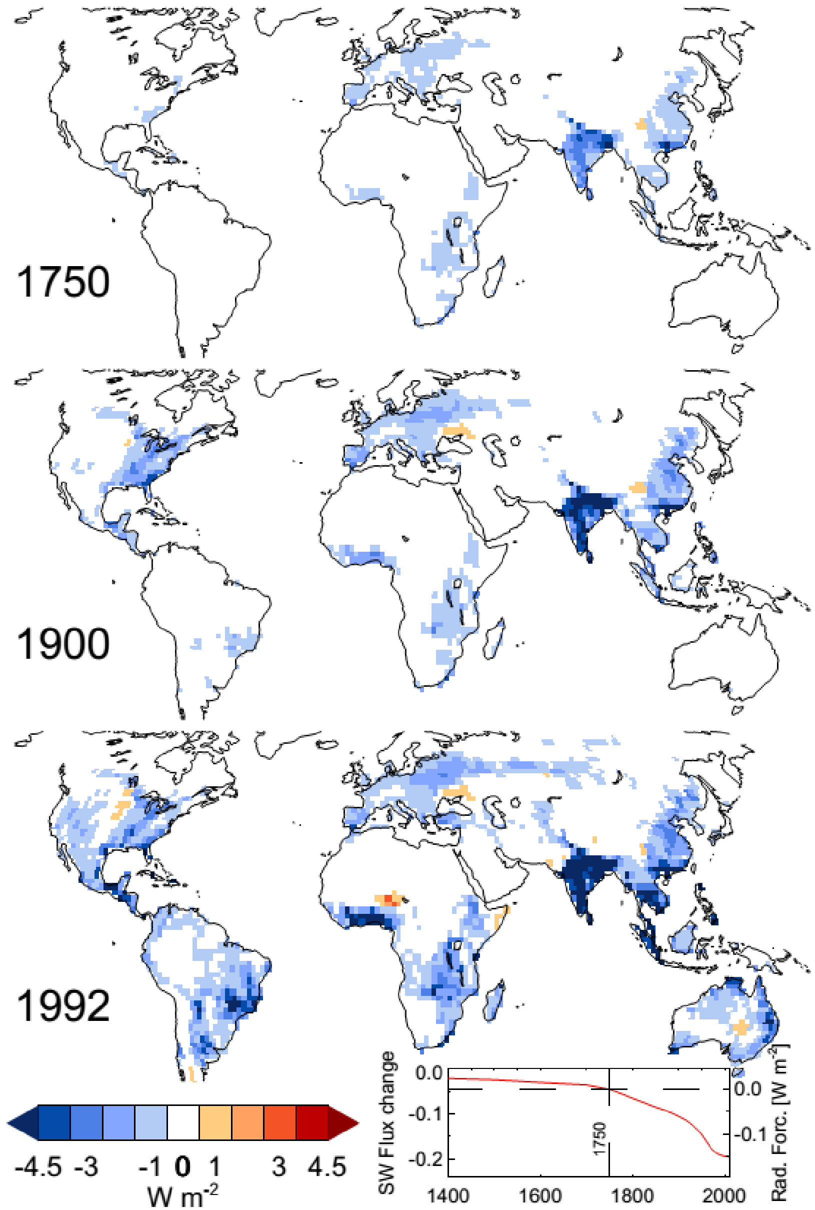
IPCC, 2013

Aerosol Effective Radiative Forcing



IPCC, 2021

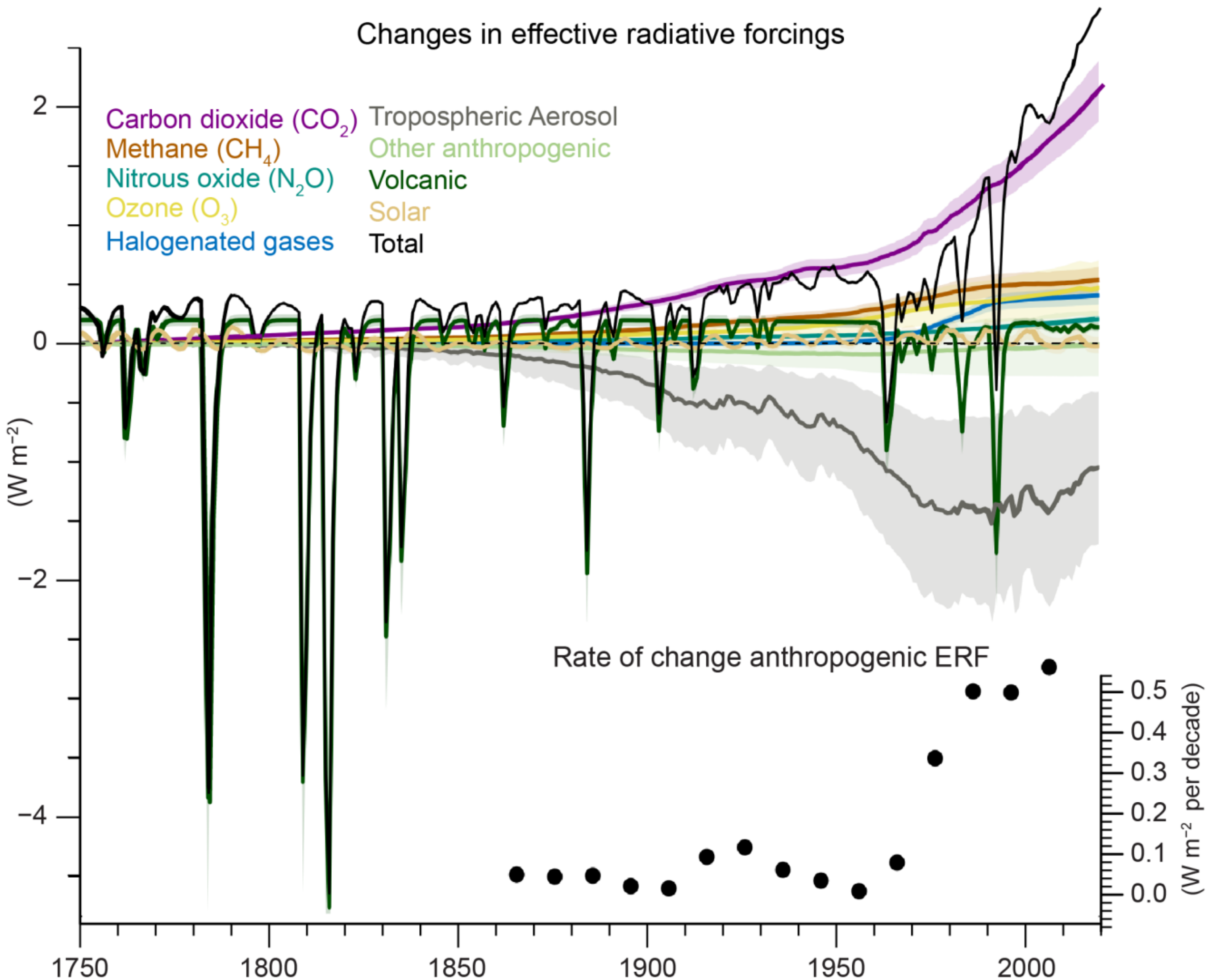
LUC-related Surface Albedo Radiative Forcing



Effects already occurred in 1750

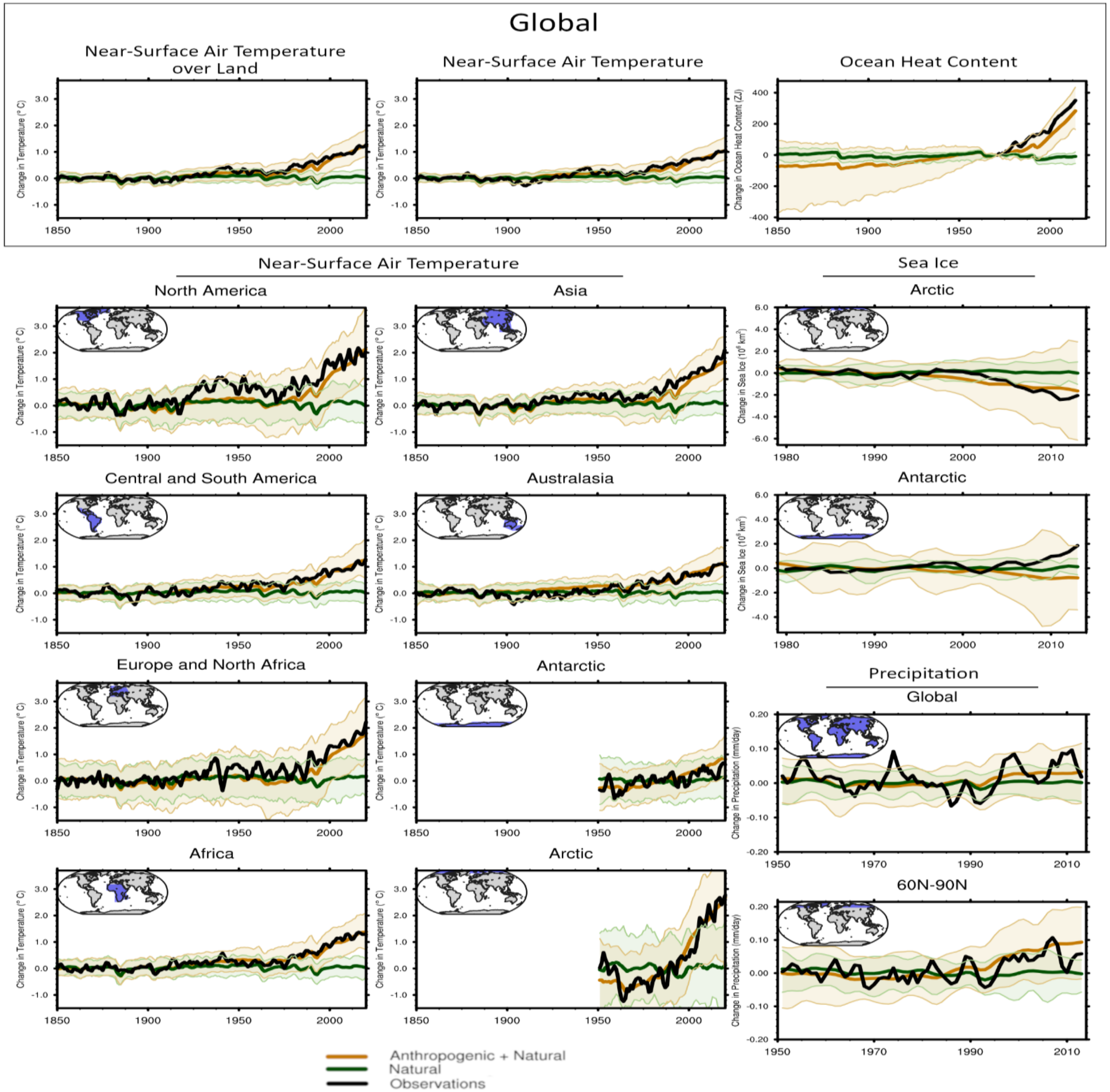
IPCC, 2013

Effective Radiative Forcing



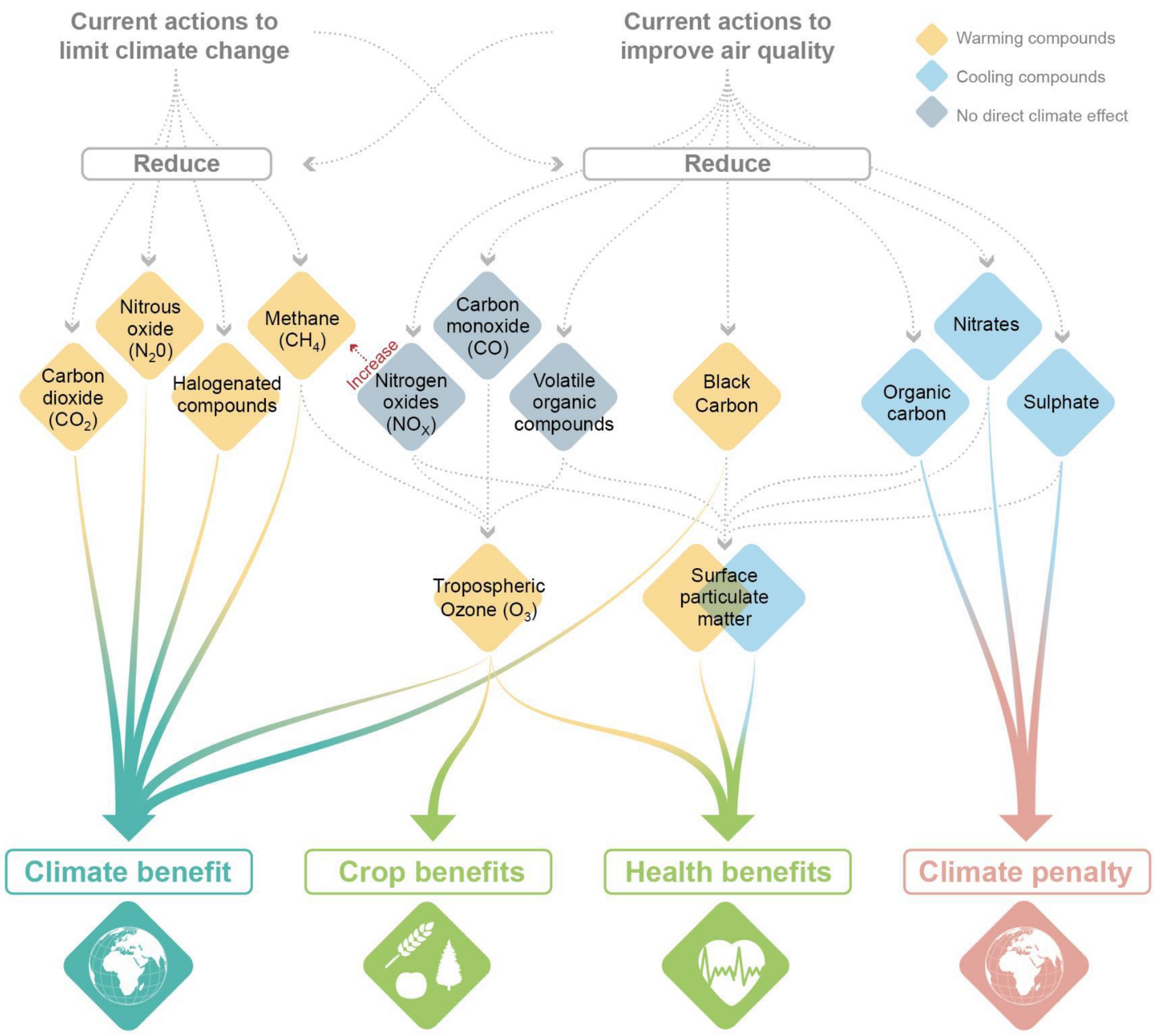
IPCC, 2021

Modeled Anthropogenic versus Natural Impacts



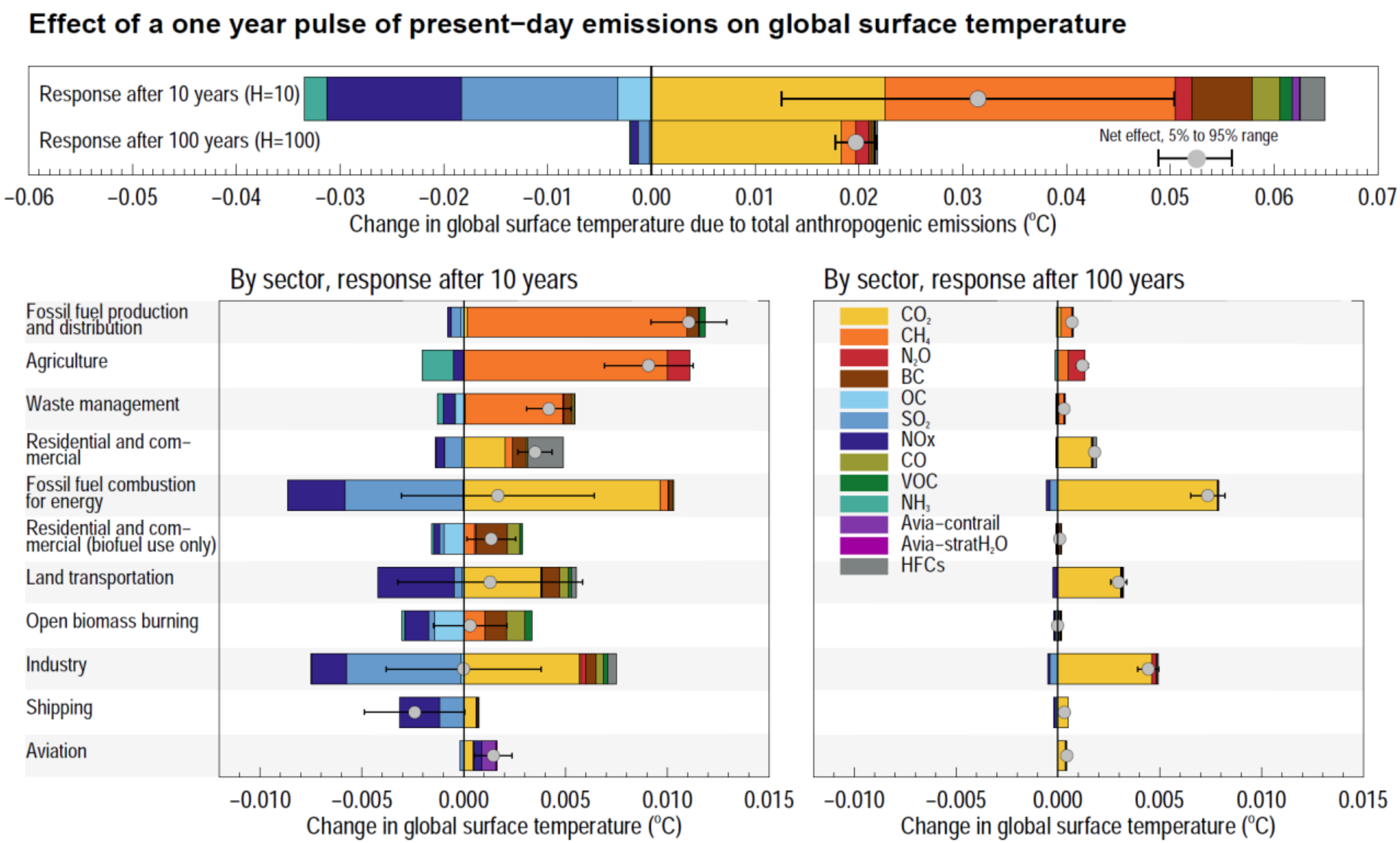
IPCC, 2021

Effects of Pollution Control on Climate: Climate-Pollution Nexus



IPCC, 2021

Temperature Response to Perturbed Emissions

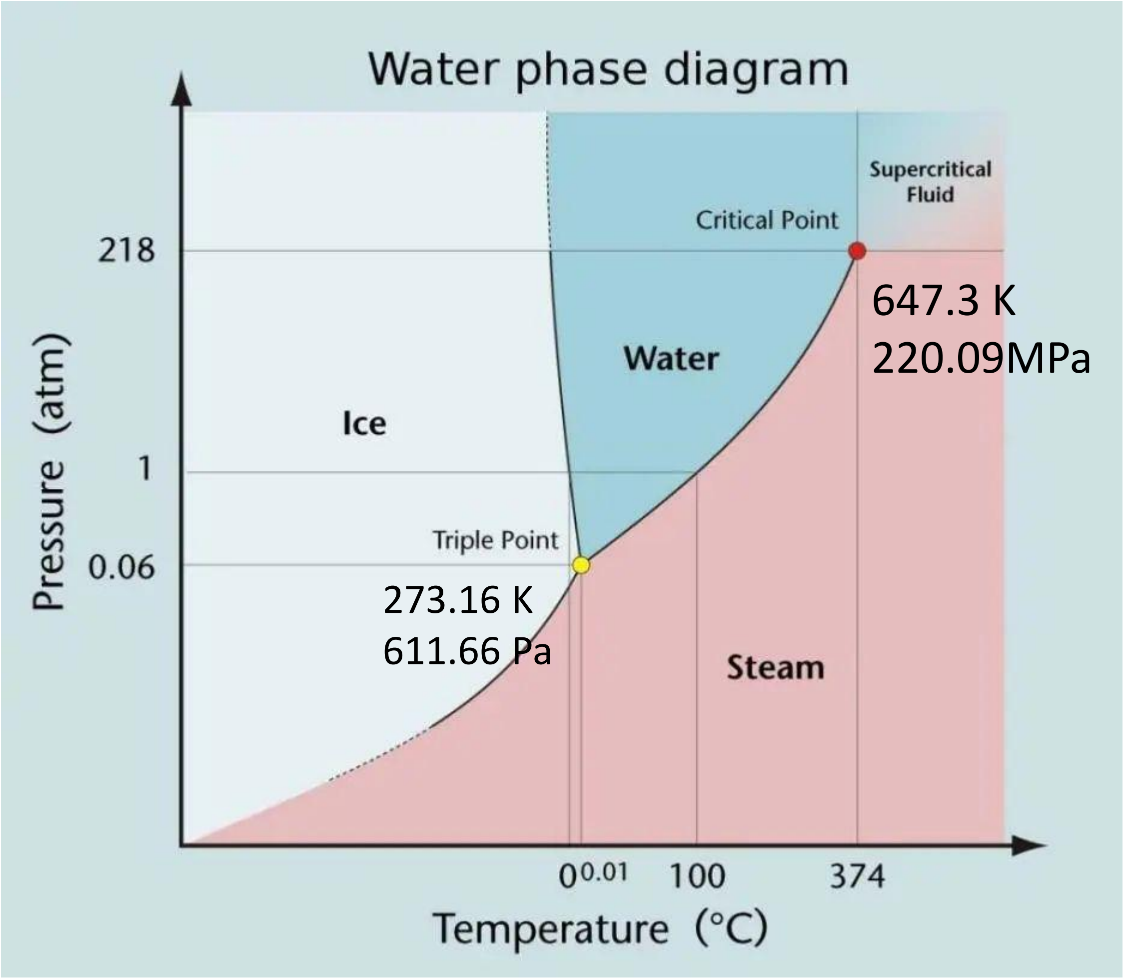


IPCC, 2021

与气候变化相关的反馈过程

- 温度（热辐射）：（-）
- 水汽：温室效应（+）
- 温度递减率：（-）
- 冰雪圈：返照率（+）
- 云水：返照率（-）、温室效应（+）
- 海洋：CO_2含量（+,-）、AMOC（？）
- 生物圈：光合作用（-）、呼吸（+）

H_2O Feedback

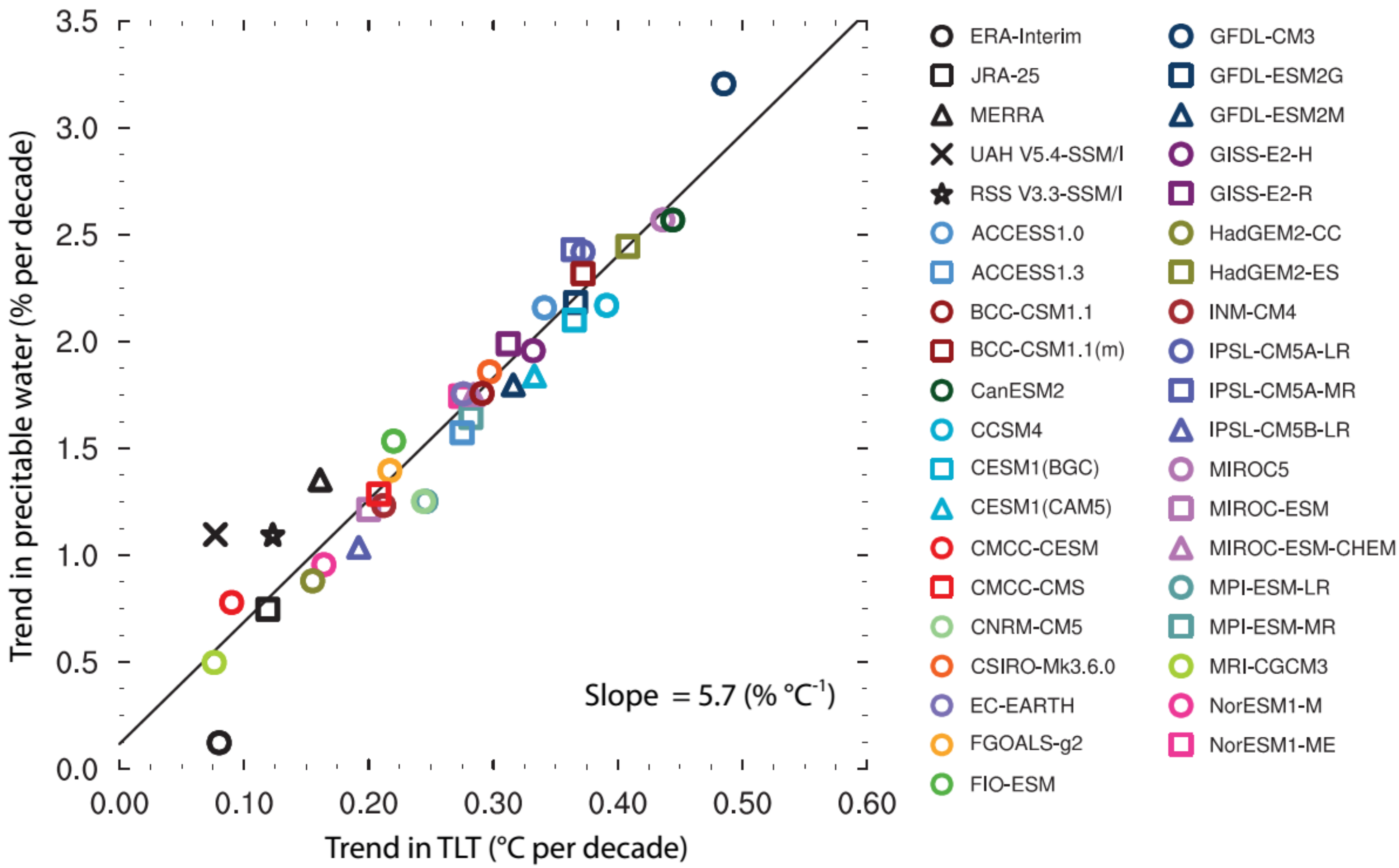


Clausius–Clapeyron Eq.:

$$\ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_{\text{vap}}}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)$$

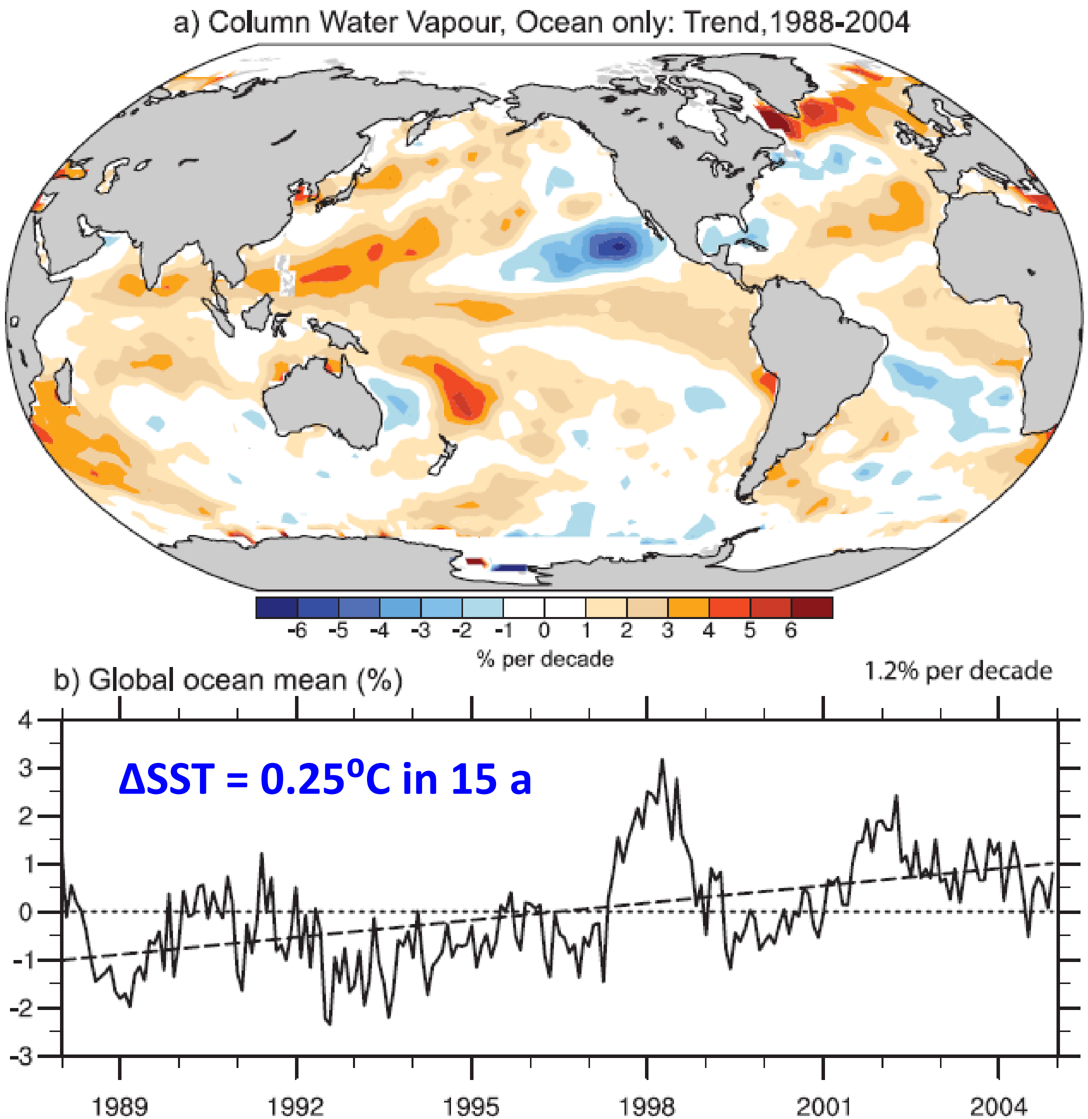
With constant RH **T ↑ → H_2O ↑ → GH effect ↑ → T ↑**

Water Vapor Increase Driven by Warming



IPCC, 2013

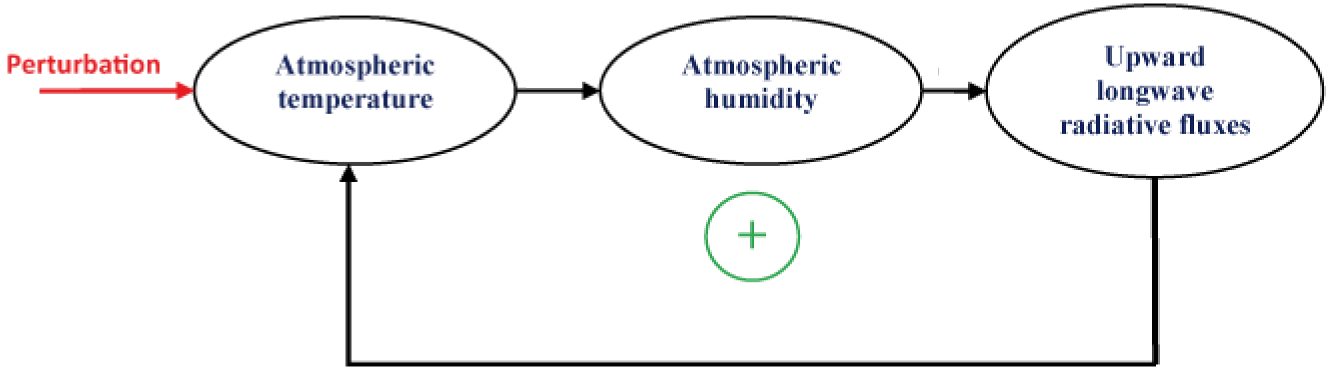
Water Vapor Change: 1988-2004



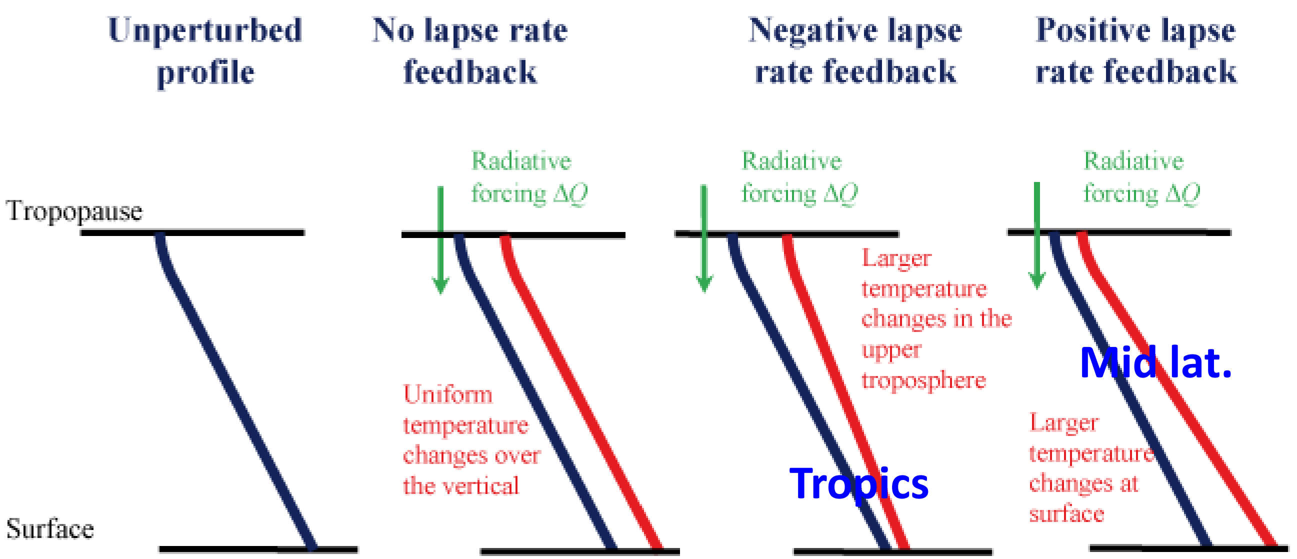
IPCC, 2007

Water Vapor – Lapse Rate Feedback

Water vapor feedback



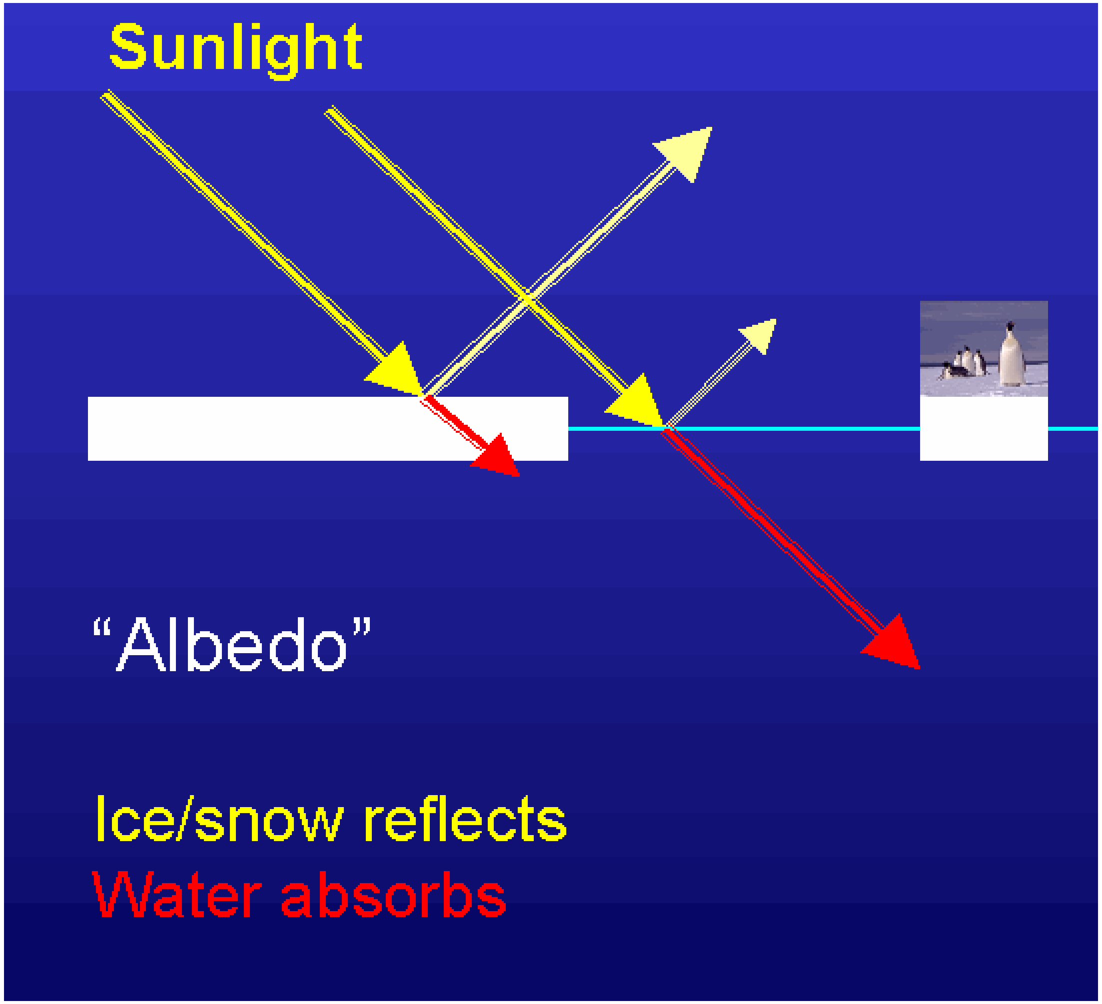
Lapse rate feedback



Water vapor feedback and lapse rate feedback are negatively correlated, and are therefore considered together.

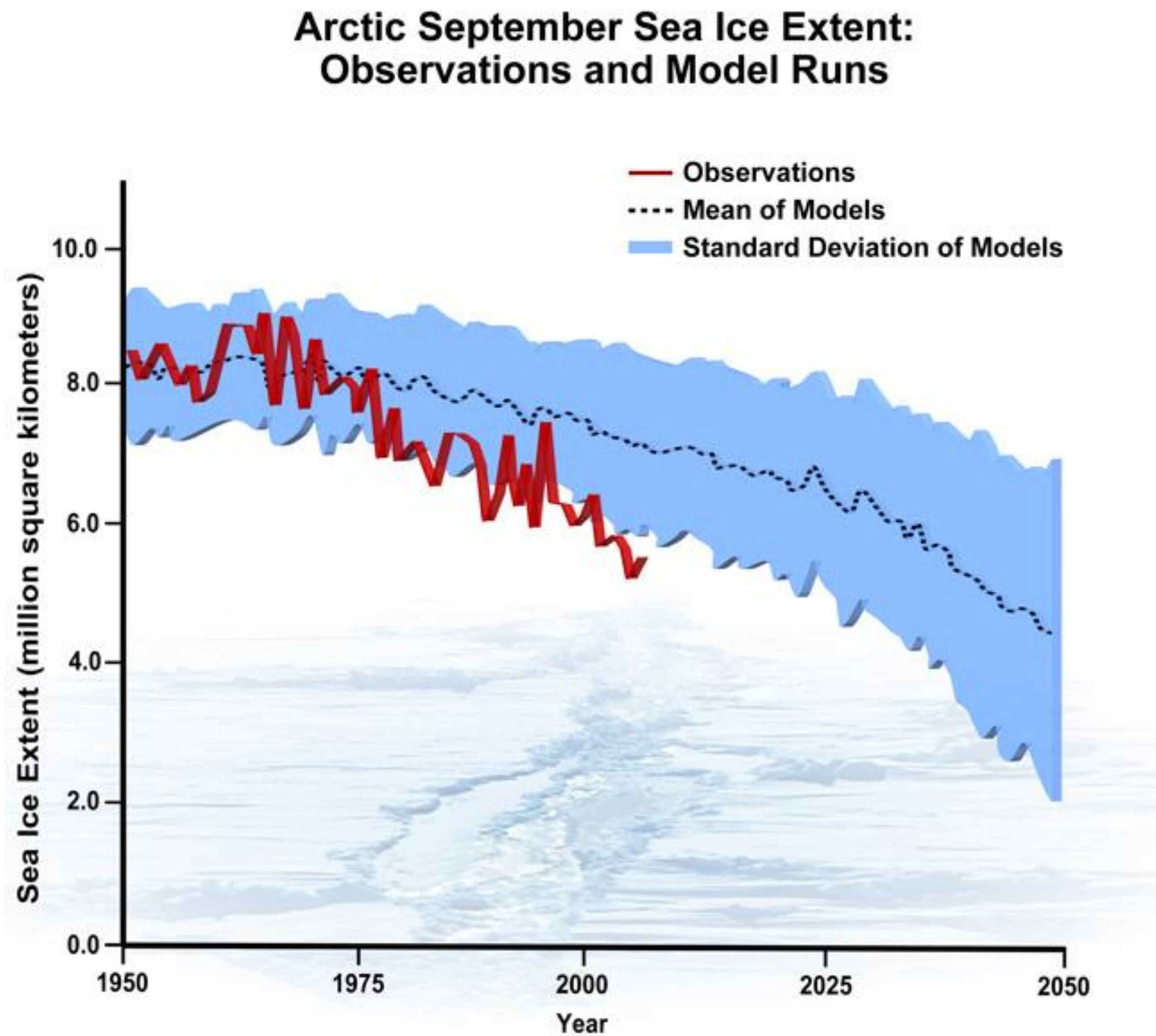
IPCC, 2007

Ice Albedo Feedback



T ↑ => Ice ↓ => Albedo ↓ => T ↑

Changes in Polar Ice

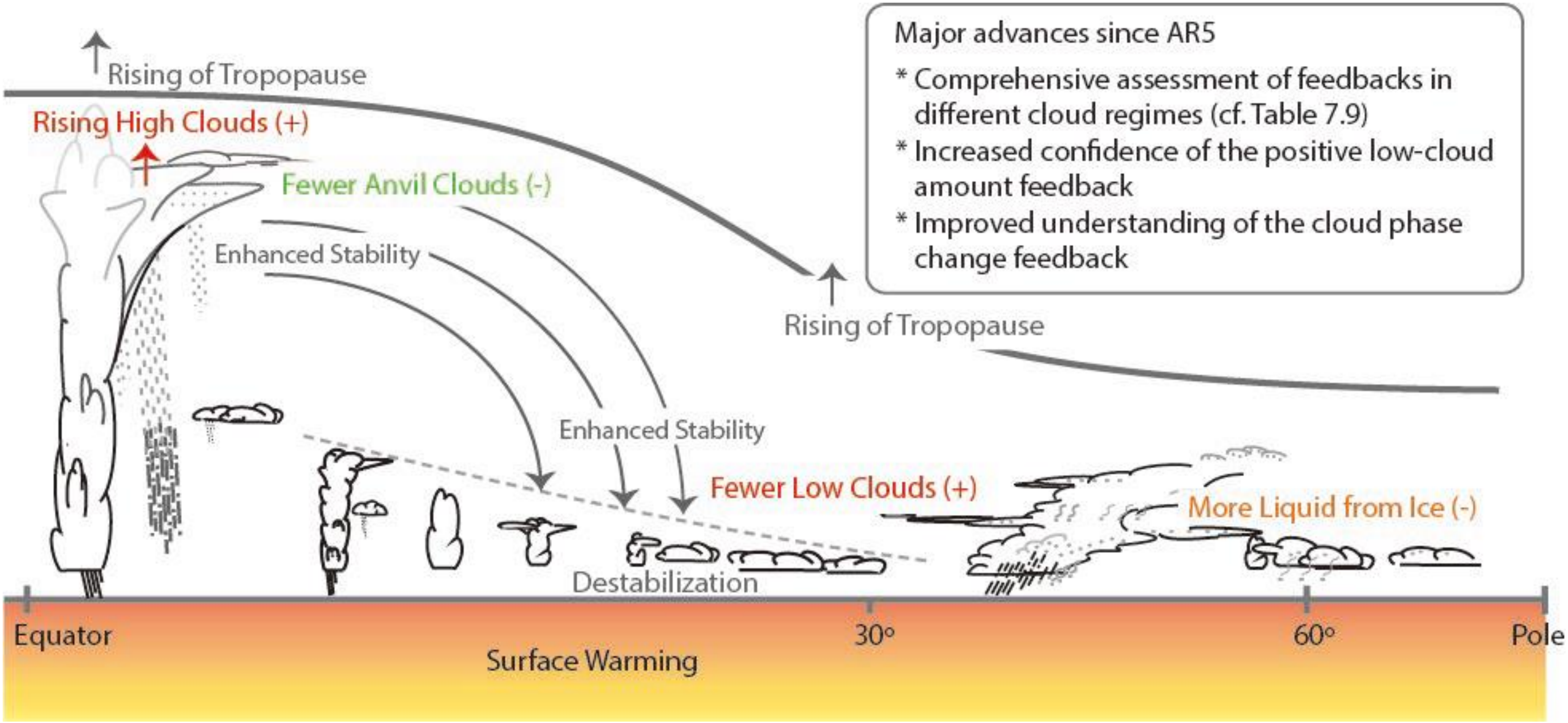


Stroeve et al. [2007]

Cloud Types and Radiative Effects

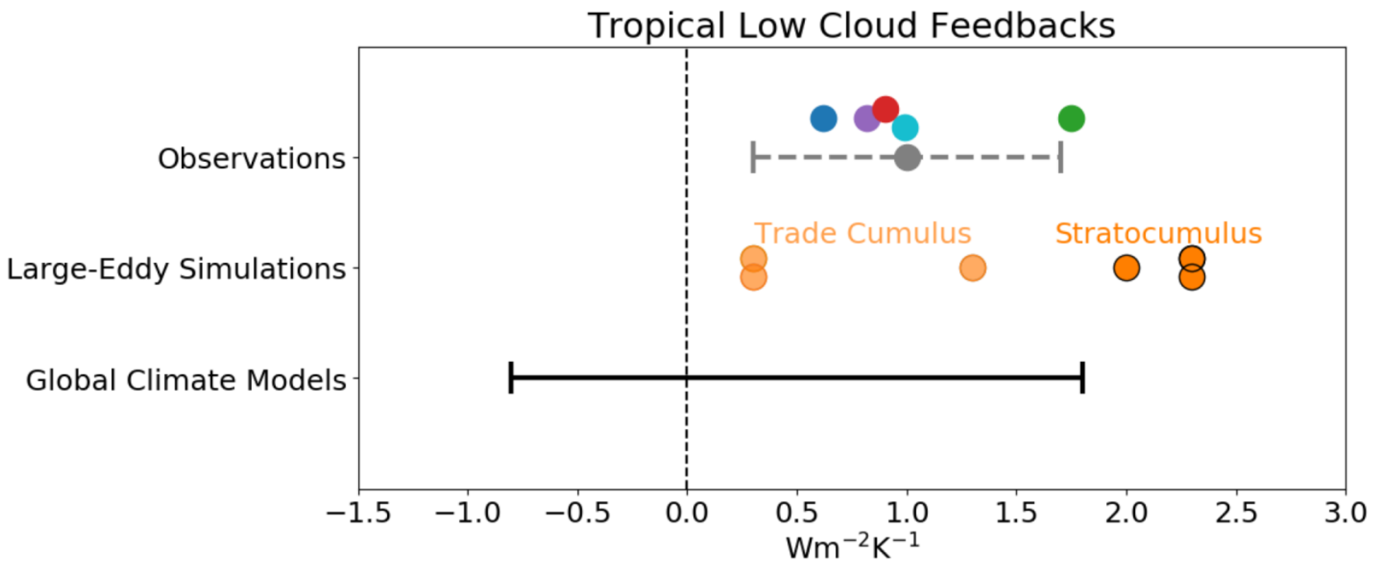
- High-level clouds: weak reflectance of SW, strong GH effect on LW
- Low-level clouds: strong reflectance of SW, weak GH effect on LW
- Convective clouds: strong SW and LW effects
- Polar clouds in different seasons?
- How to affect clouds: height, fraction, thickness, droplet size, phase (liquid or ice), life time
- Changes in CRF are extremely difficult to quantify, leading to large uncertainty in current estimates

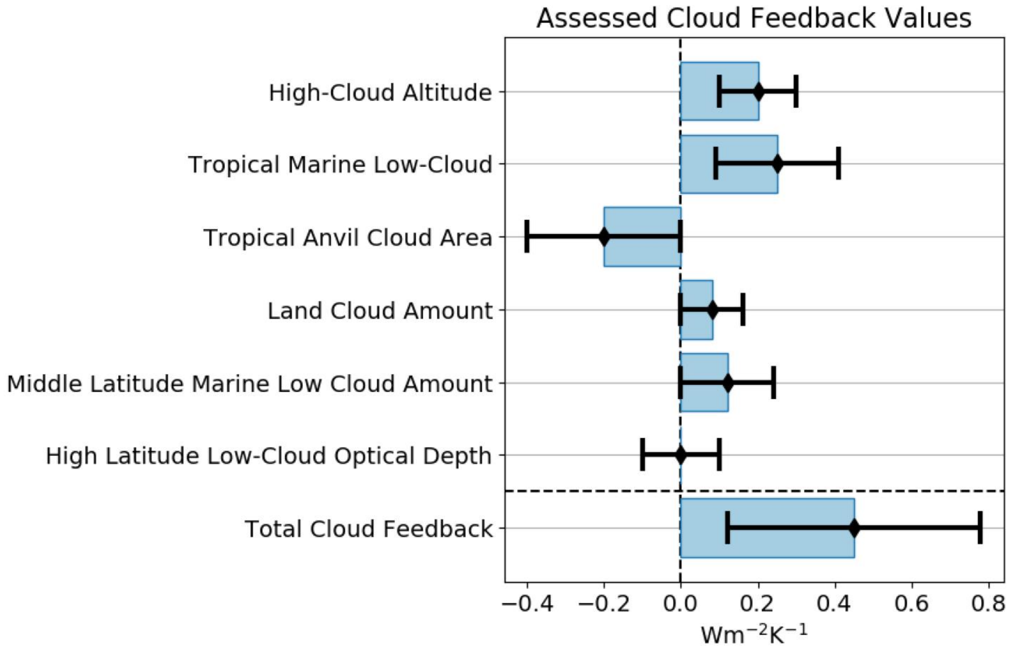
Changes in Cloud



IPCC, 2021

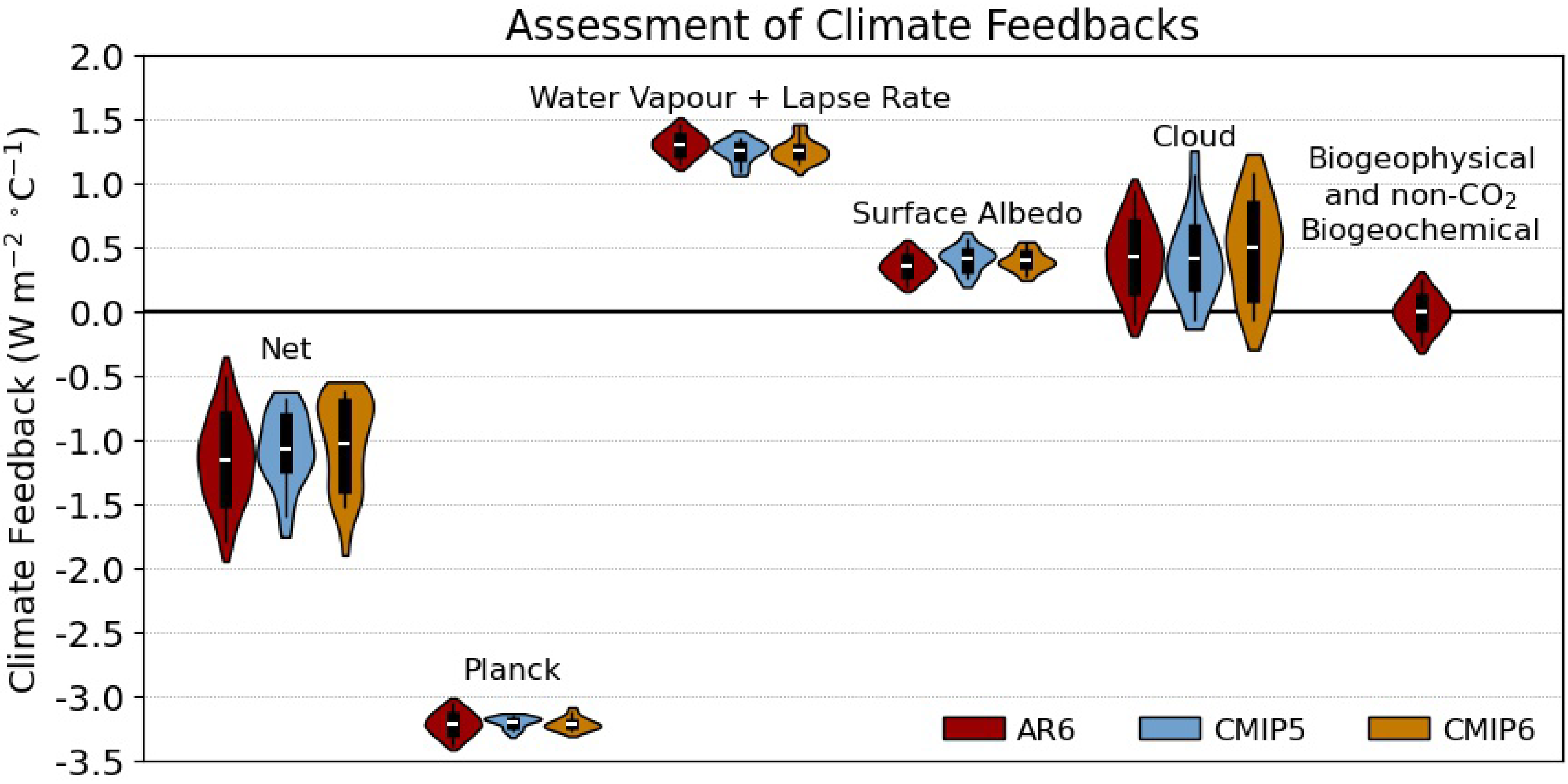
Cloud Feedbacks





Sherwood et al., 2020 RoG

Summary of Feedbacks



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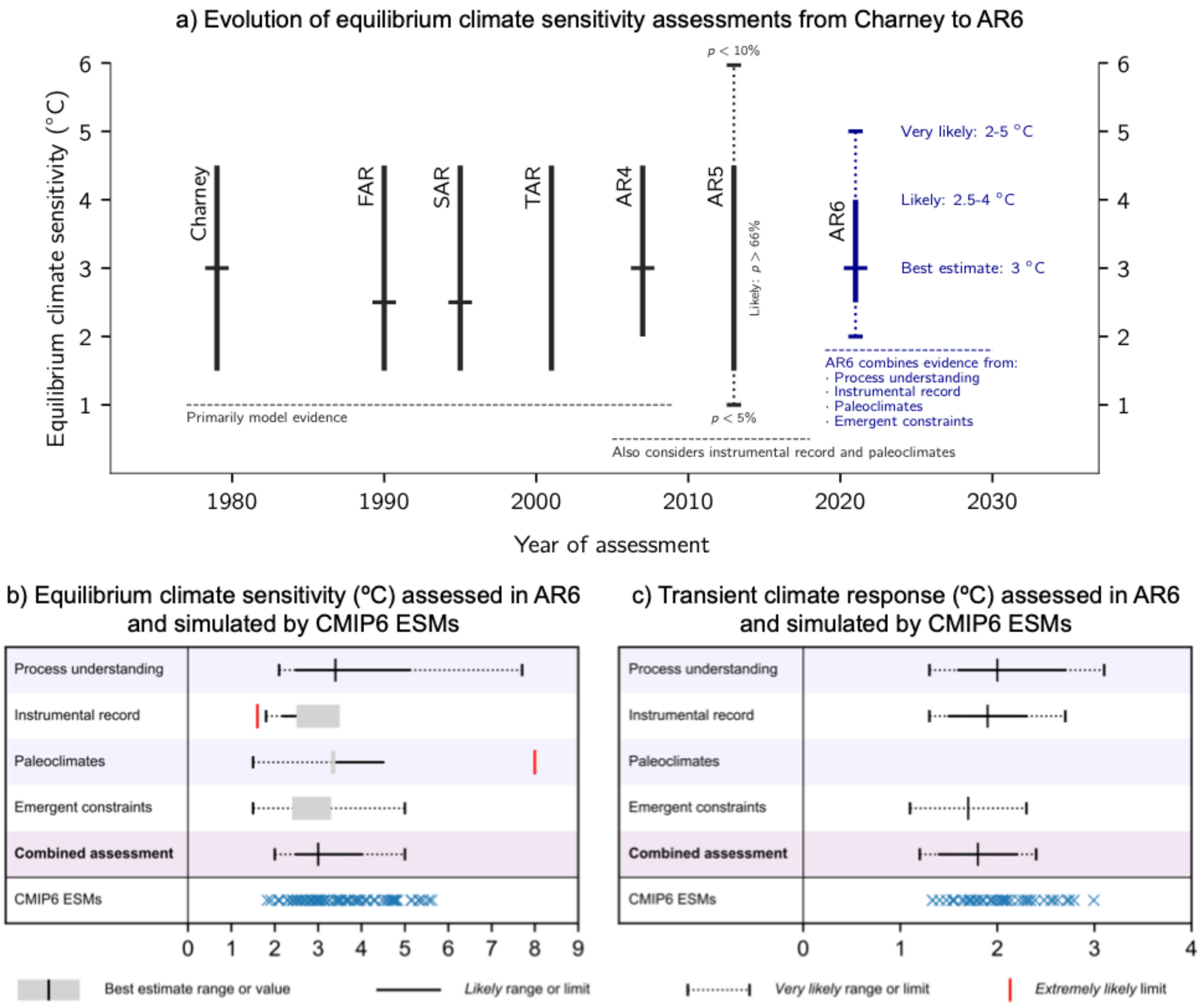
Climate Sensitivity



Science 125

$$F = -\lambda \Delta T$$

Instantaneous forcing = 3.7 w m^{-2} with 2 x CO_2

T increment at new equilibrium

Total Feedback

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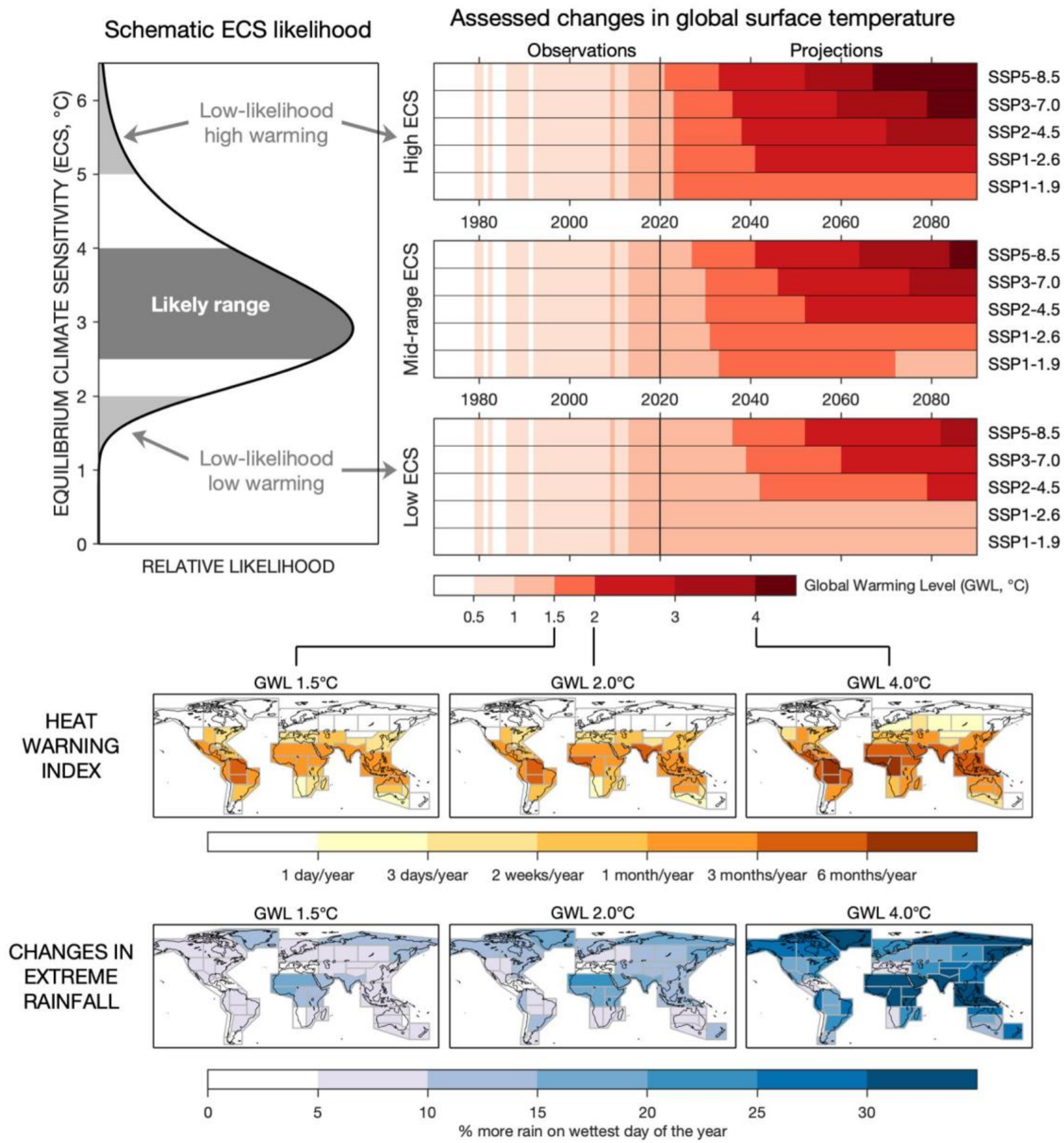
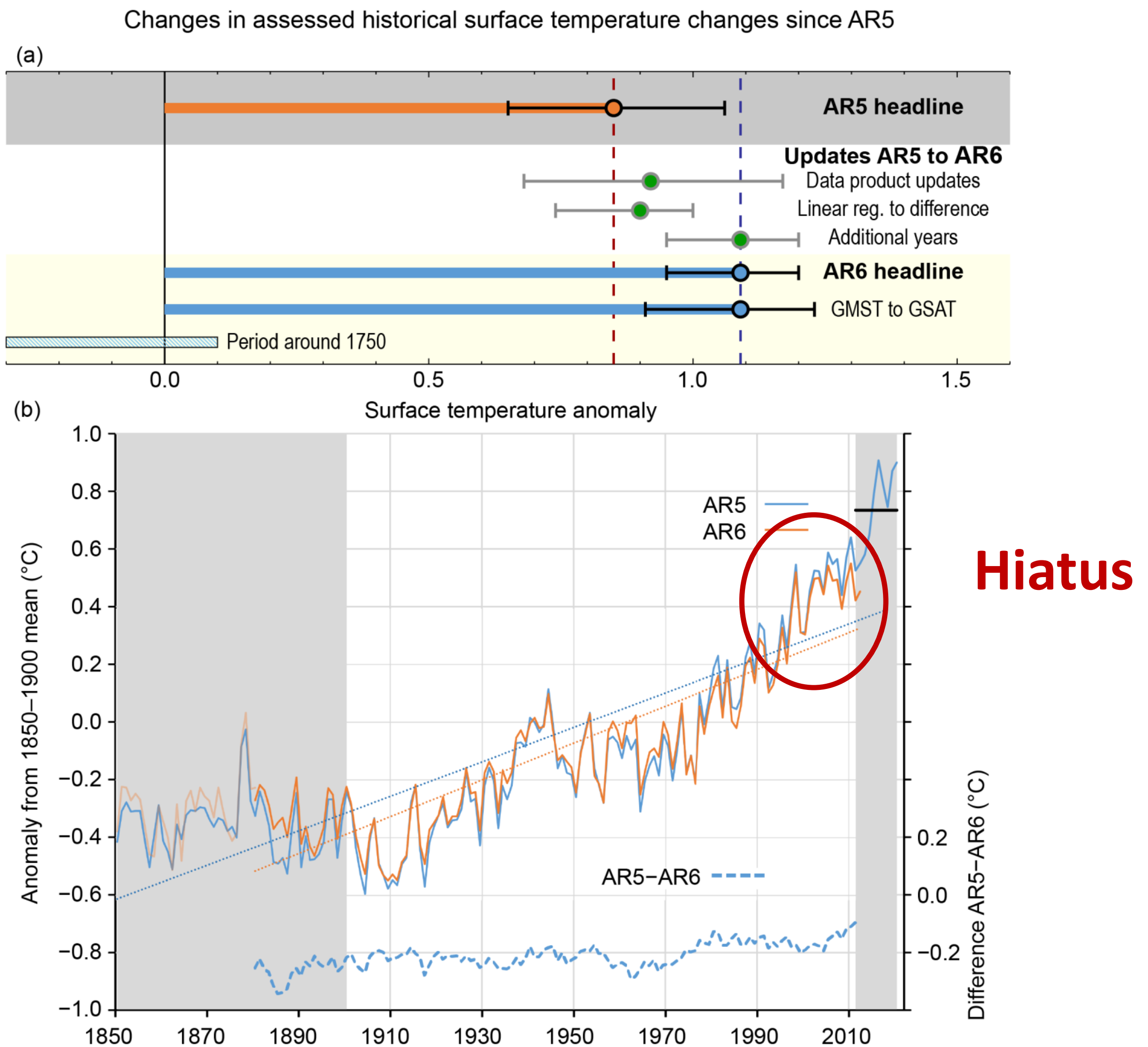
Climate Sensitivity and Warming



IPCC, 2021

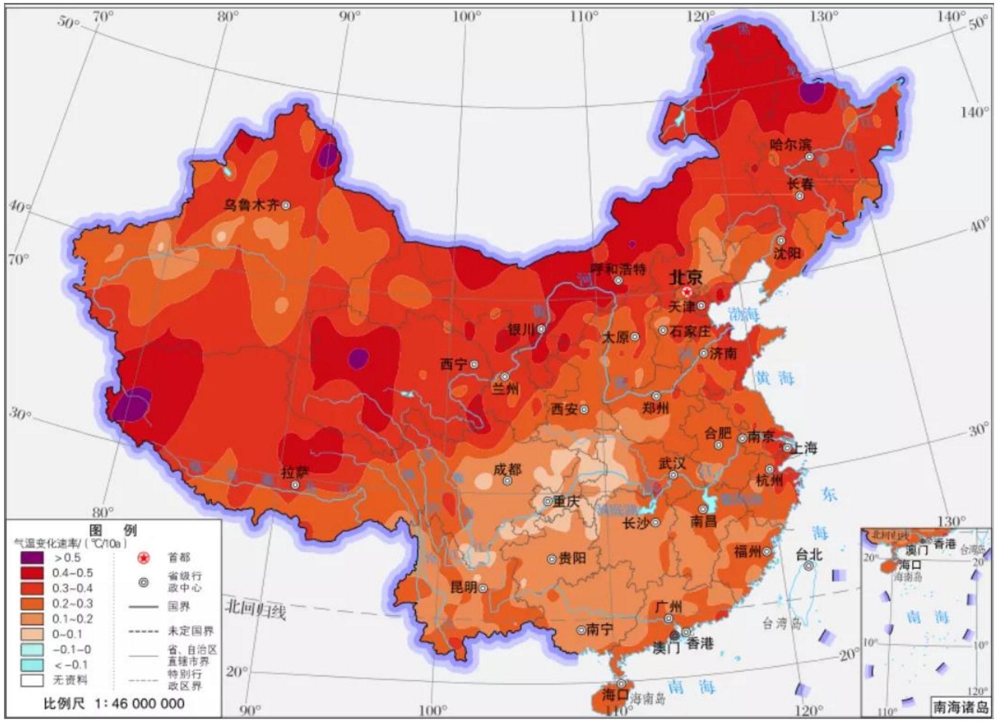
Past Climate Change

Global Temperature Anomaly: 1850-2020

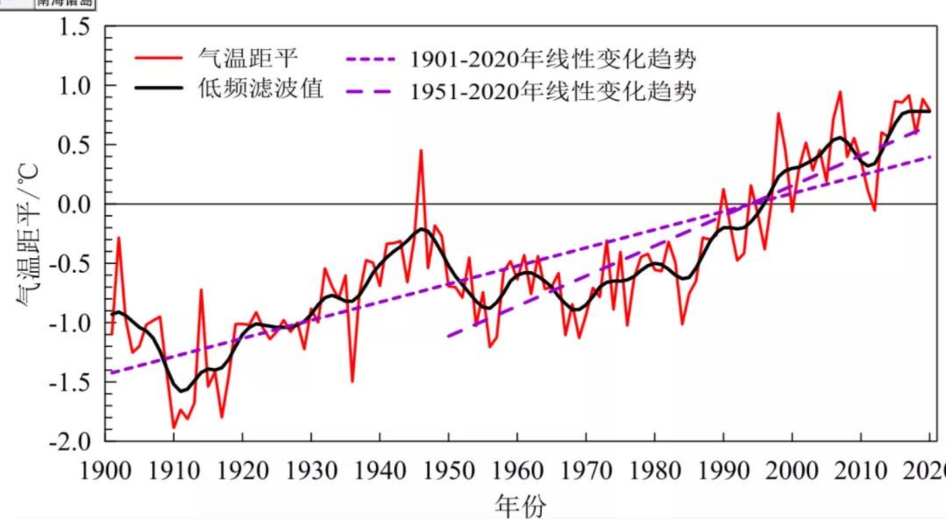


IPCC, 2021

China Temperature Anomaly: 1901-2020

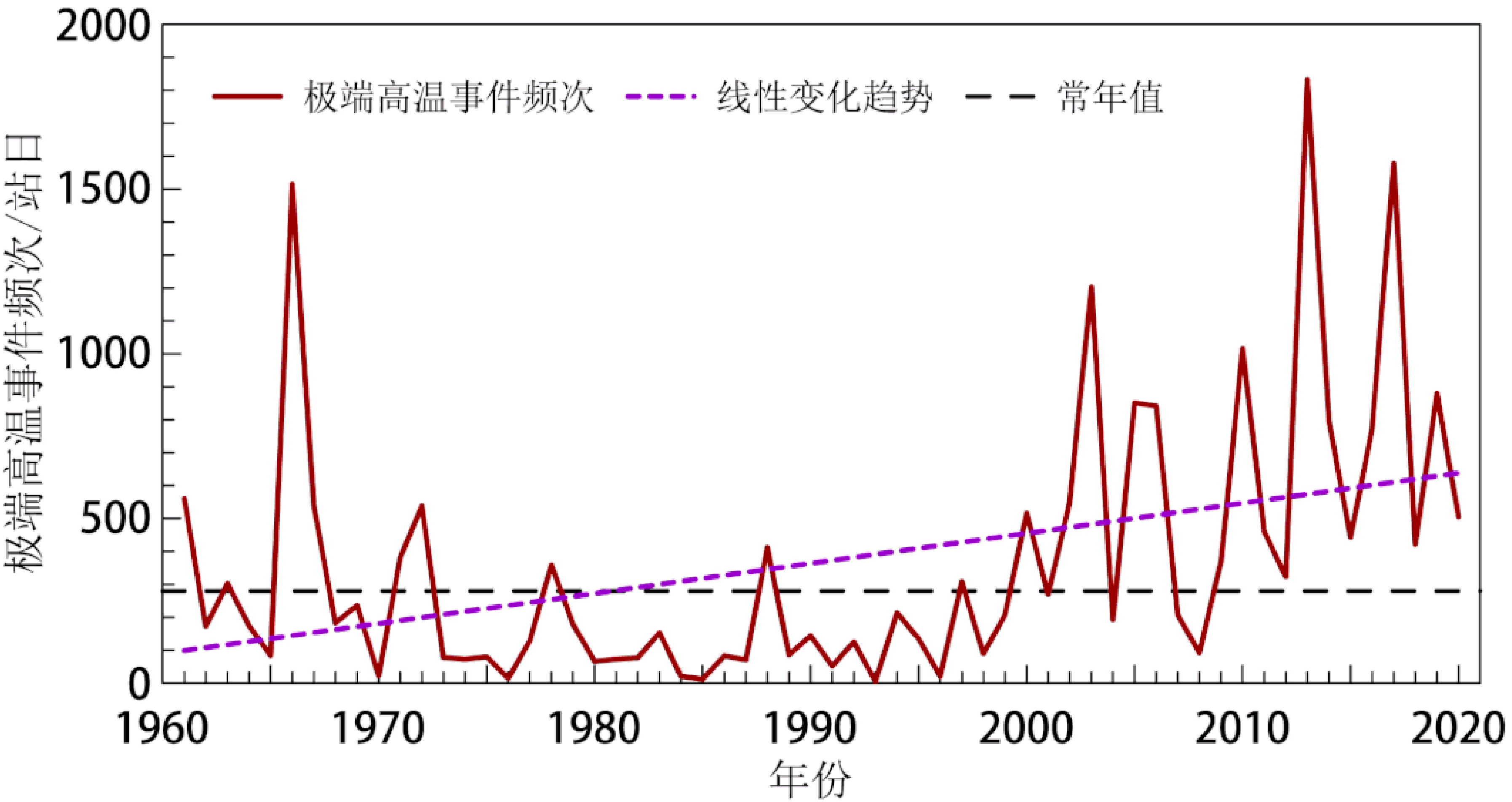


- 中国是全球气候变化的敏感区和影响显著区，升温速率明显高于同期全球平均水平。
- 1951~2020年，中国地表年平均气温呈显著上升趋势，升温速率为0. 26℃/10年。
- 近20年是20世纪初以来的最暖时期，1901年以来的10个最暖年份中，除1998年，其余9个均出现在21世纪。



中国气候变化蓝皮书（2021）

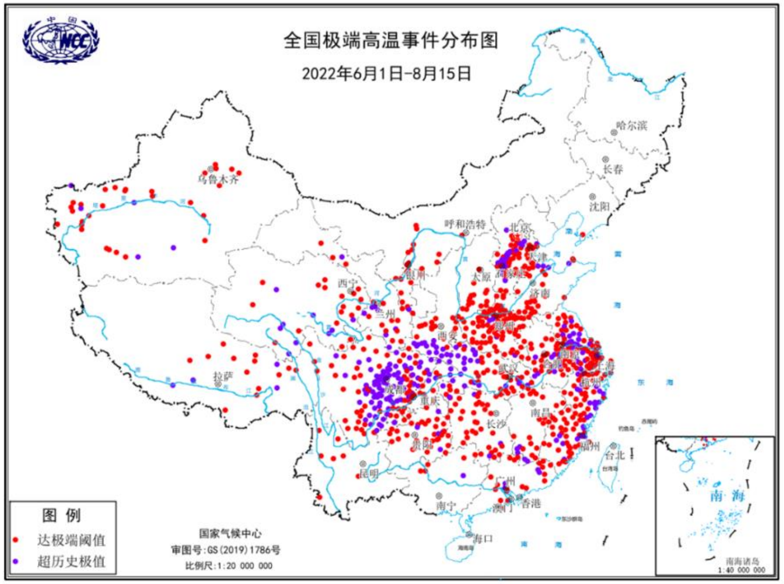
China Extreme Weather Changes



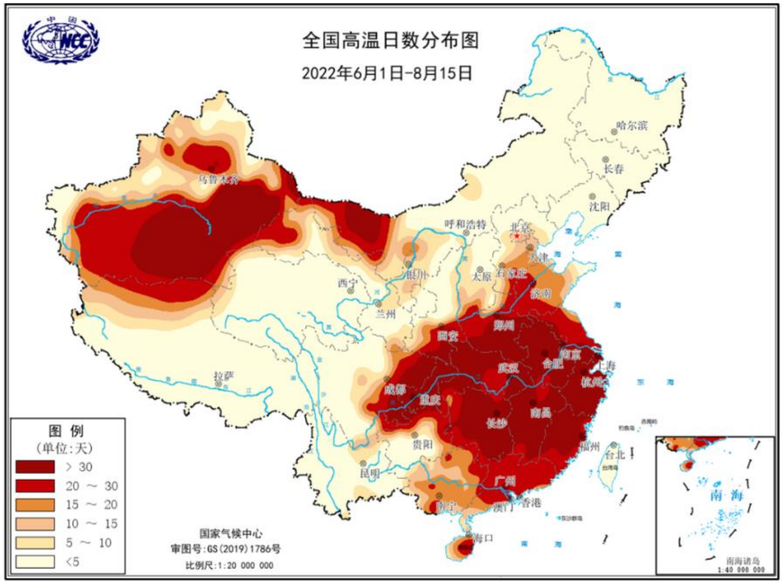
中国气候变化蓝皮书（2021）

Heatwave in 2022 in China

极端高温事件（6月1日-8月15日）

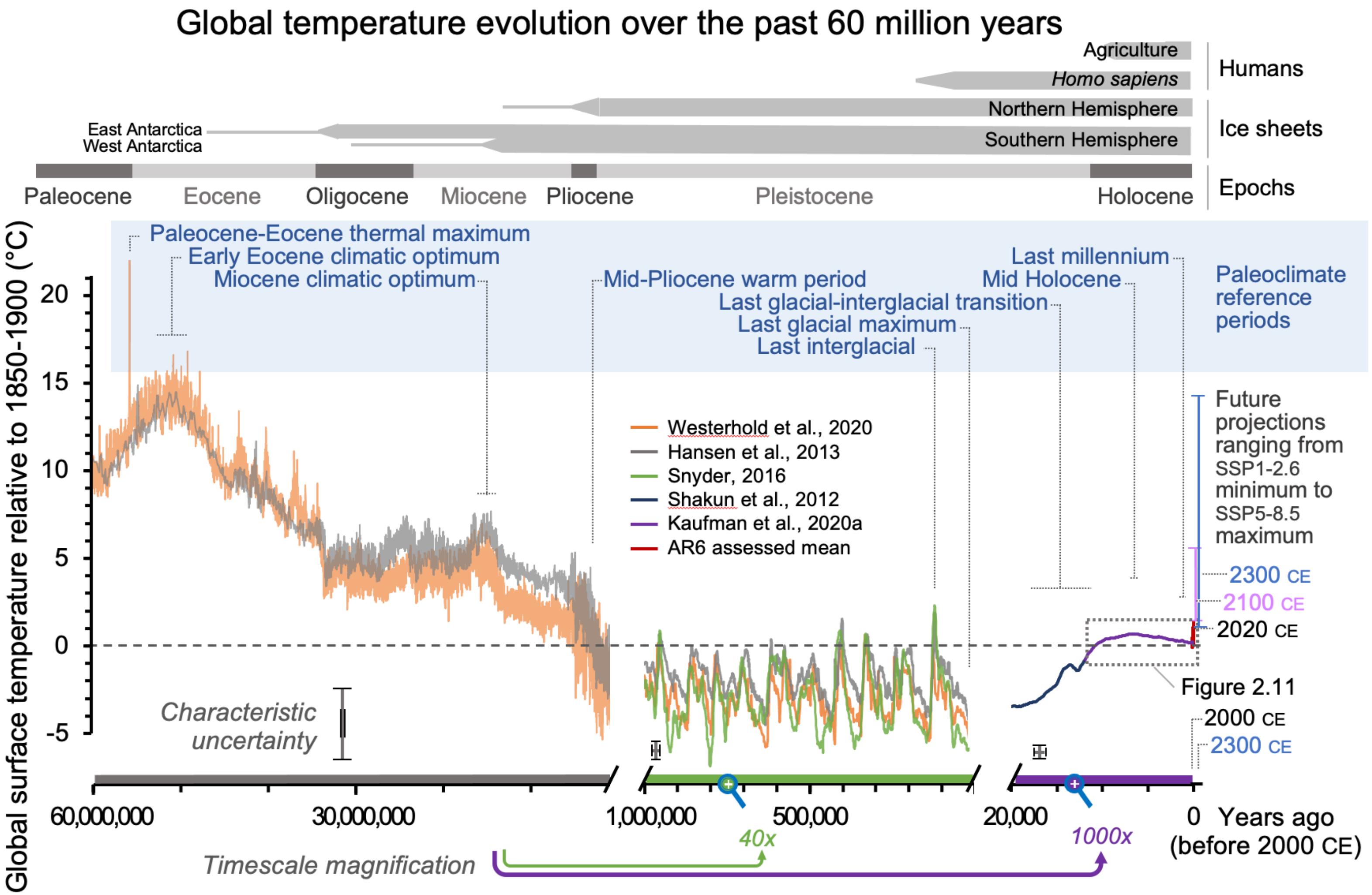


高温日数（6月1日-8月15日）



国家气候中心：
综合考虑高温热浪事件的平均强度、影响范围和持续时间，从今年6月13日开始至8月17日的区域性高温事件**综合强度已达到1961年有完整气象观测记录以来最强**

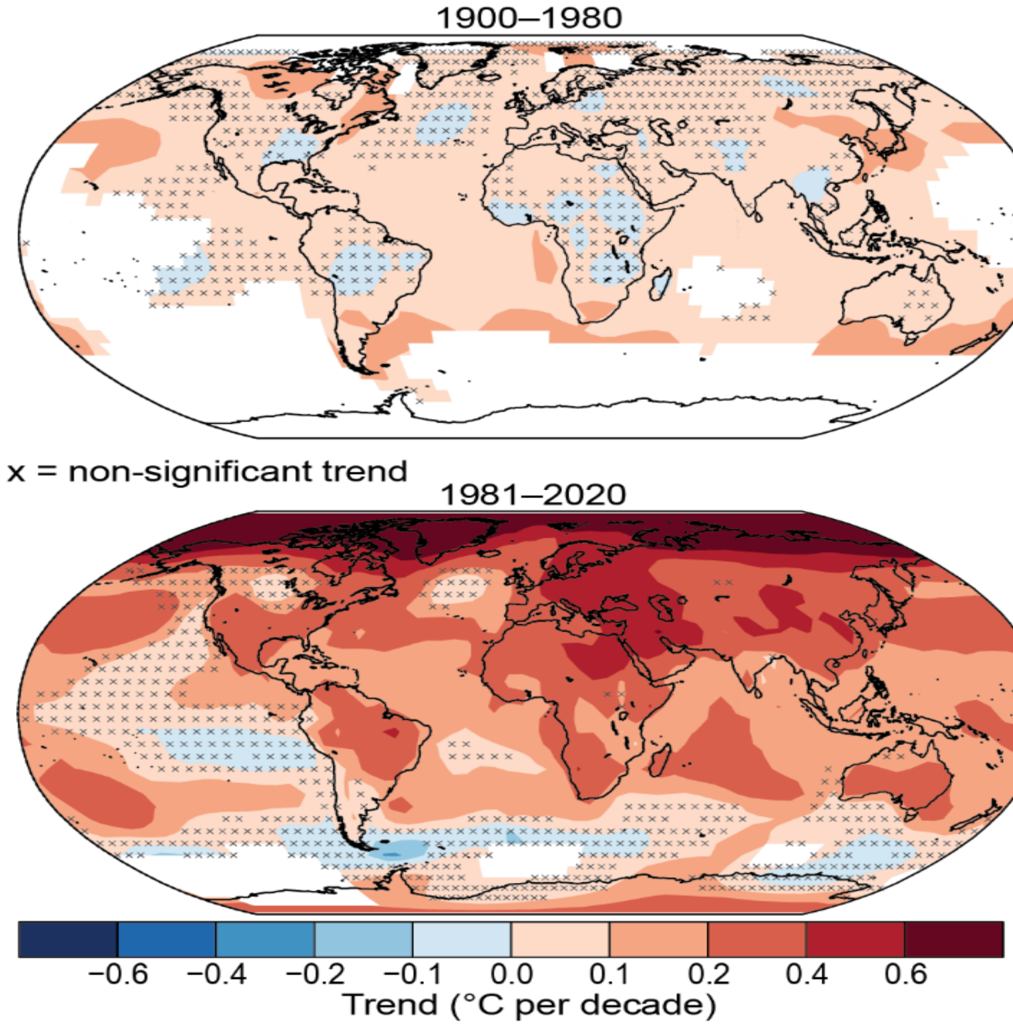
Global Temperature Anomaly: 1850-2020



IPCC, 2021

Paleocene 古新世； Eocene 始新世； Oligocene 渐新世； Miocene 中新世；
Pliocene 上新世； Pleistocene 更新世； Holocene 全新世； Quaternary 第四纪

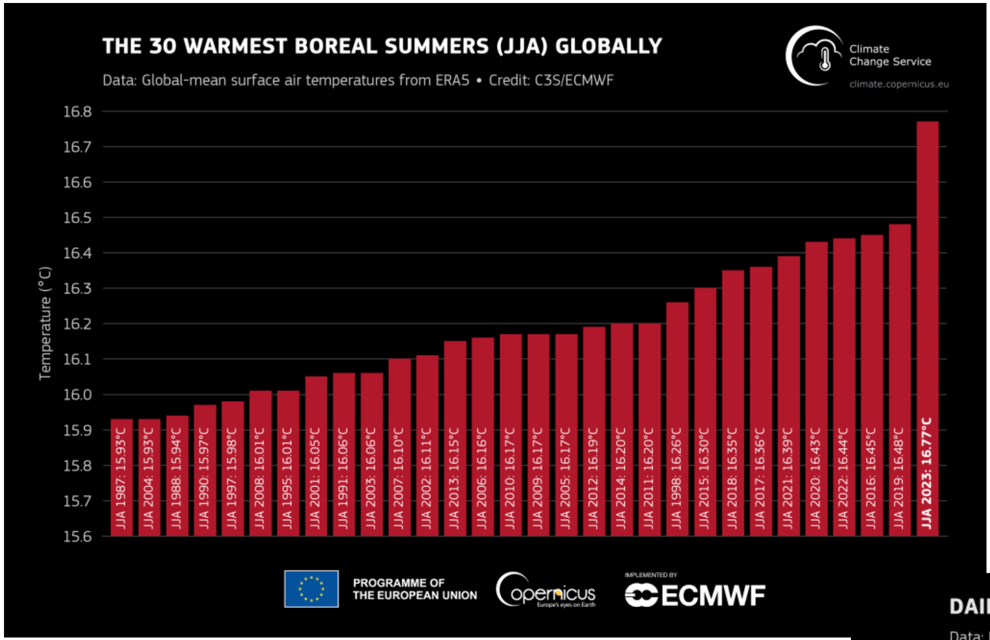
Global Temperature Anomaly: 1850-2020

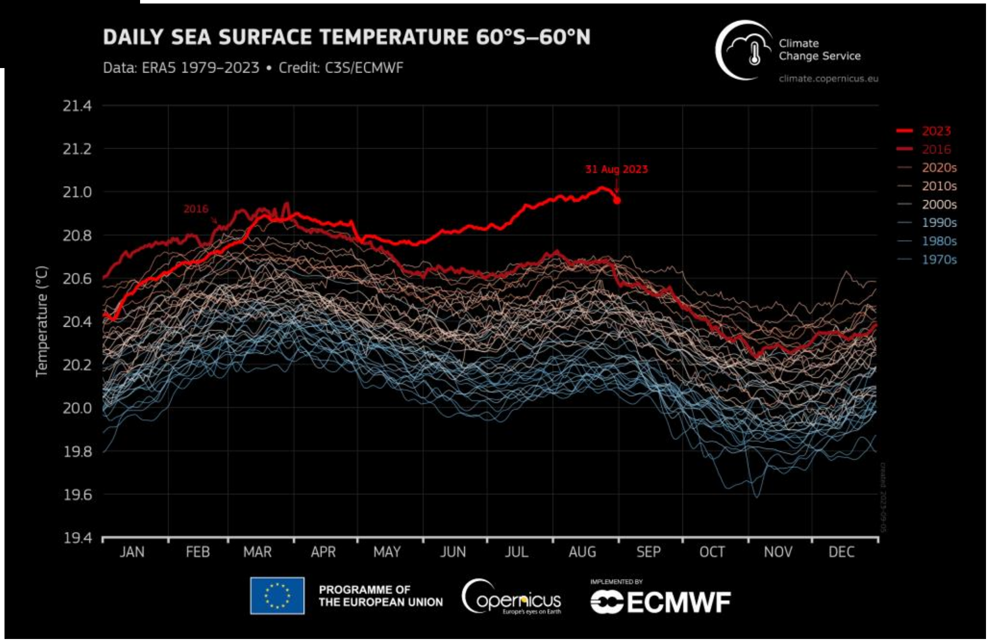


IPCC, 2021

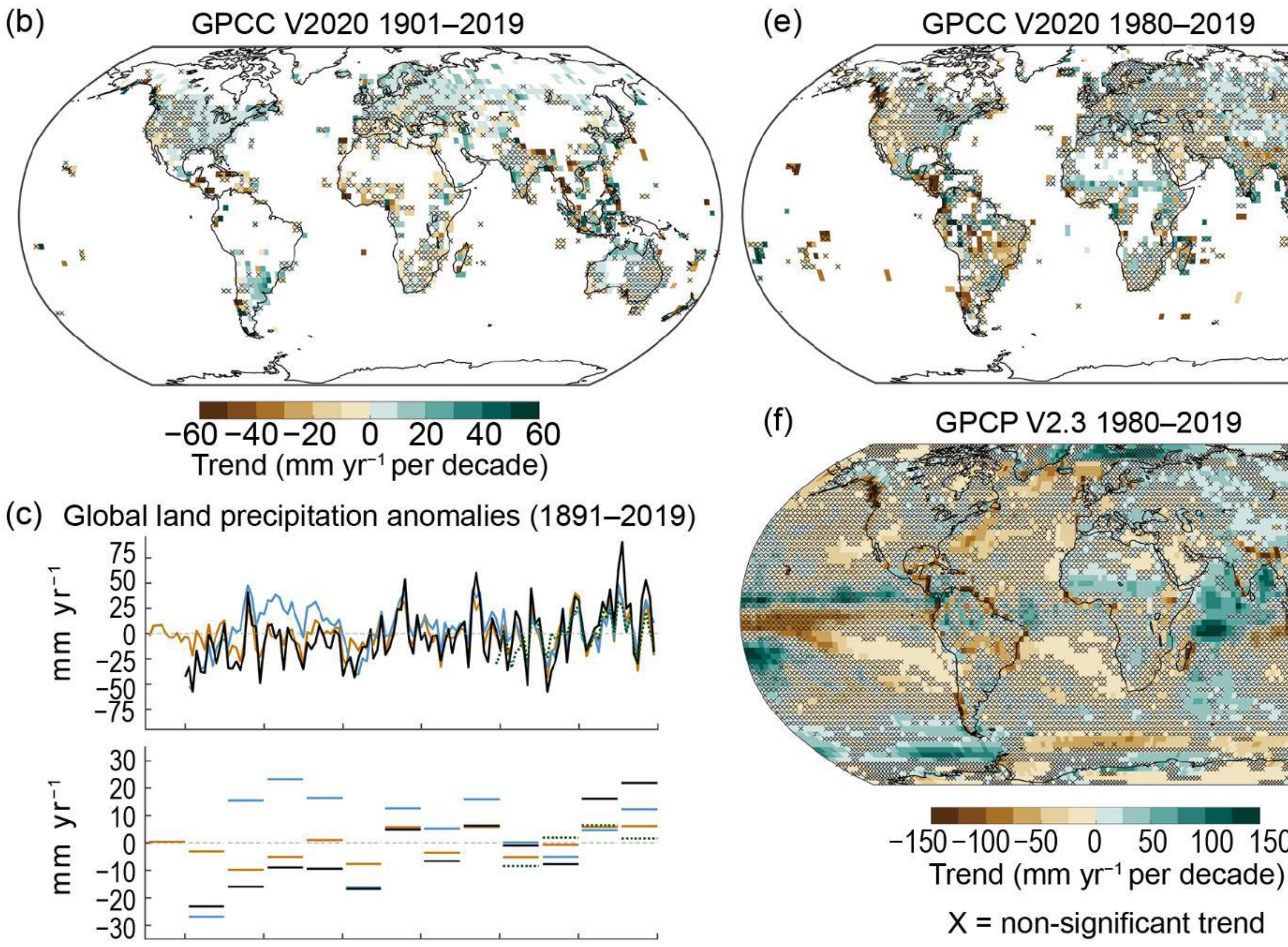
Jim Hansen: ΔT variability and biodiversity?

Global Temperature in 2023





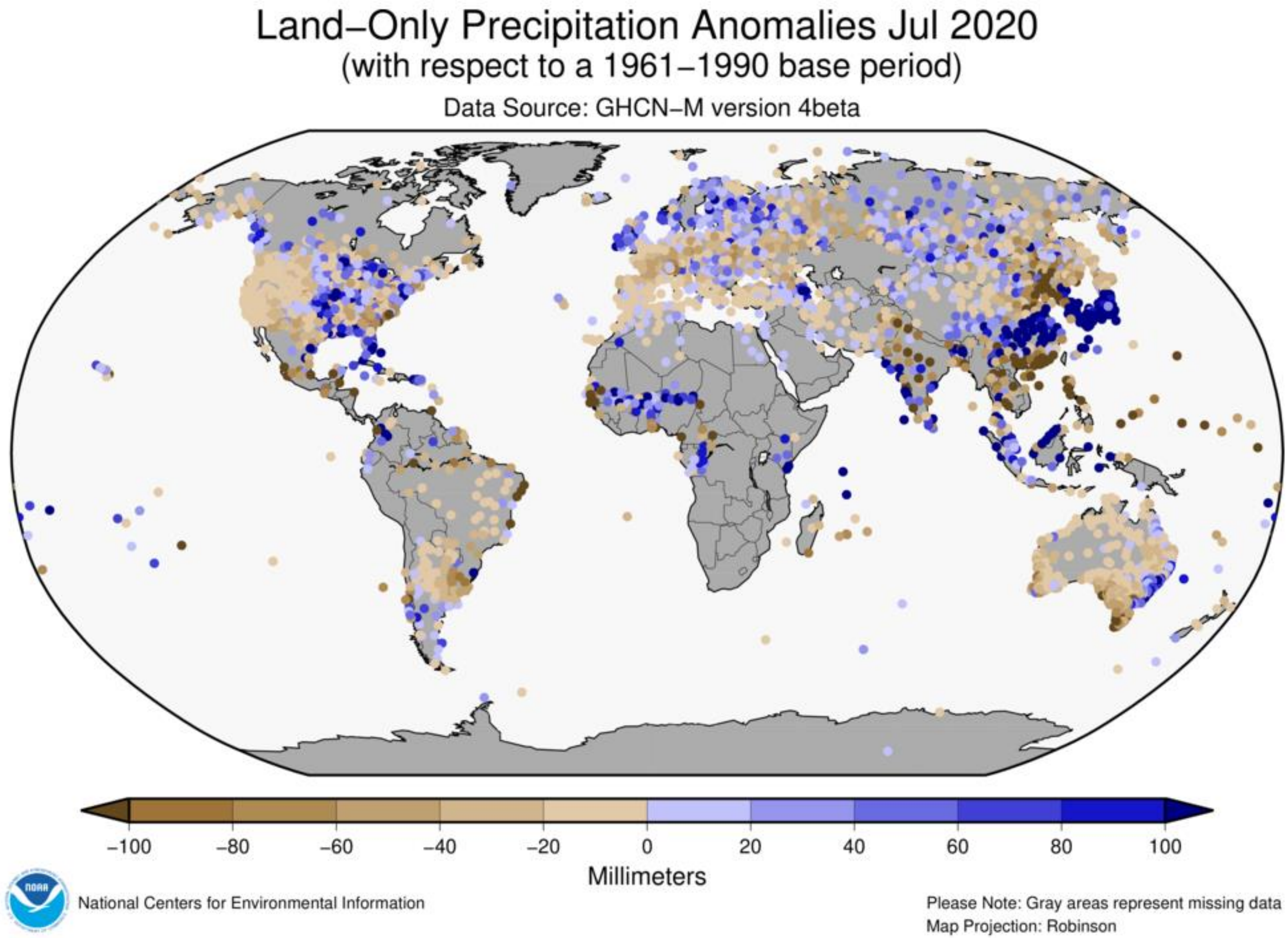
Global Precipitation Anomaly: 1901–2019



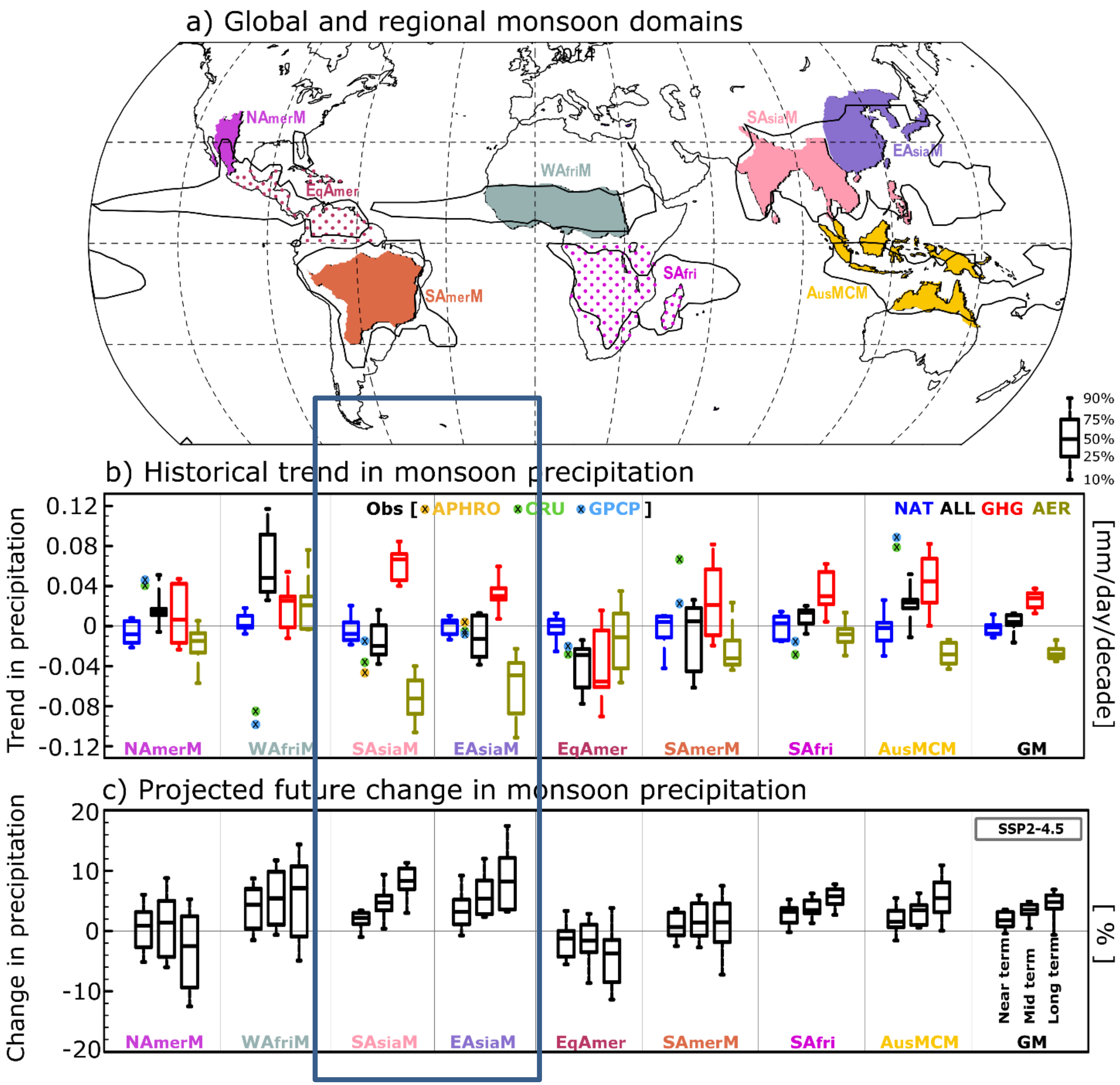
IPCC, 2021

Wet gets wetter over tropical oceans?

Global Precipitation Anomaly

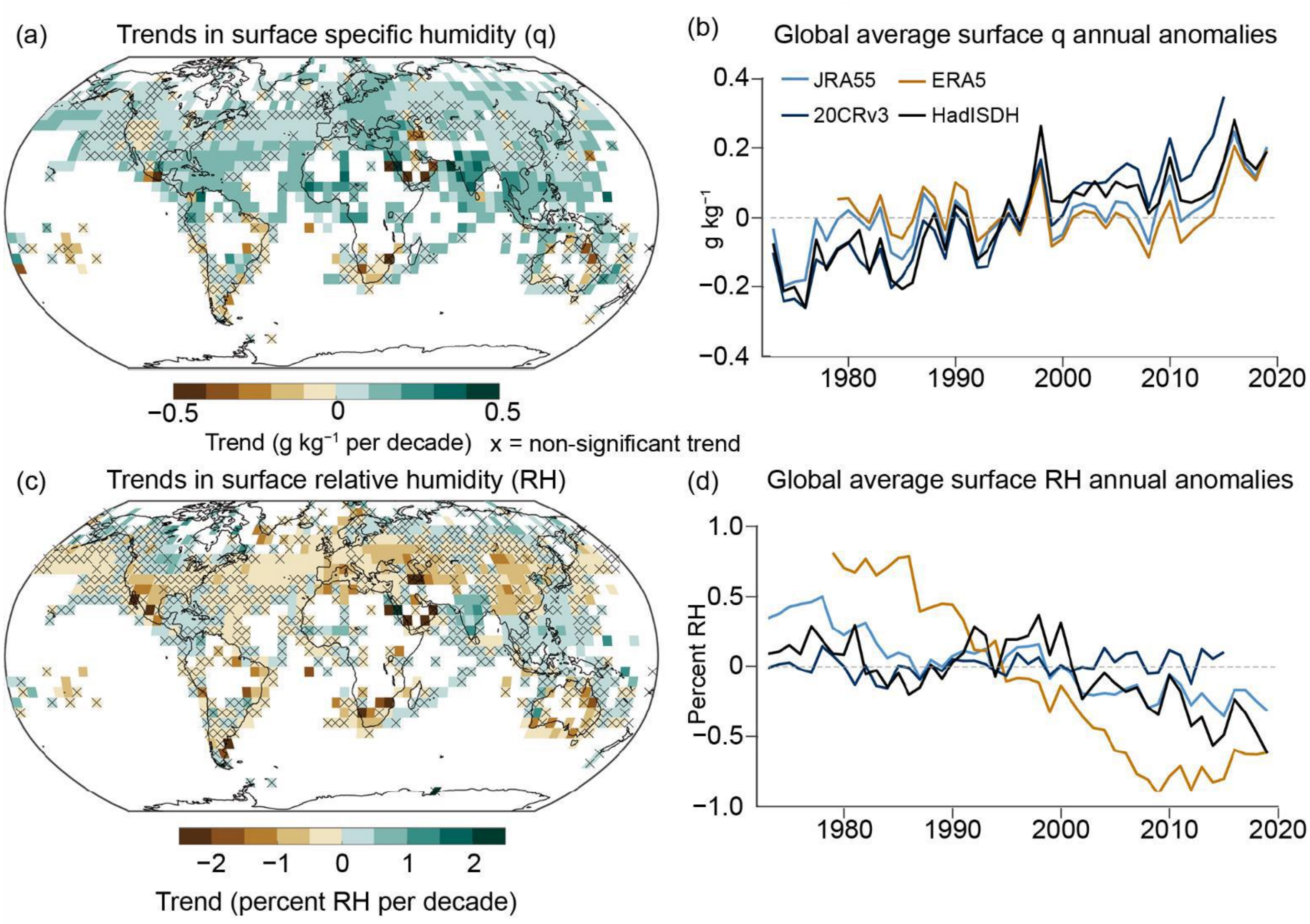


Changes in Global Monsoon Precipitation



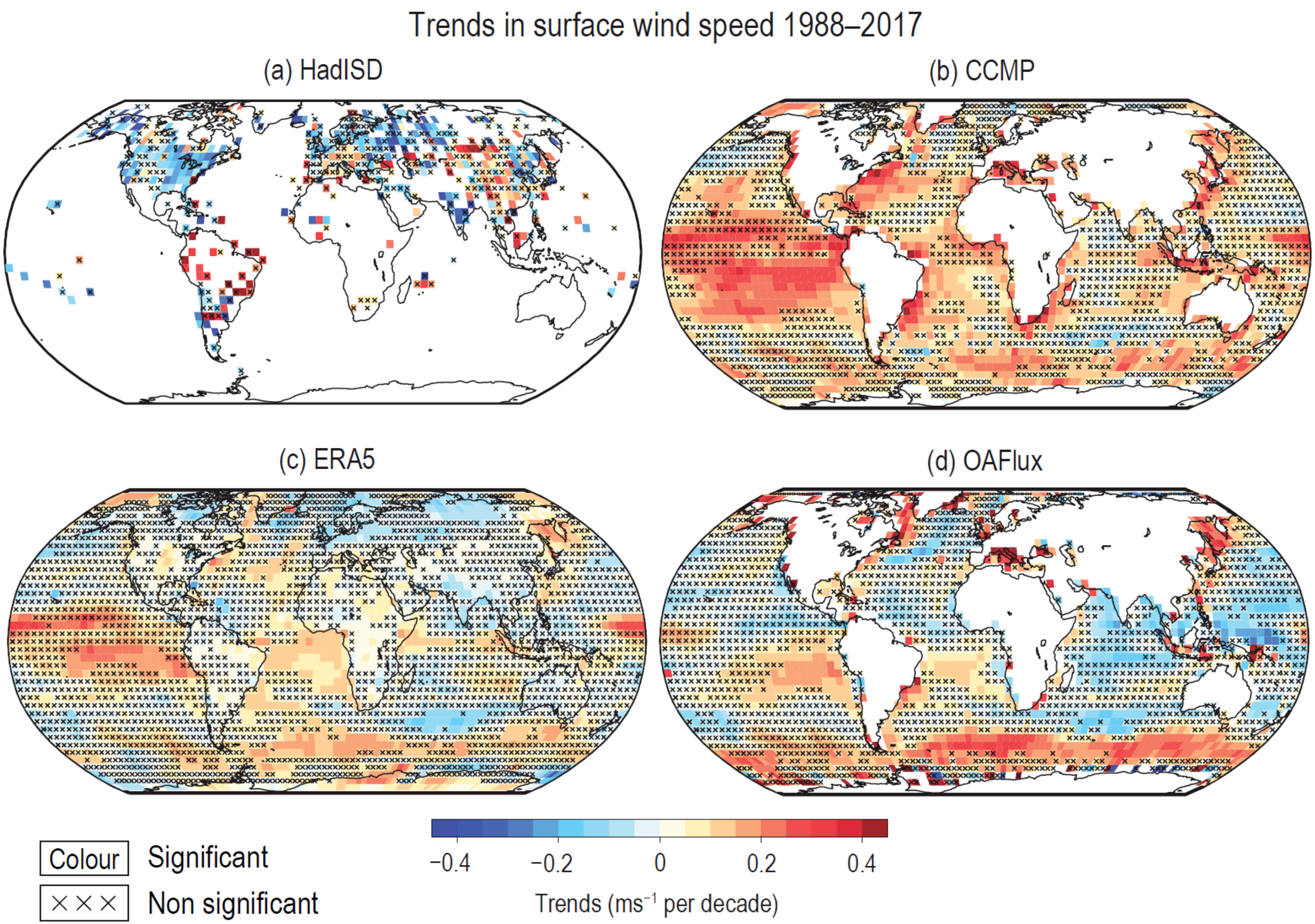
IPCC, 2021

Humidity Change



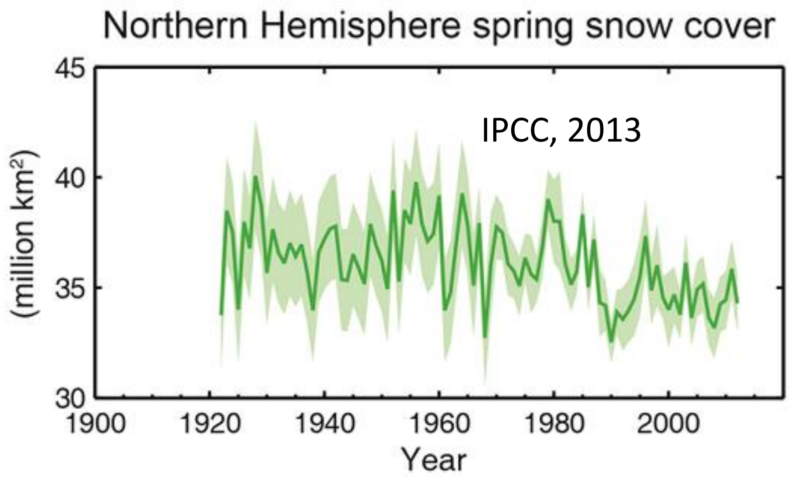
IPCC, 2021

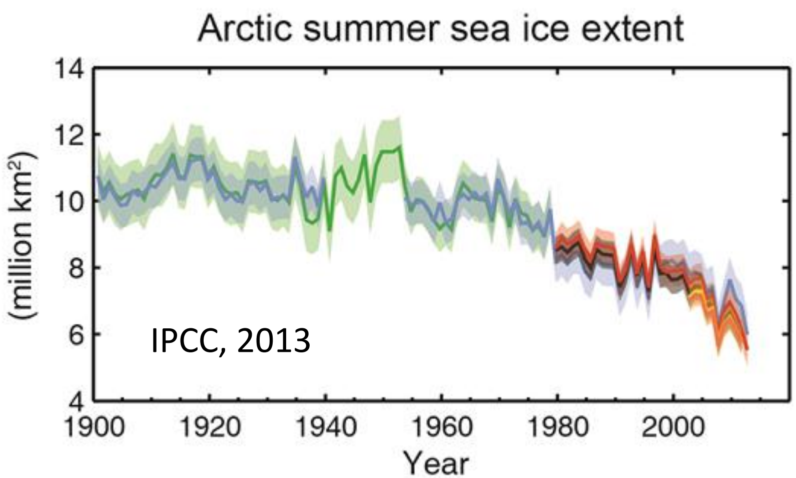
Surface Wind Speed Change: 1988–2017



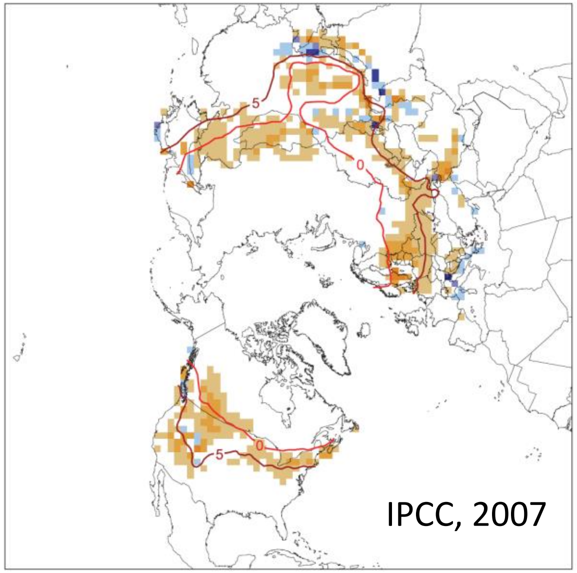
IPCC, 2021

Changes in Cryosphere and Its Components





March — April Snow Departure
(1988 - 2004) minus (1967 - 1987)



-36 to -26 -25 to -16 -15 to -6 -5 to 5 6 to 15 16 to 25 26 to 38

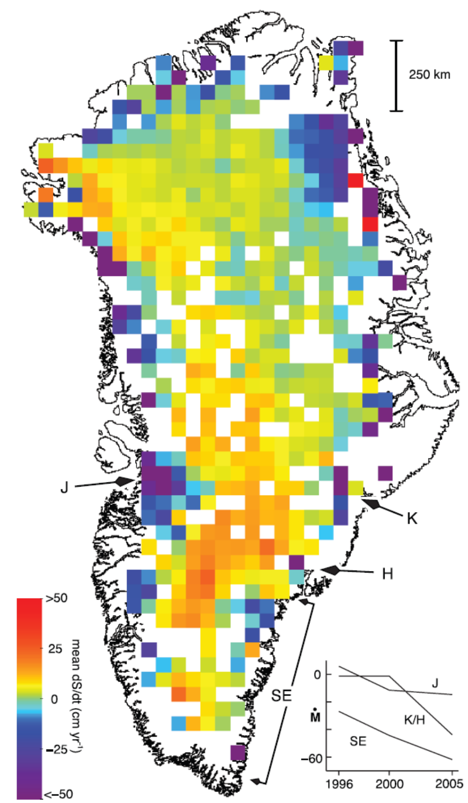
天山乌鲁木齐河源1号冰川

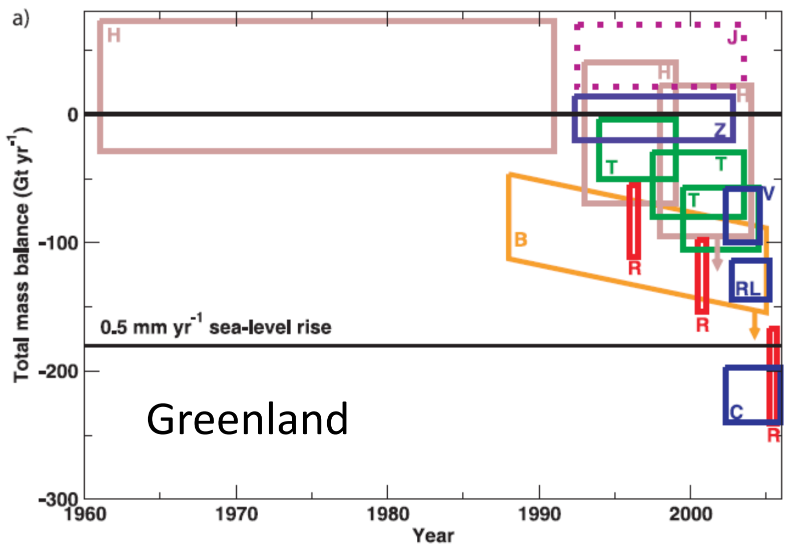
中国气候变化蓝皮书（2021）

Changes in Greenland and Antarctic Ice Sheets

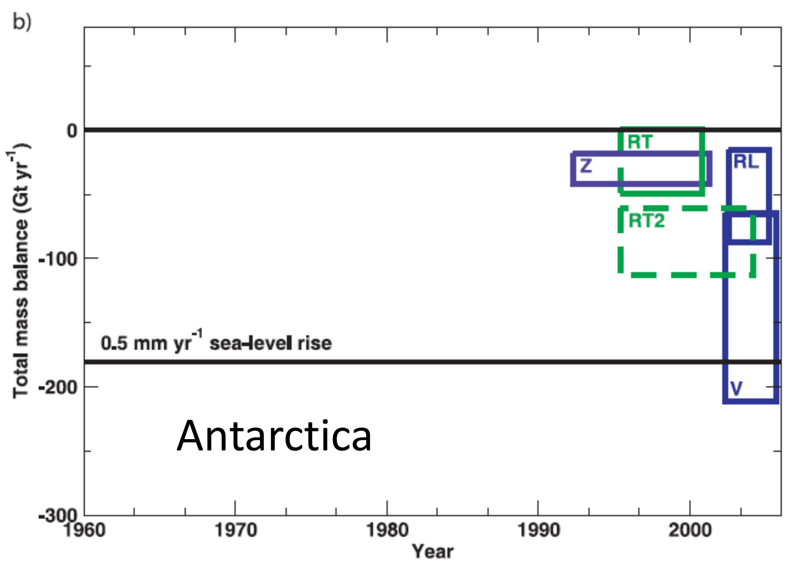
Total mass change

Height change

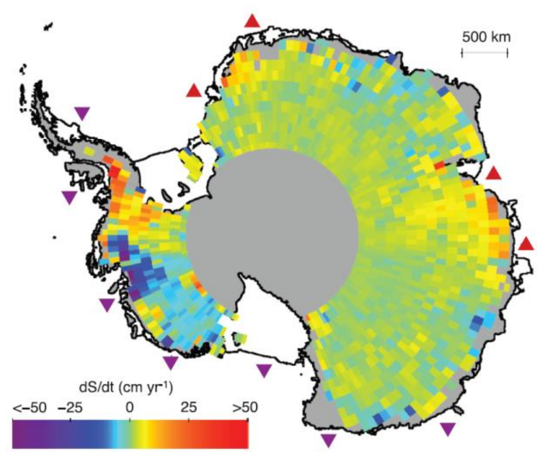




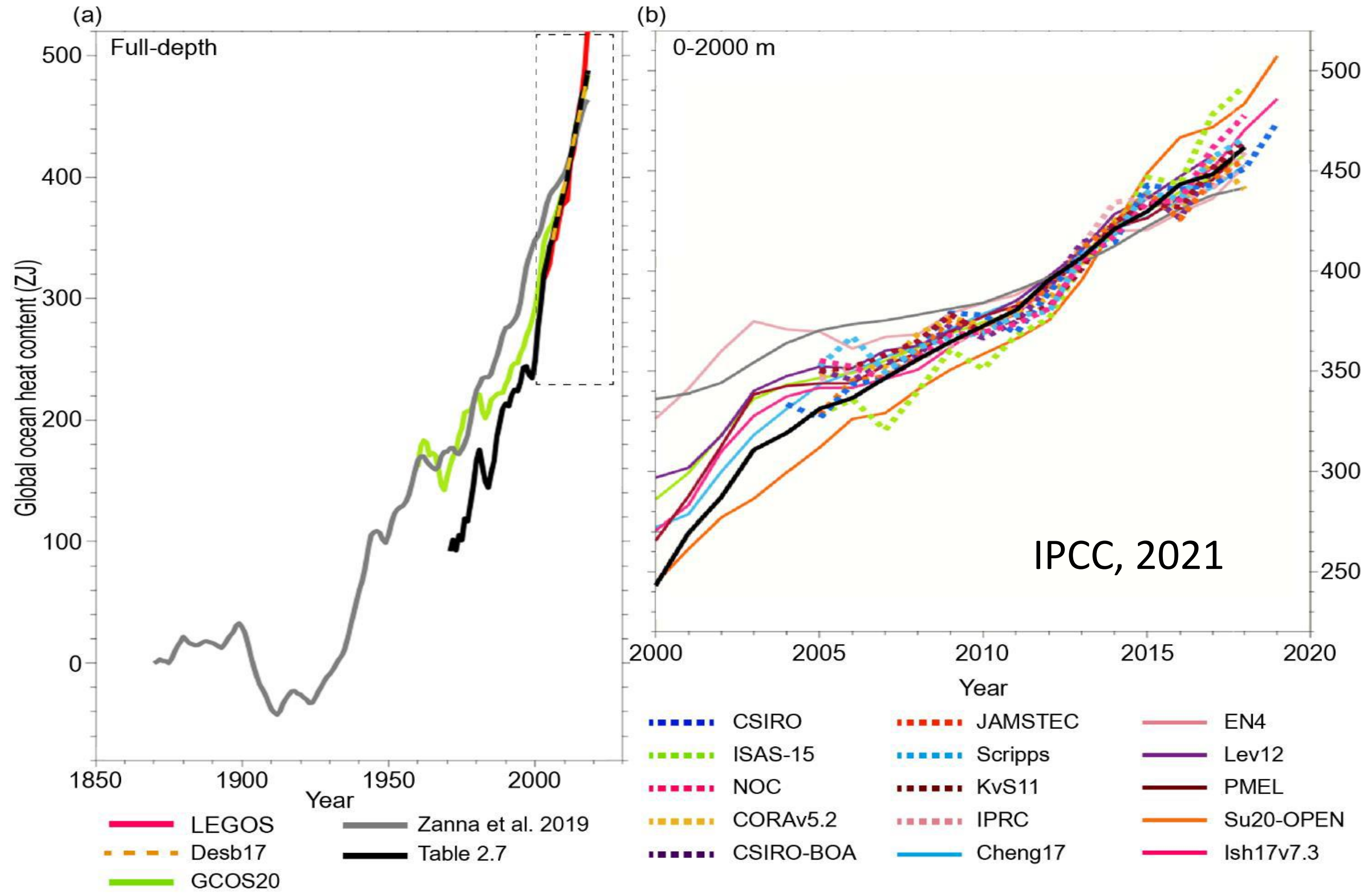
IPCC, 2013



Height change

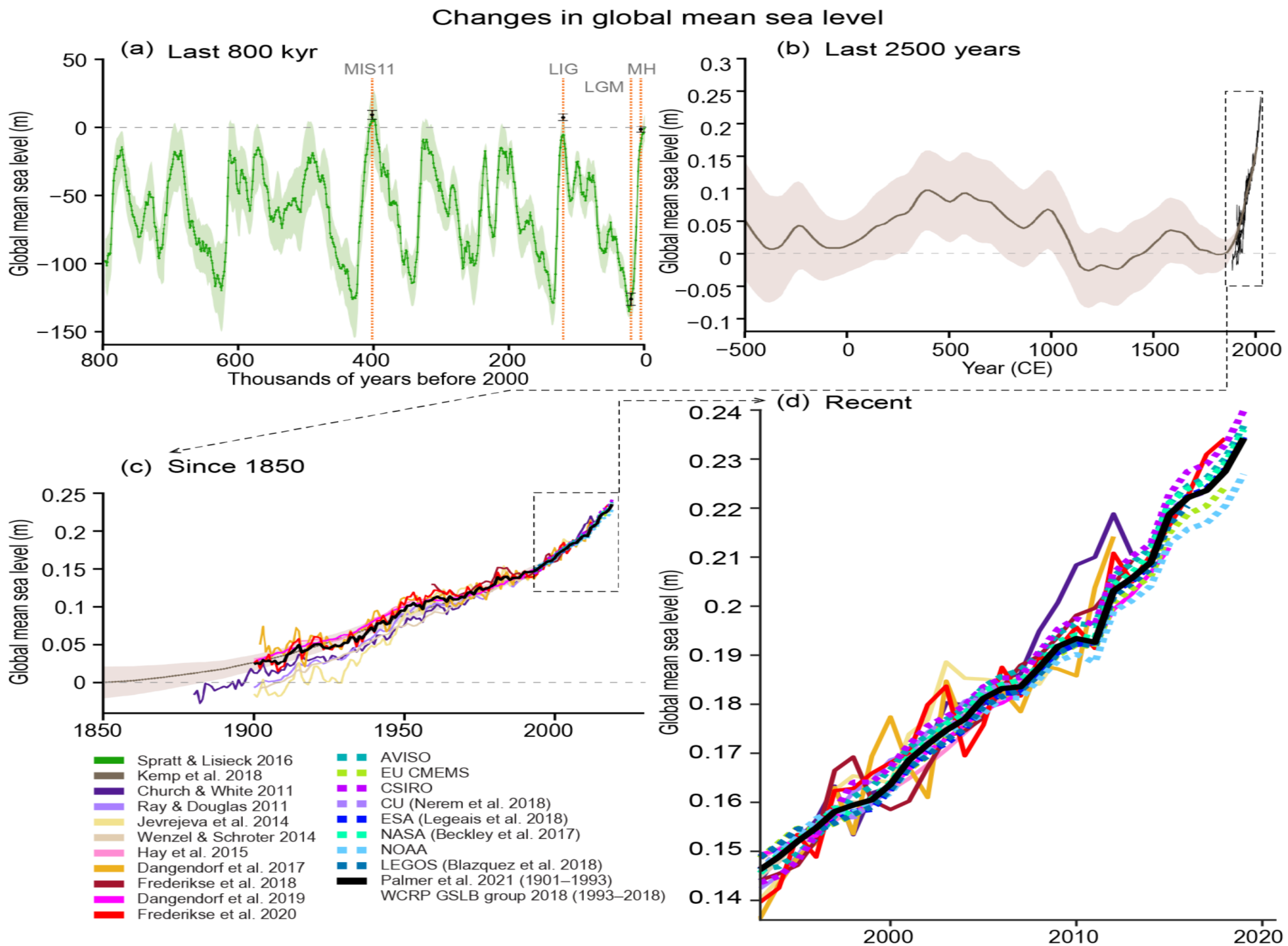


Ocean Heat Content Change



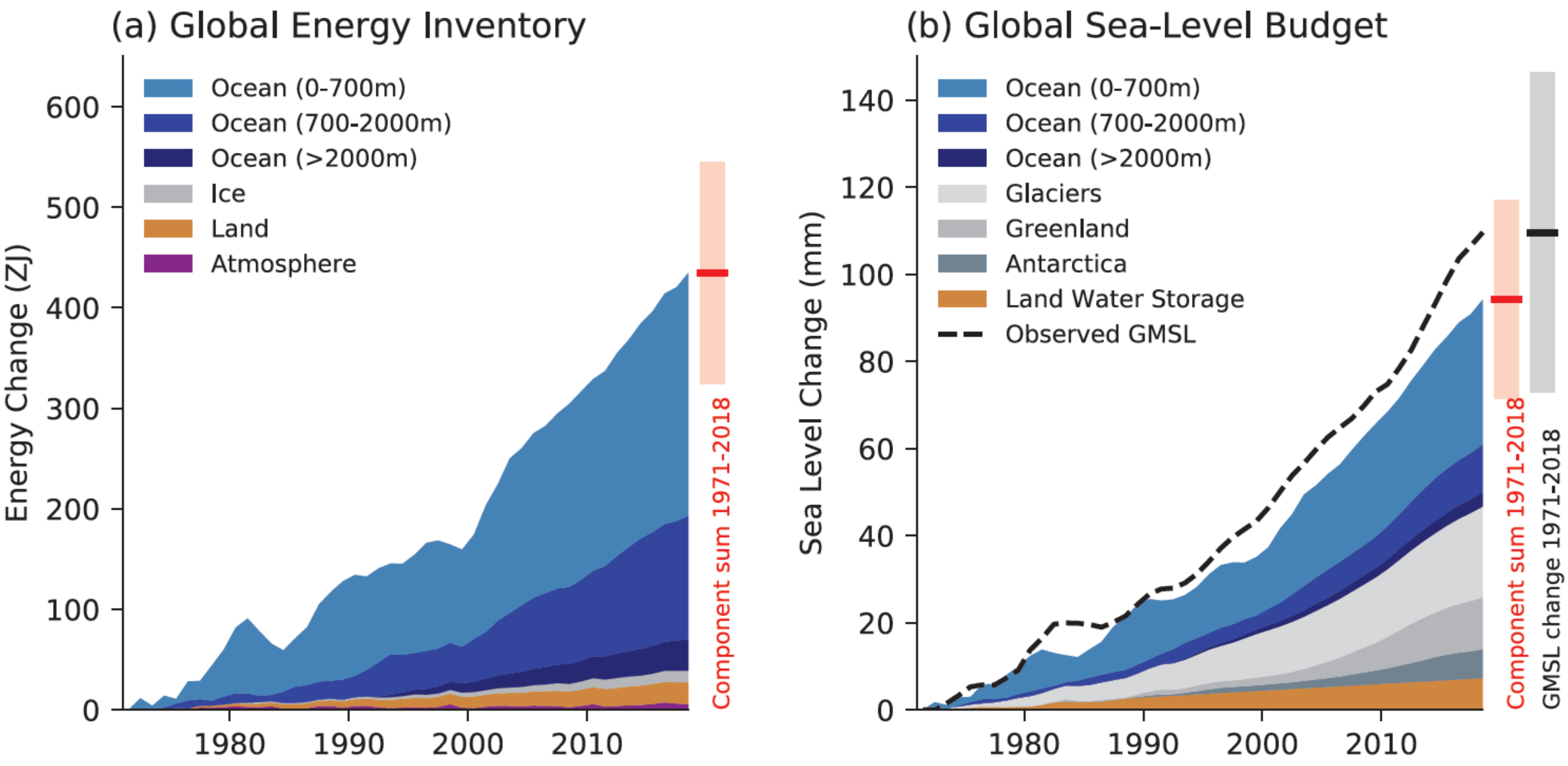
- World energy consumption in 2019: ~ 5.5e20 J
- Radiative forcing for 1750–2019: 2.7 w/m^2 = 4.3e22 J/yr

Sea Level Change



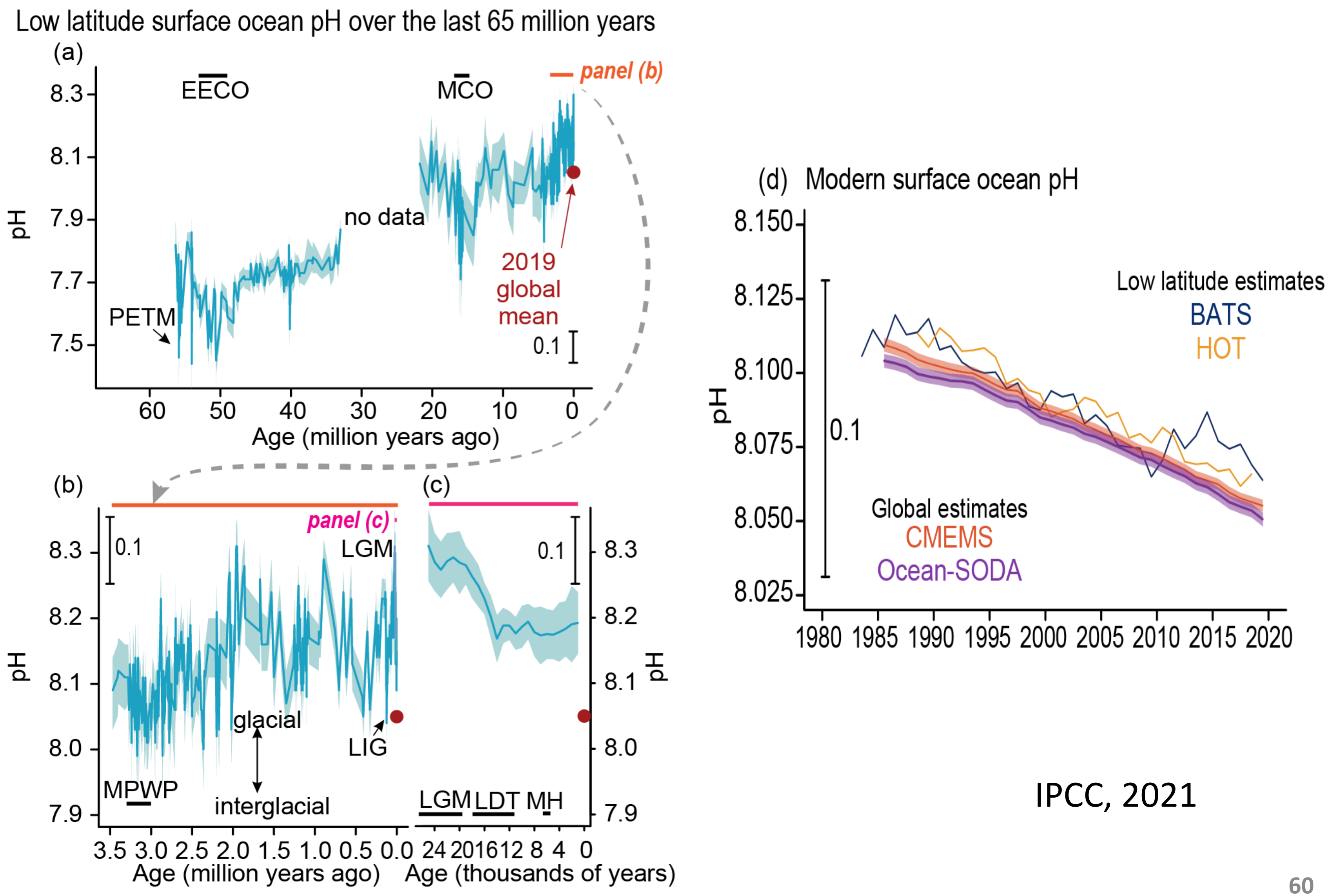
IPCC, 2021

Sea Level Rise and Its Causes



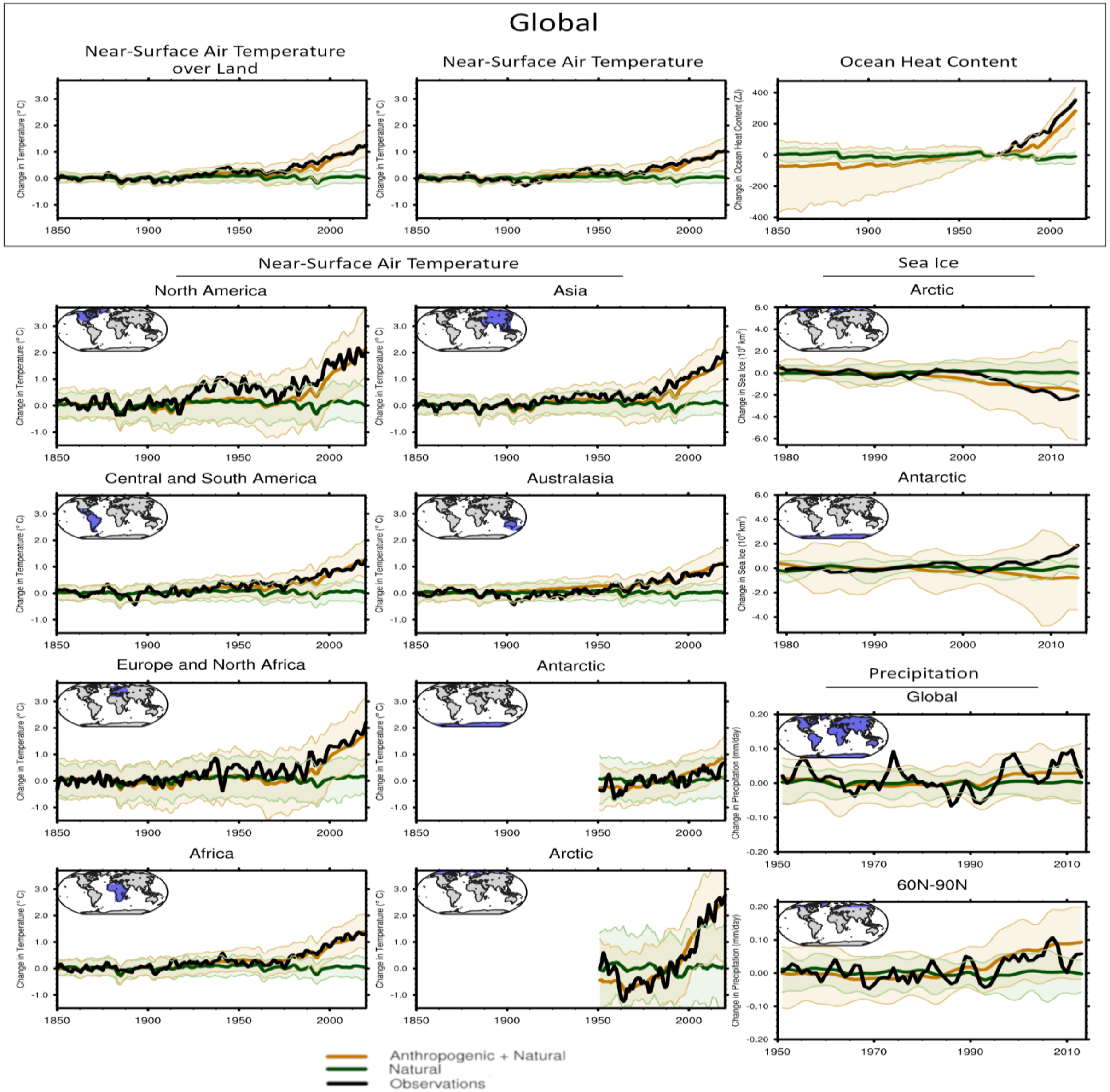
IPCC, 2021

Changes in Ocean pH



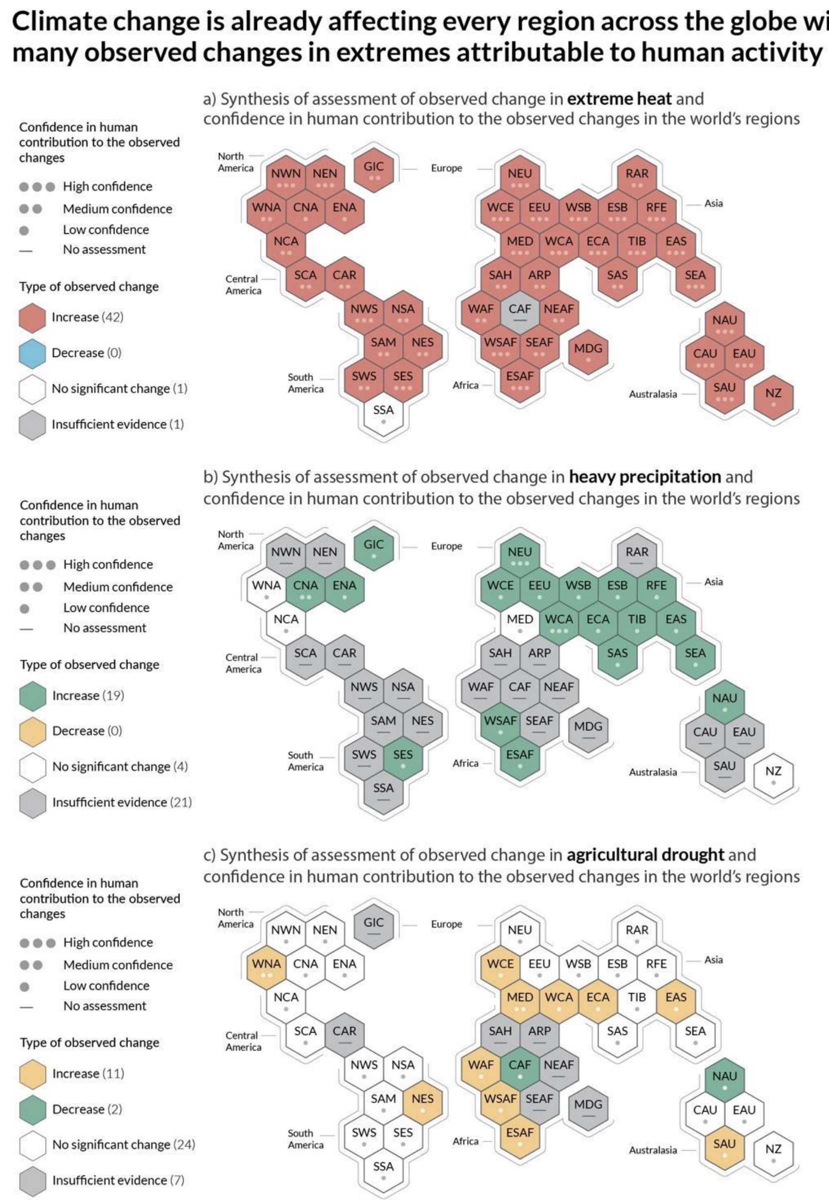
IPCC, 2021

Modeled Anthropogenic versus Natural Impacts



IPCC, 2021

Changes in Climate Extremes and Attribution



Extreme heat

Heavy prec.

Agri. drought

IPCC, 2021

Future Climate Change Projections

Future Climate Change: From Emissions to Climate

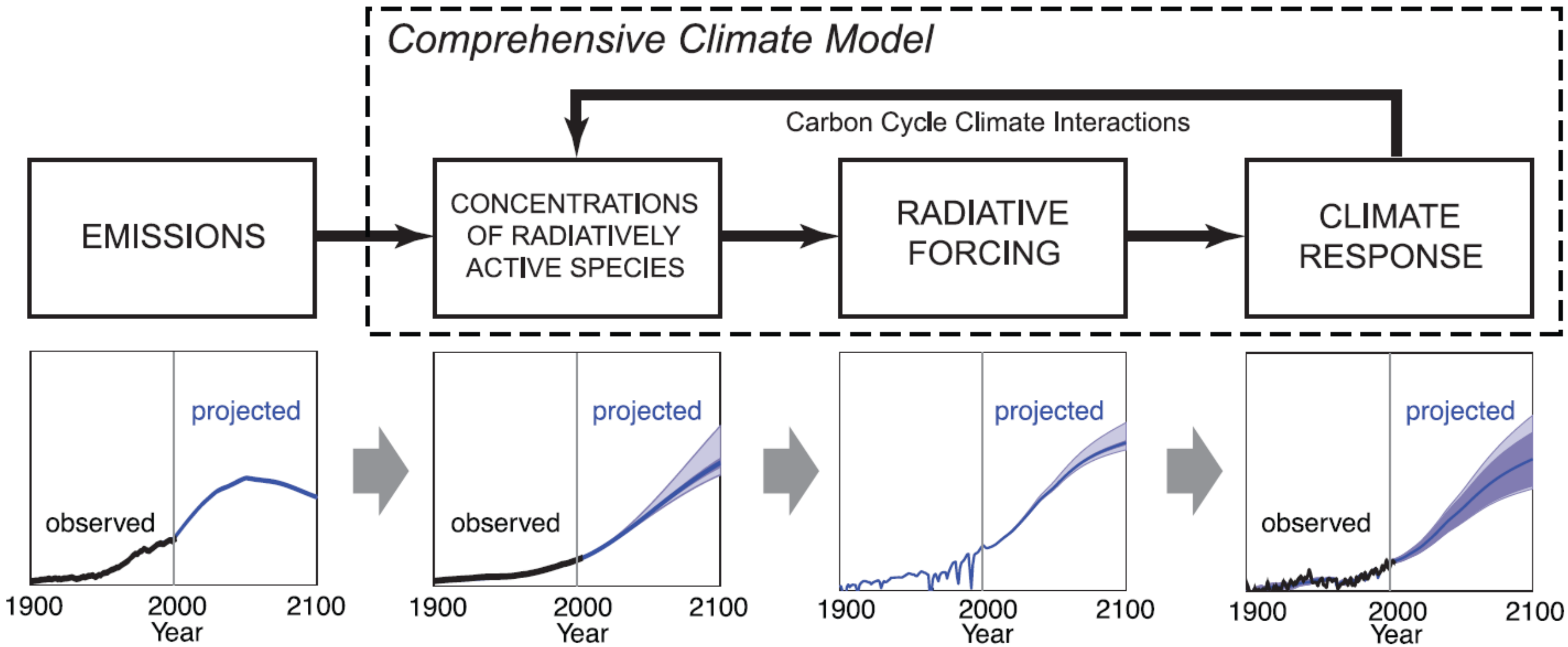
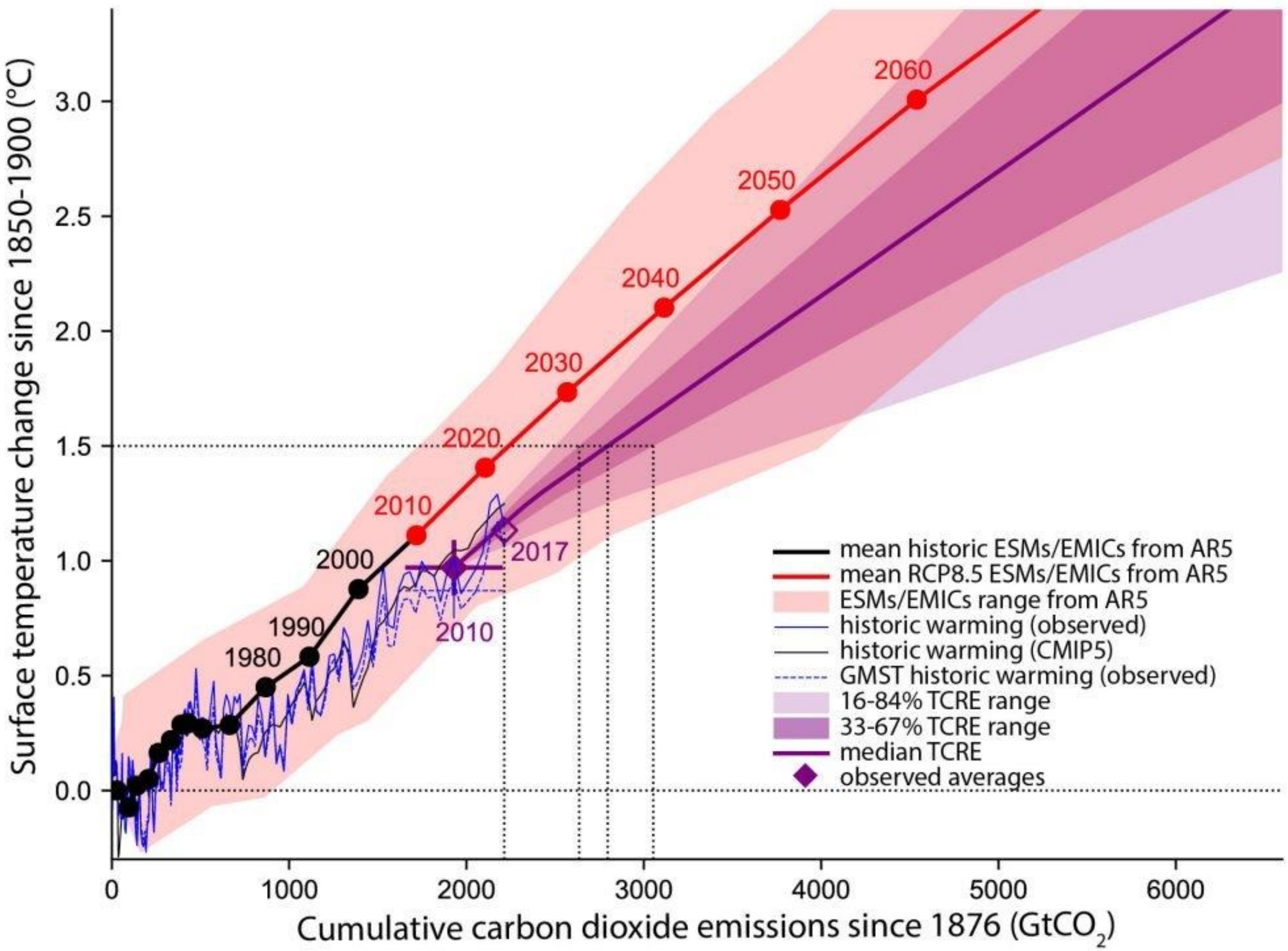


Figure 10.1. *Several steps from emissions to climate response contribute to the overall uncertainty of a climate model projection. These uncertainties can be quantified through a combined effort of observation, process understanding, a hierarchy of climate models, and ensemble simulations. In a comprehensive climate model, physical and chemical representations of processes permit a consistent quantification of uncertainty. Note that the uncertainty associated with the future emission path is of an entirely different nature and not addressed in Chapter 10. Bottom row adapted from Figure 10.26, A1B scenario, for illustration only.*

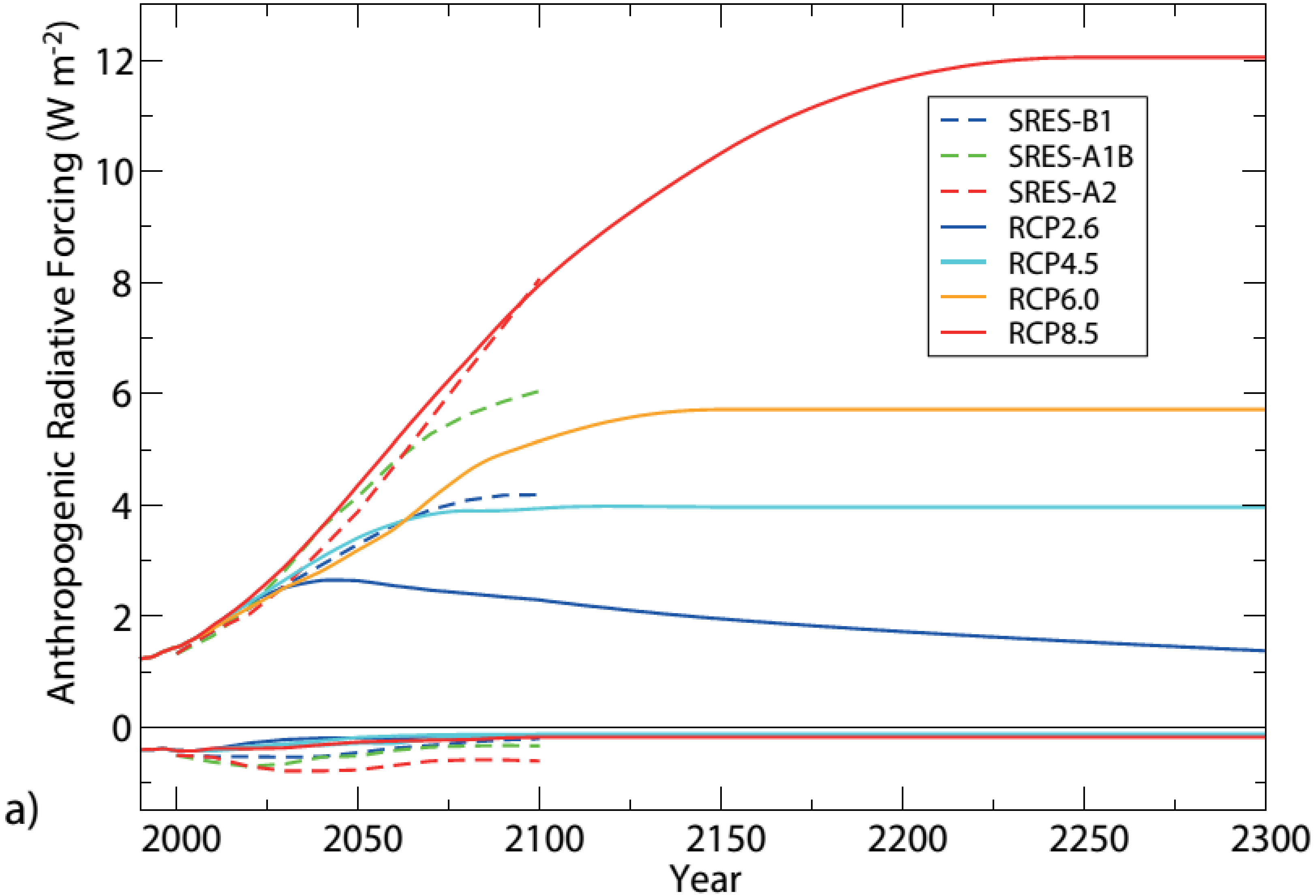
IPCC, 2013

Projected GHG Emissions versus Temperature Rise



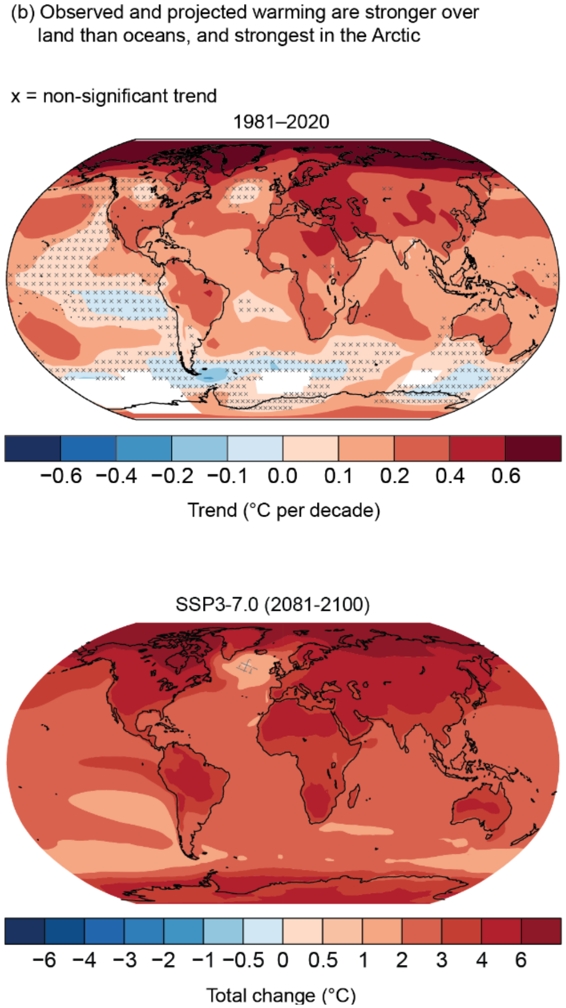
Special Report on 1.5^{o}C Warming

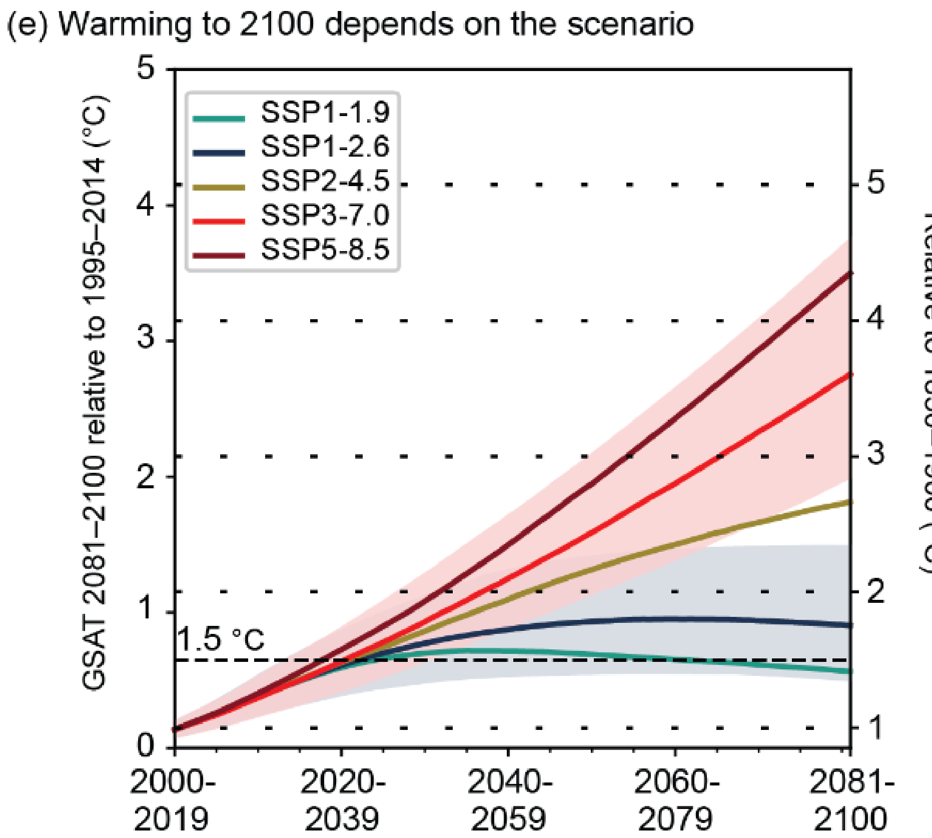
Radiative Forcing: 2000 – 2300



IPCC, 2013

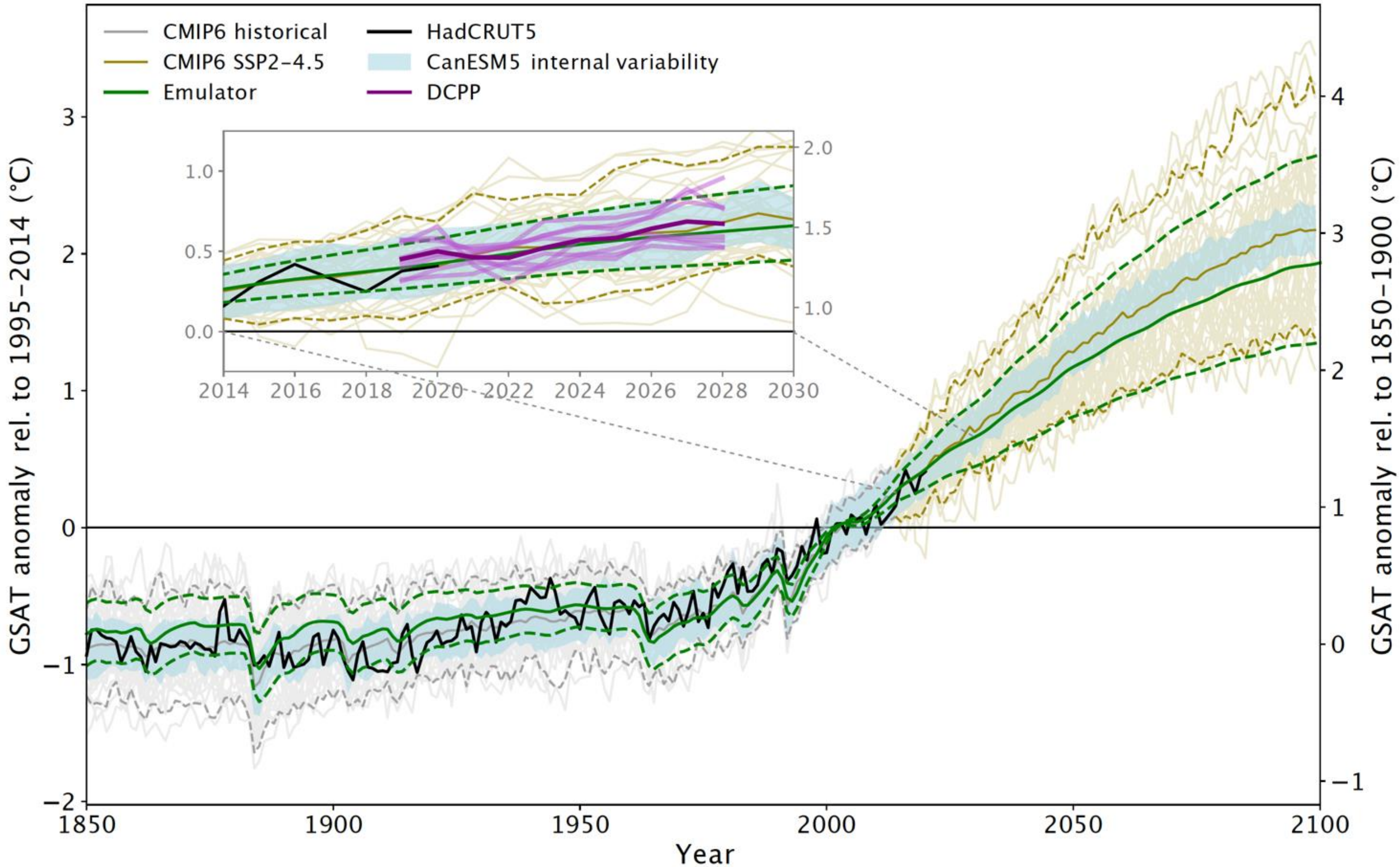
Projected Temperature Change





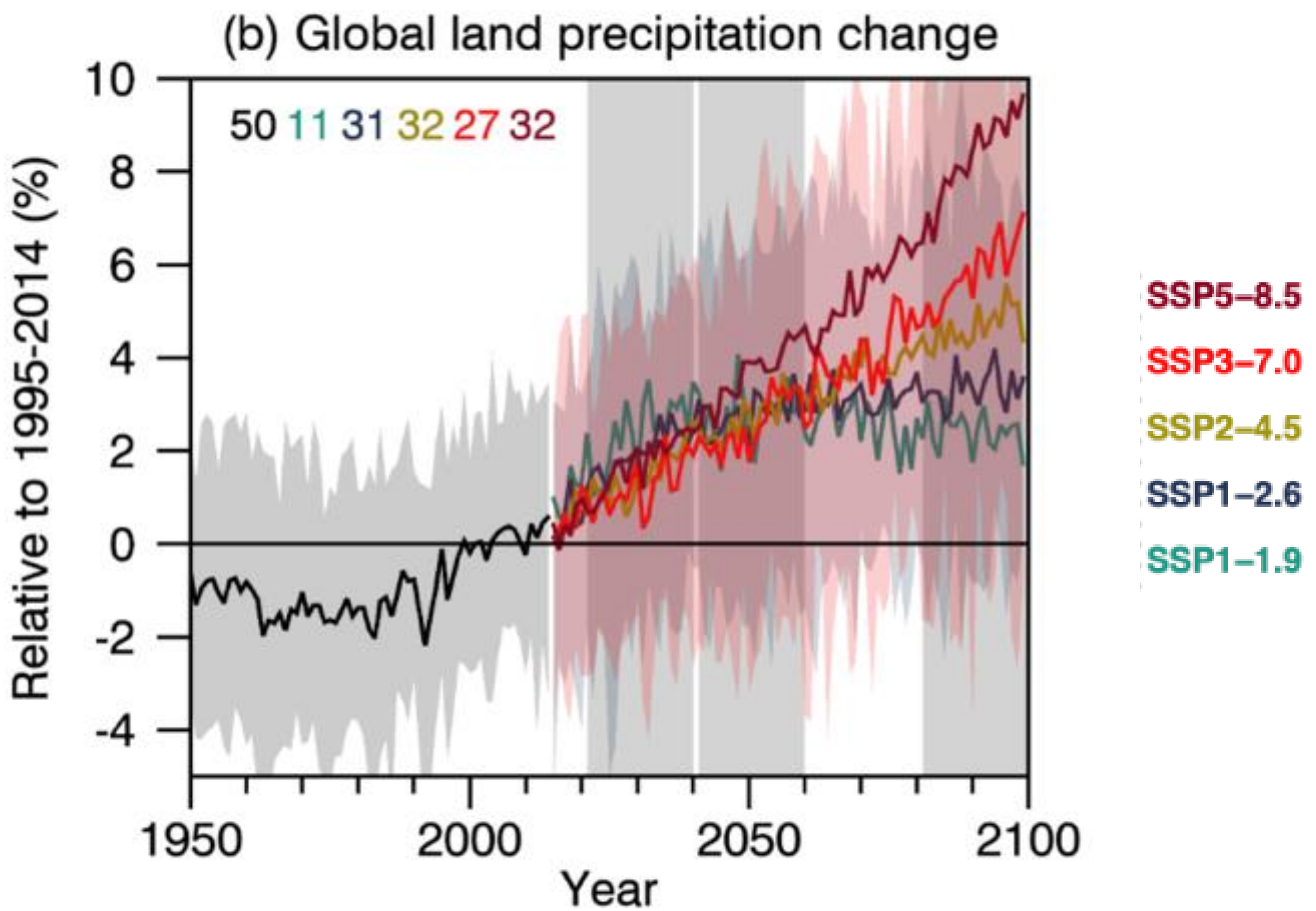
IPCC, 2021

Uncertainty in Temperature Projections



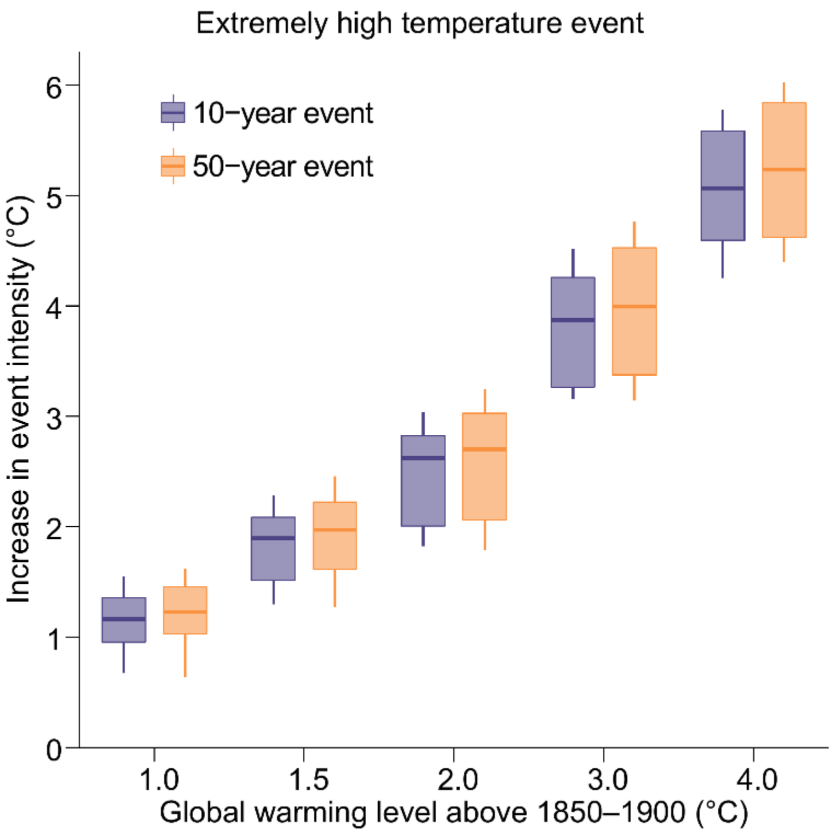
IPCC, 2021

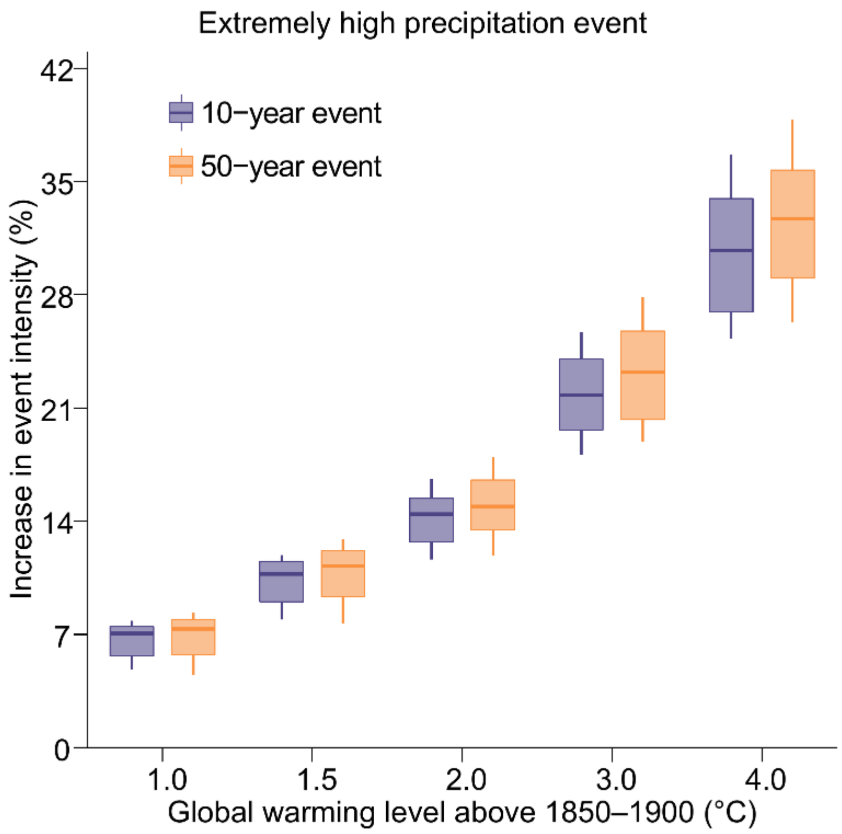
Projected Precipitation Change



IPCC, 2021

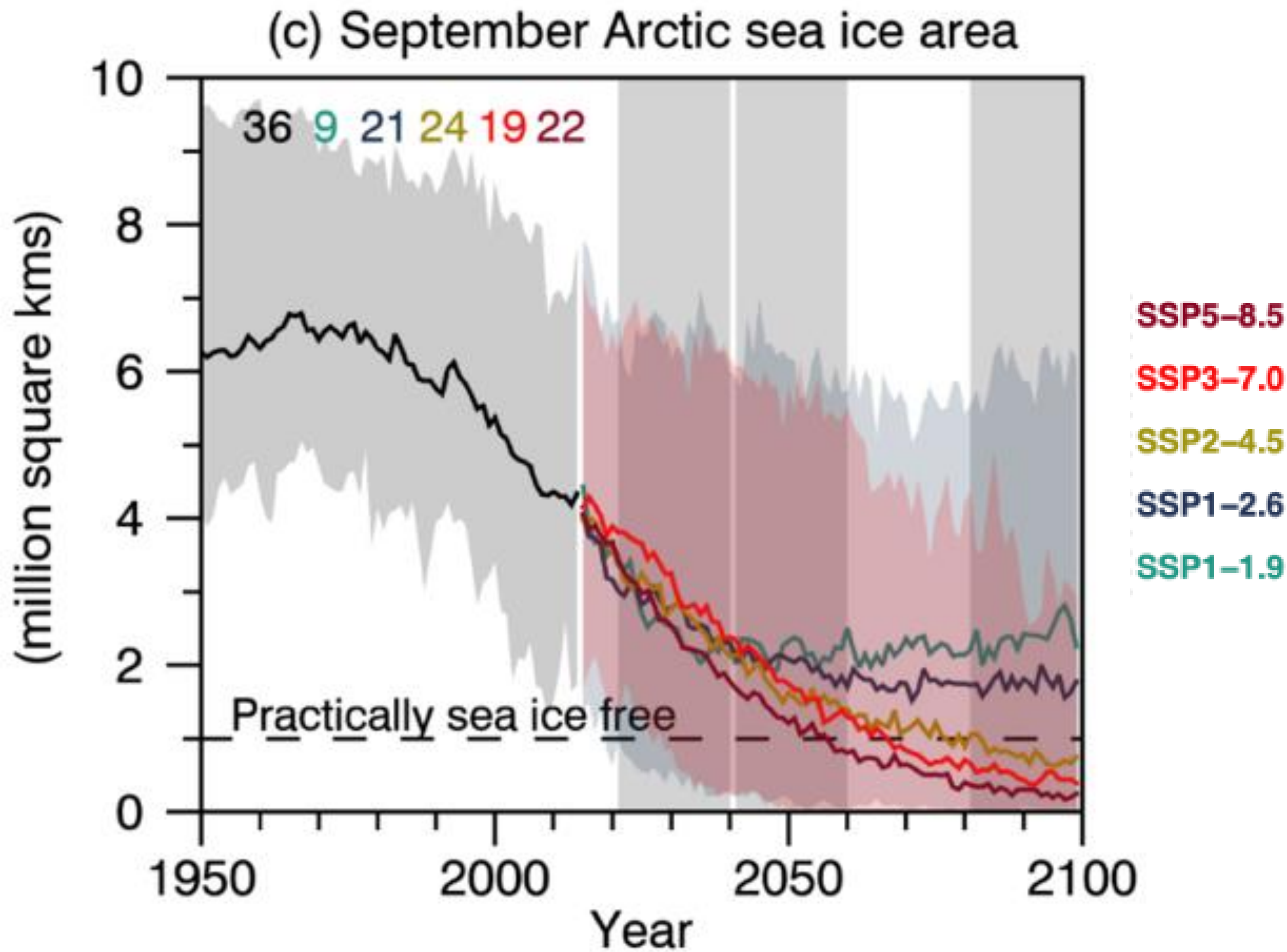
Projected Change in Extreme Events





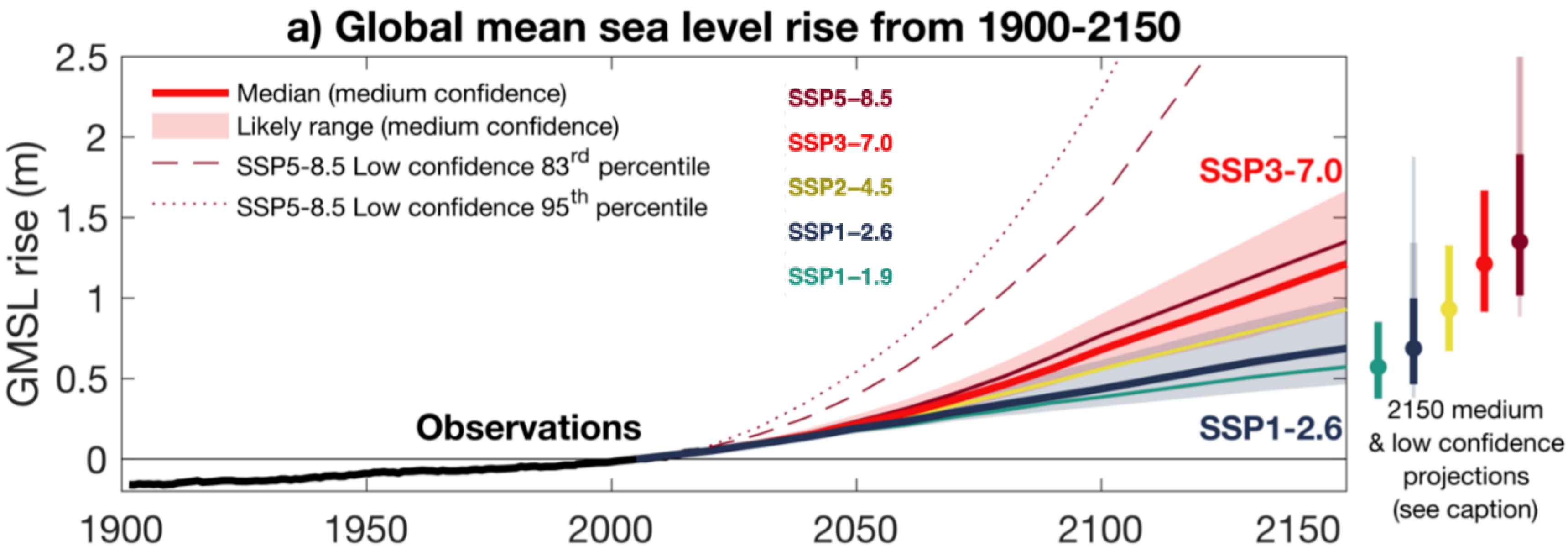
IPCC, 2021

Projected Change in Sea Ice Extent



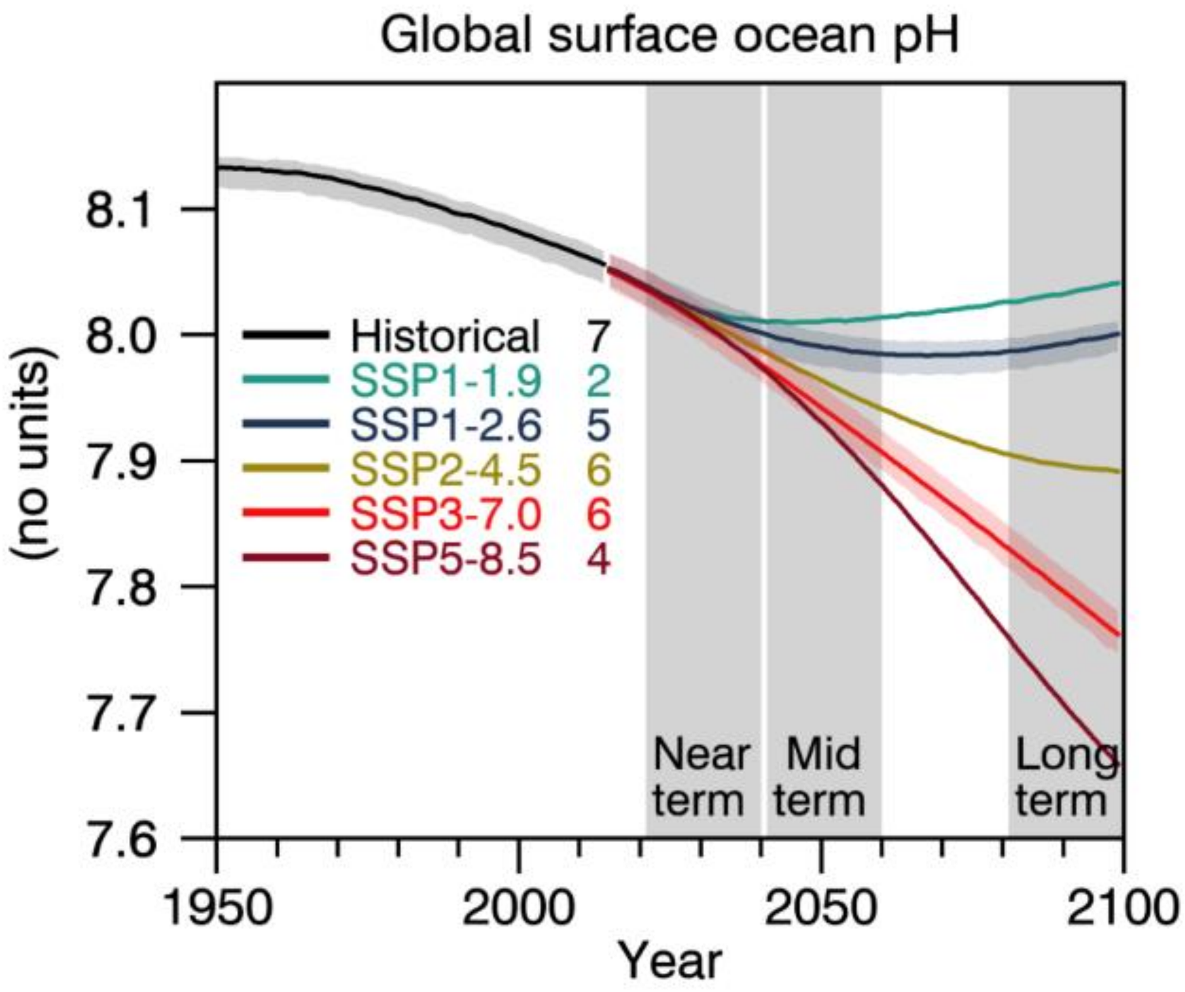
IPCC, 2021

Projected Change in Sea Level



IPCC, 2021

Projected Change in Ocean Acidification



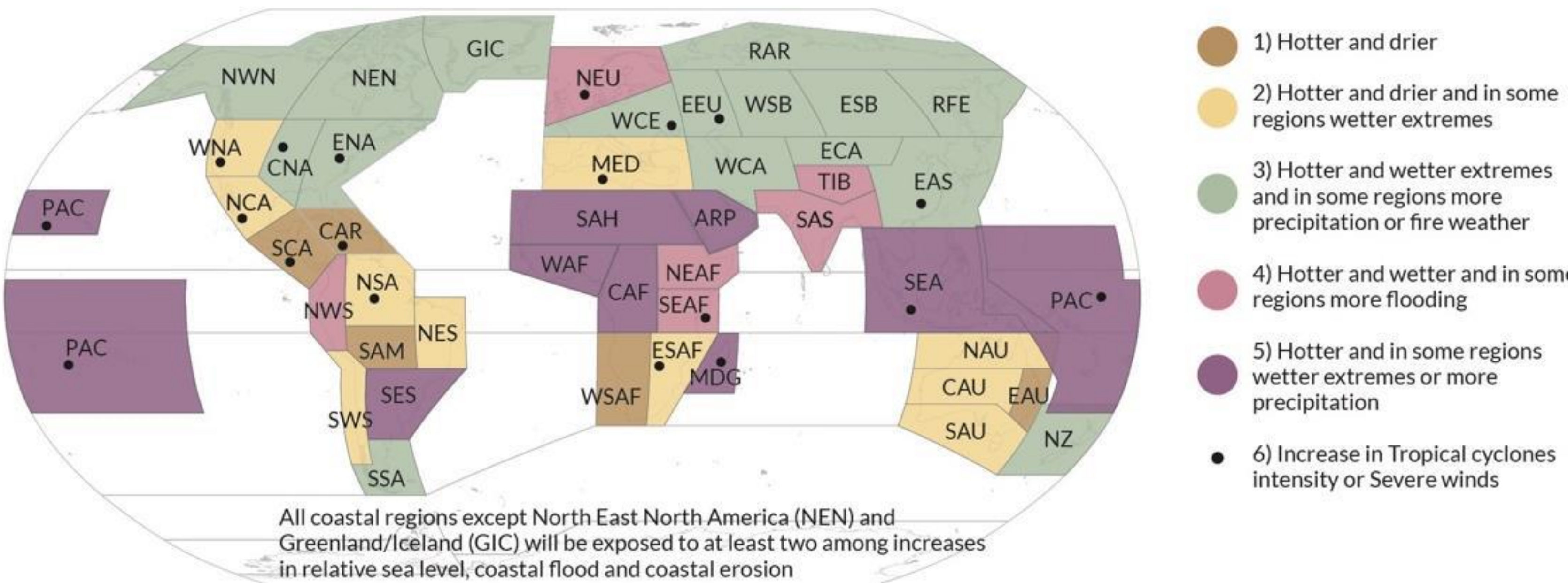
IPCC, 2021

Projected Changes in Regional Climate Impact-Drivers

While changes in climatic impact-drivers will happen everywhere, there is a specific combination of changes each region will experience

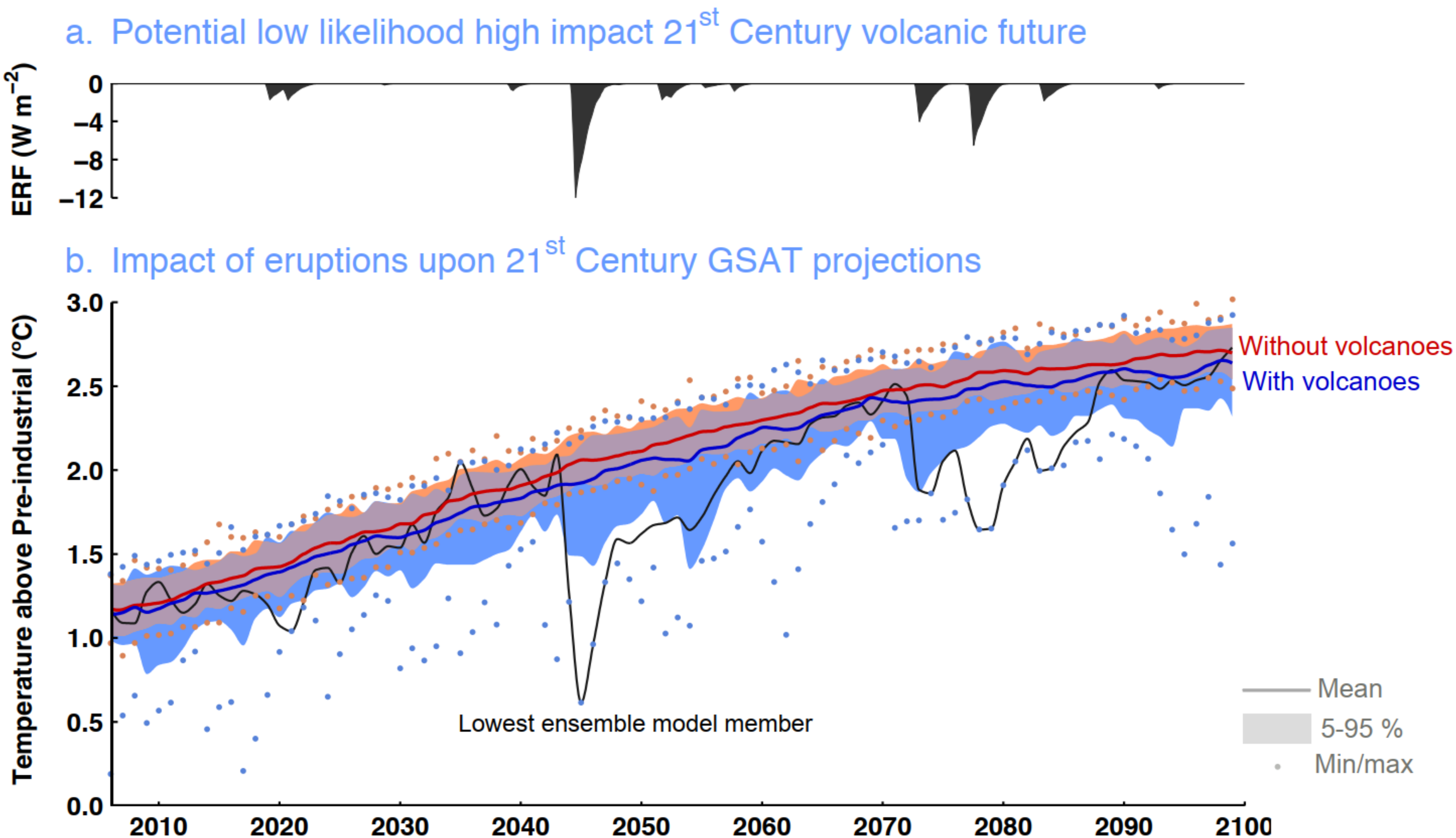
World regions grouped into five clusters, each one based on a combination of changes in climatic impact-drivers

Reference period: Mid 21st century or 2oC GWL compared to a climatological reference period included within 1960-2014



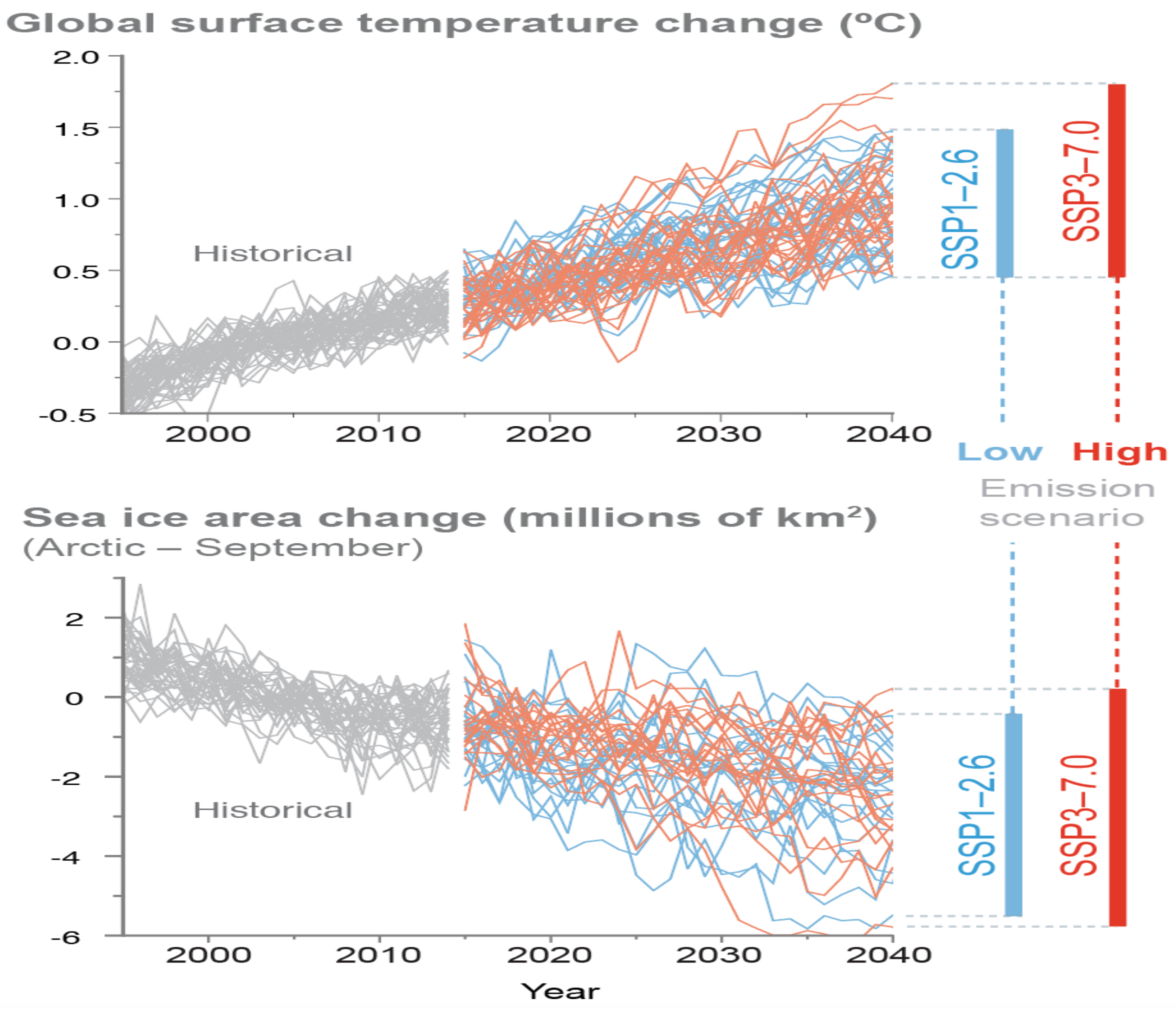
IPCC, 2021

Projected Warming with Natural Influences



IPCC, 2021

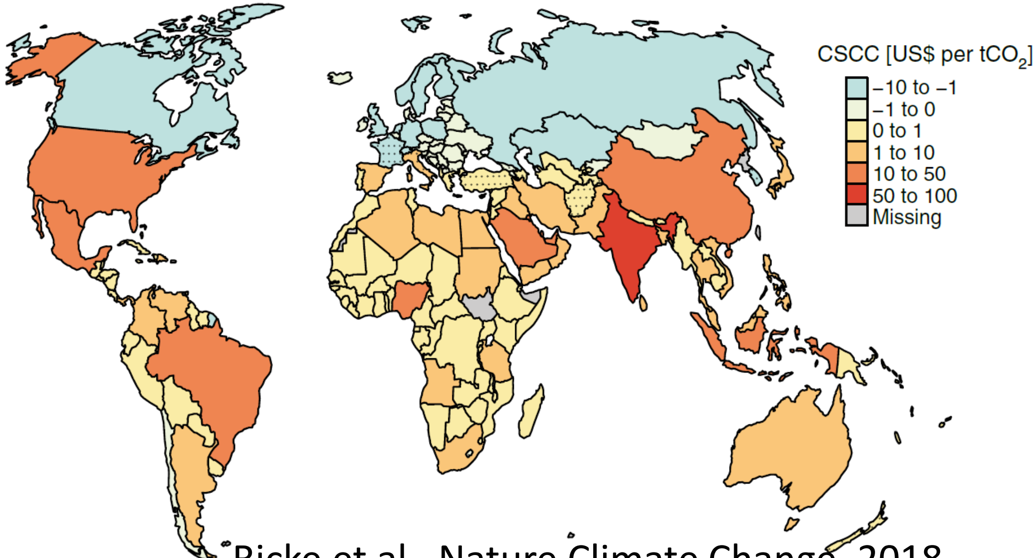
Near-Term Climate Change Under Natural Variability



IPCC, 2021

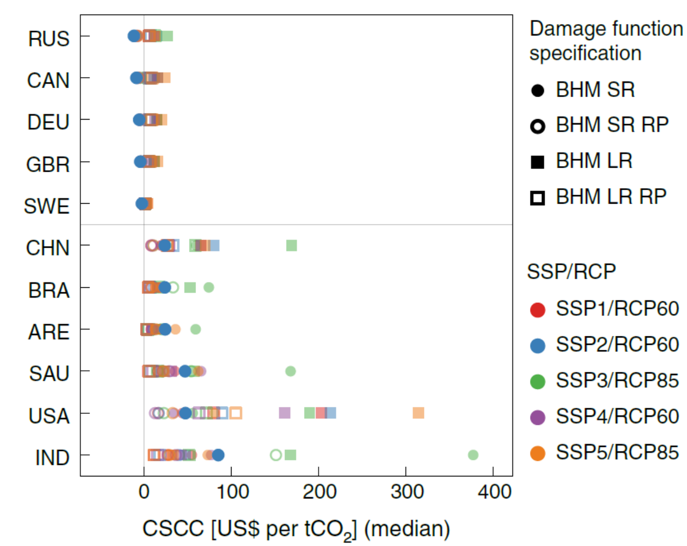
气候变化的影响：Social Cost of Carbon

情景：SSP2/RCP6.0 + BHM-SR + Discount



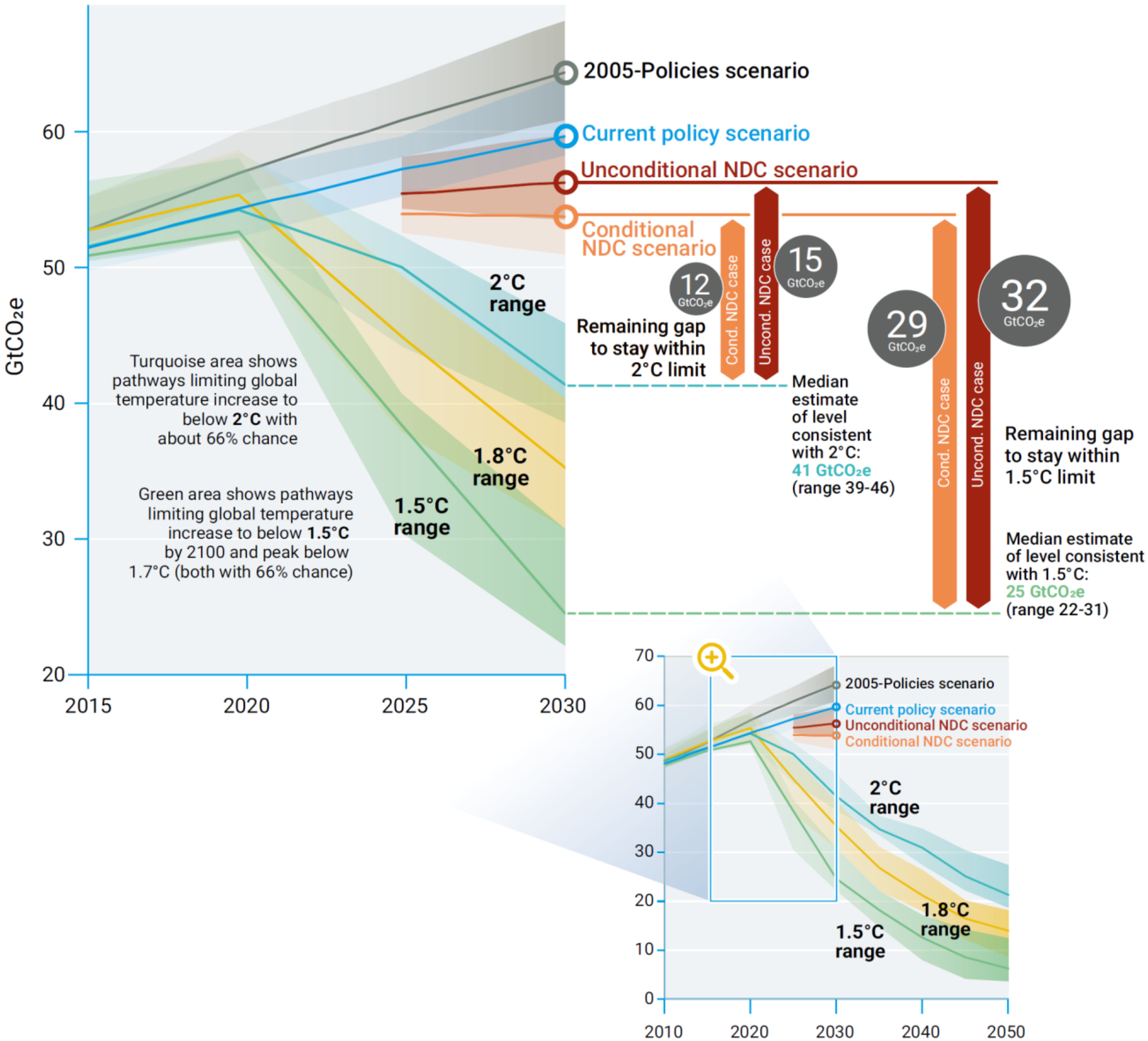
Ricke et al., Nature Climate Change, 2018

多个情景下的差异



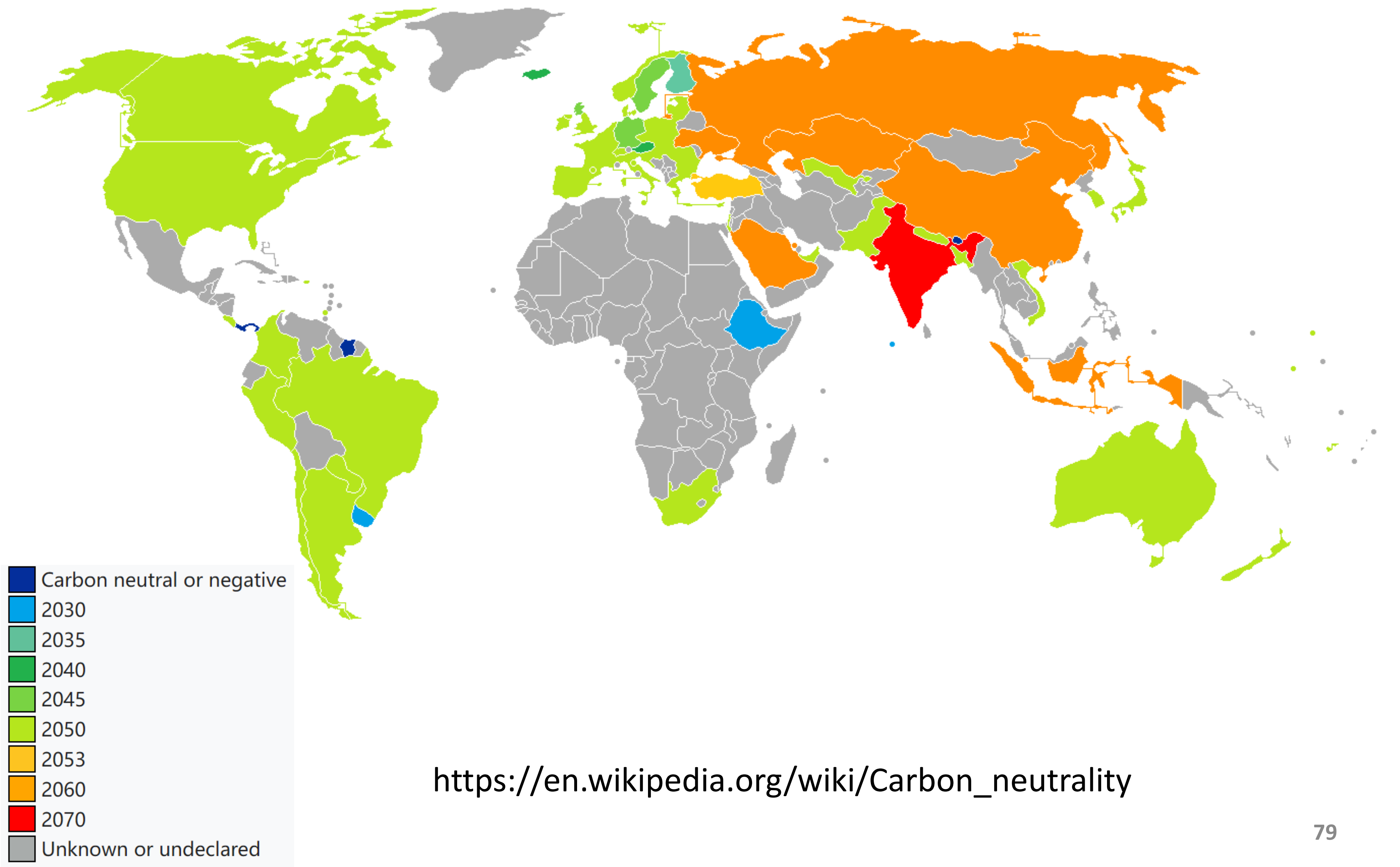
- SCC计算不确定性很大：受未来情景、气候模拟、经济计算影响
- 相比之下，目前碳价为：中国 < 10 US$/$tCO_2$；欧盟 > 60 US$/tCO_2

Towards 1.5^oC Warming: Is It Possible ?



Emissions Gap Report 2019

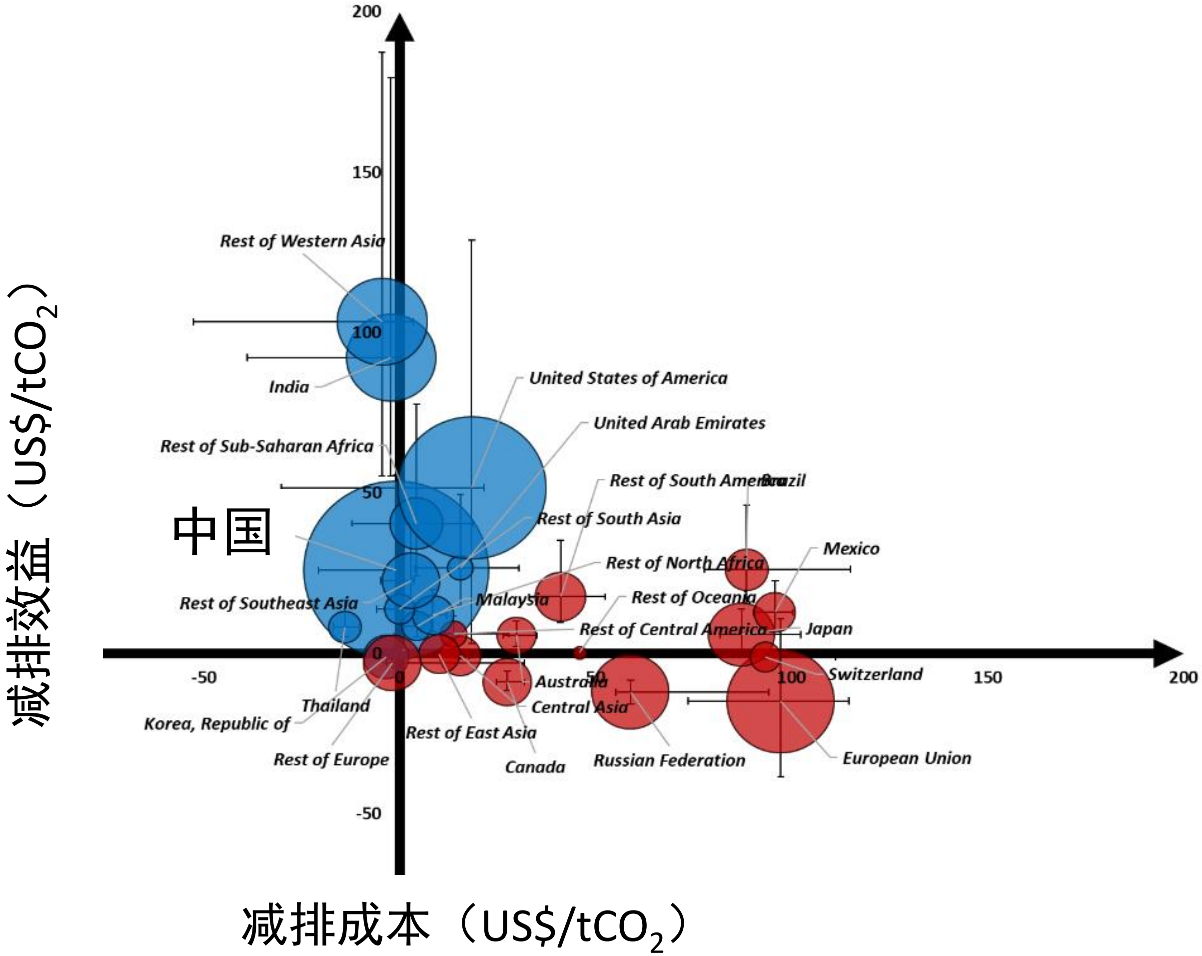
Carbon Neutrality ?



https://en.wikipedia.org/wiki/Carbon_neutrality

各地区碳减排成本与潜在效益呈现负相关
中国减排适合性？国际减排合作？

SSP2-RCP4.5情景相比于SSP5-RCP8.5情景的减排成本和潜在效益

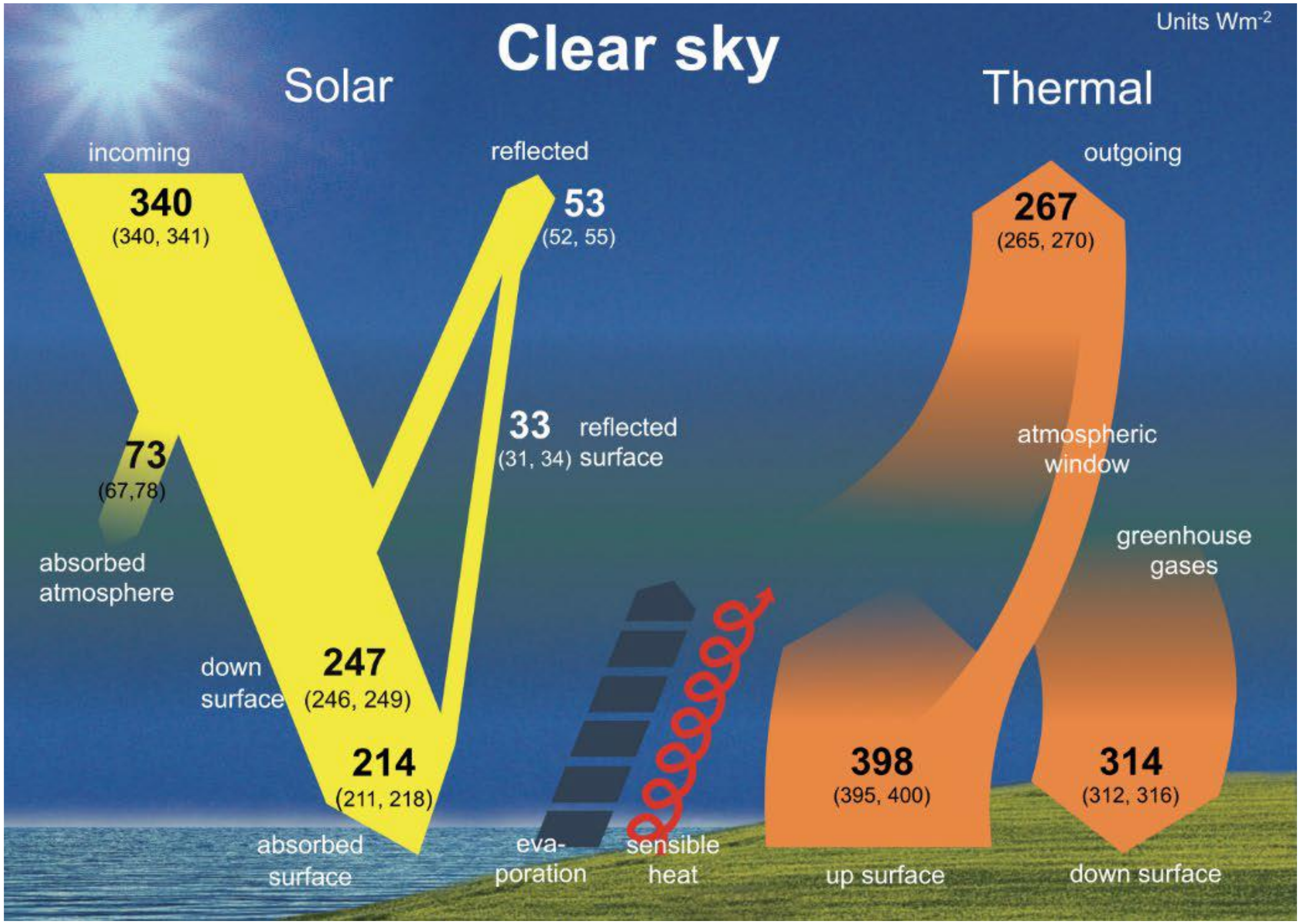


Liu et al., Nature Communications, 2022

Quiz

1. **Explain the direct, semi-direct and indirect radiative forcing of aerosols**
2. **Explain the different effects of CH_4 emission changes and CH_4 concentration changes in climate forcing**
3. **Explain the role of NO_x emissions in climate forcing**
4. **Surface warming in the Arctic is most significant, why?**
5. **Discuss the roles of clouds in climate change**
6. **Why do the oceans matter for the climate?**
7. **How do you think future warming will affect precipitation (total, distribution, intensity, etc.)?**

Clear Sky Radiative Budget of Earth



IPCC, 2021

Changes in Climate Indicators

Selected large-scale climate indicators from the Cenozoic era to the recent past

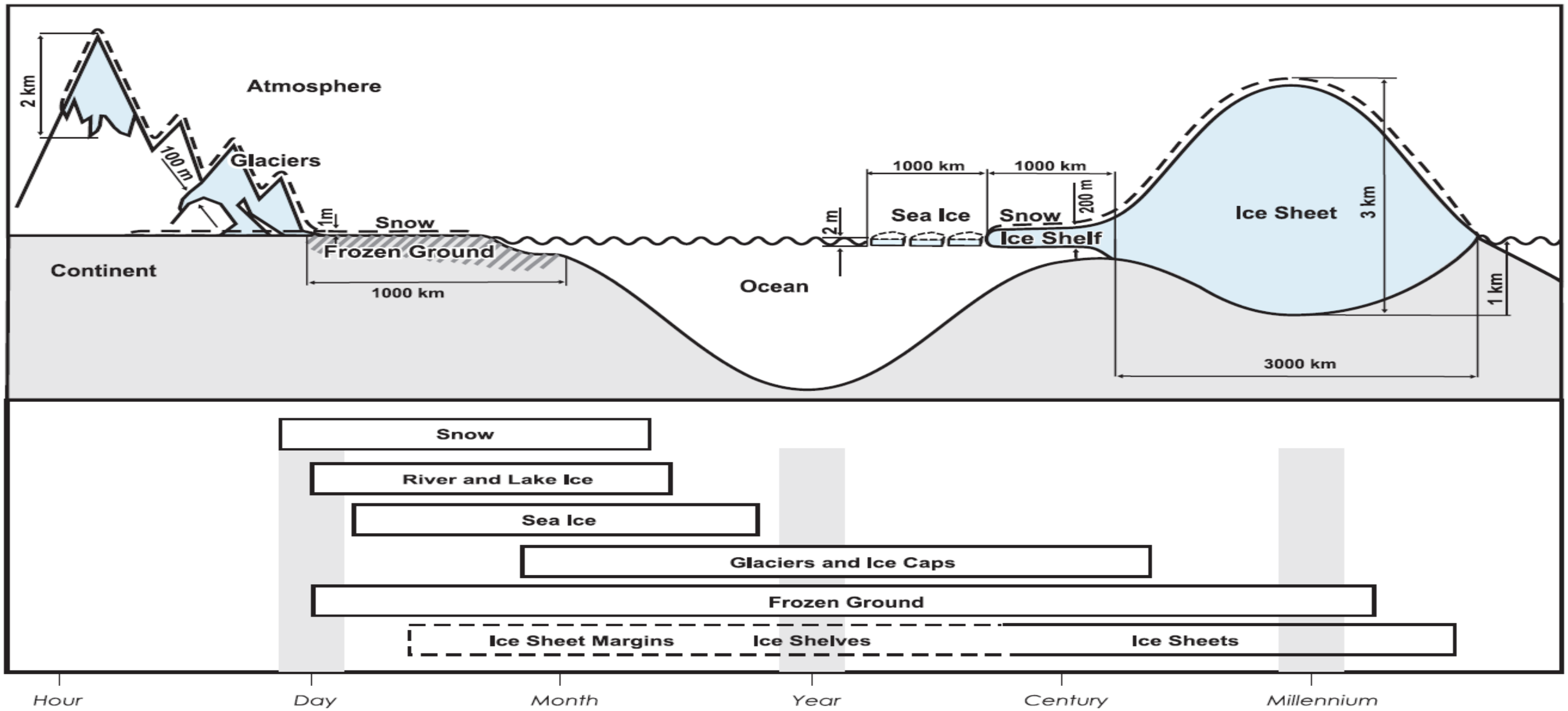
	Atmosphere: CO_2 (ppm)	CO_2 rate of change (ppm/100 yr)	Temperature relative to 1850–1900 (°C)	Cryosphere: Glacier extent relative to 1850–1900	Biosphere: Northern tree line relative to 1850–1900 (°lat)	Ocean: Sea level relative to 1900 (m)	Sea level rate of change (mm/yr or m/1000 yr)
younger Recent past (1995–2014 CE)	360→397	192 to 198	0.66 to 1.00		0.5 to 1.0	0.15 to 0.25	2.9 to 3.6
Approximate pre-industrial (1850–1900 CE)	286→296	17 to 27	−0.15 to +0.11		0	−0.03 to 0.00	0.4 to 0.6
Last Millennium (850–1850 CE)	278 to 285	-7~5	-0.14~0.24		−1.5 to 1.5	−0.05 to 0.03	-1.1~0.7
Mid-Holocene (6.5–5.5 ka)	260 to 268		0.2 to 1.0		1 to 3	−3.5 to 0.5	
Last Deglacial Transition (18–11 ka)	193→271	10			−6→1	−120→−50	24 to 44
Last Glacial Maximum (23–19 ka)	188 to 194		−5 to −7		−23 to −17	−134 to −125	
Last Interglacial (129–116 ka)	266 to 282		0.5 to 1.5		8 to 2	5 to 10	
Mid-Pliocene warm period (3.3–3.0 Ma)	360 to 420		2.5 to 4.0		4 to 10	5 to 25	
Early Eocene climate optimum (53–49 Ma)	1150 to 2500		10 to 18			70 to 76	
Paleocene-Eocene thermal maximum (55.9–55.7 Ma) *older*	900→2000	4 to 42	10 to 25				

X to Y: *very likely* range, unless otherwise stated in FAIR data table
X→Y: start to end of period, with no stated uncertainty
X~Y: lowest and highest values, with no stated uncertainty

Minimum — Pre-industrial Level — Maximum
Colder / Lower sea level / More ice — Warmer / Higher sea level / Less ice — Insufficient data or not assessed

IPCC, 2021

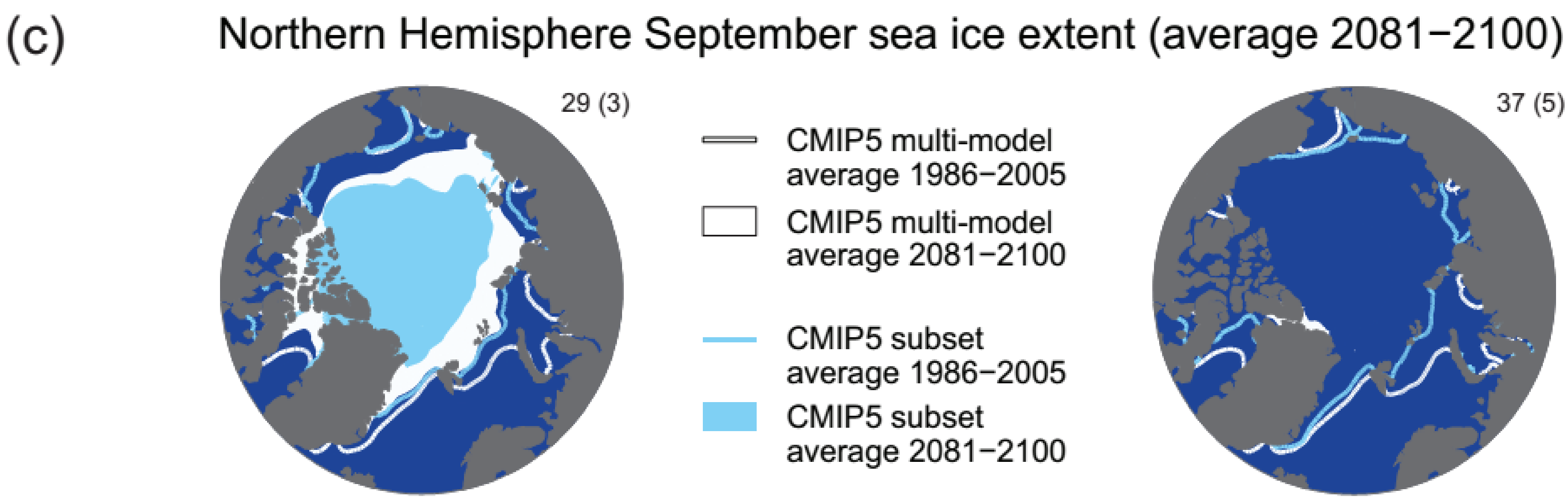
Cryosphere and Its Components



Cryospheric Component	Area (10^6 km²)	Ice Volume (10^6 km³)	Potential Sea Level Rise (SLE) (m)[g]
Snow on land (NH)	1.9–45.2	0.0005–0.005	0.001–0.01
Sea ice	19–27	0.019–0.025	~0
Glaciers and ice caps			
Smallest estimate[a]	0.51	0.05	0.15
Largest estimate[b]	0.54	0.13	0.37
Ice shelves[c]	1.5	0.7	~0
Ice sheets	14.0	27.6	63.9
Greenland[d]	1.7	2.9	7.3
Antarctica[c]	12.3	24.7	56.6
Seasonally frozen ground (NH)[e]	5.9–48.1	0.006–0.065	~0
Permafrost (NH)[f]	22.8	0.011–0.037	0.03–0.10

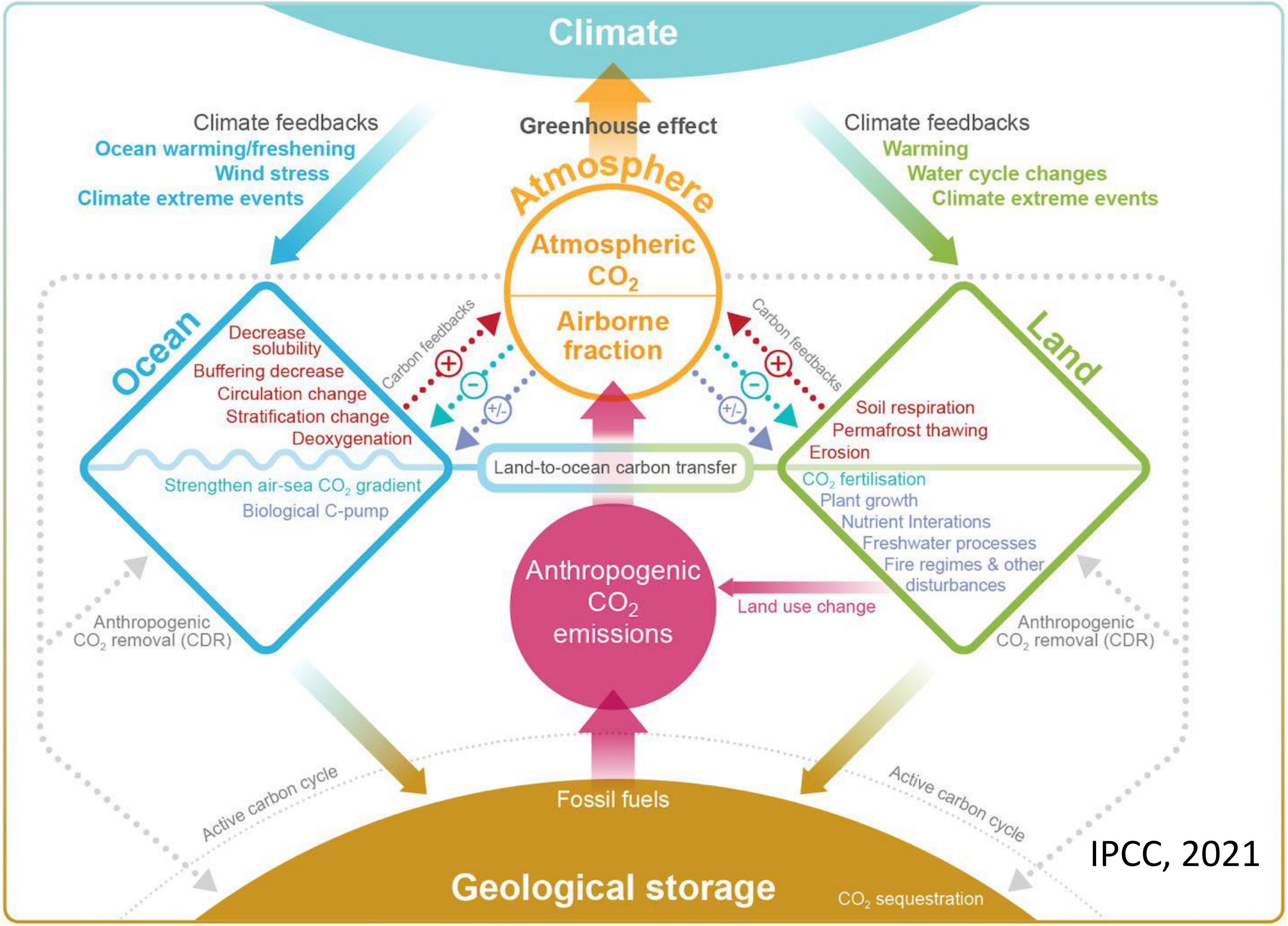
IPCC, 2007

Projected Change in Sea Ice Extent



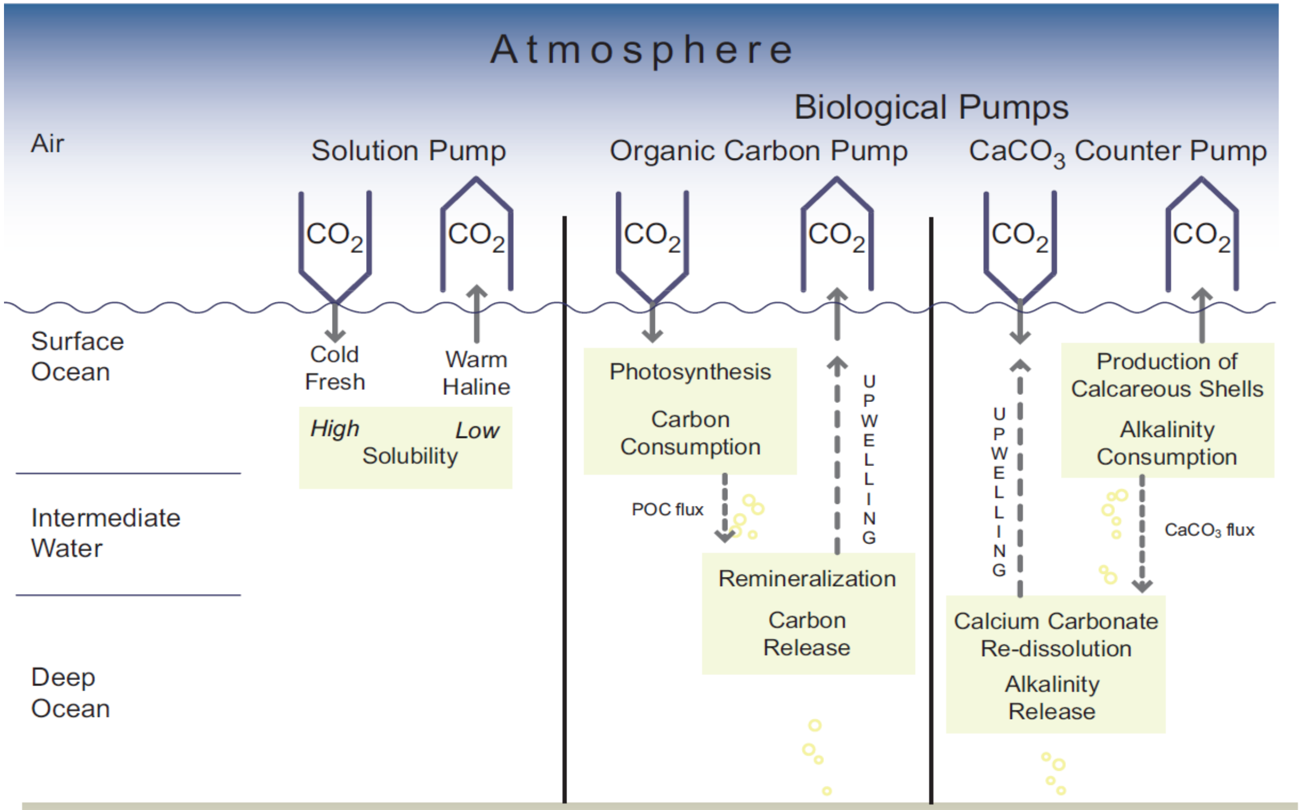
IPCC, 2013

Feedbacks of Carbon Cycle



IPCC, 2021

Feedbacks of Ocean Carbon Cycle



$$CO_2 + CO_3^{2-} \leftrightarrow HCO_3^-$$

- CO_3^{2-}
- acidification
- CO_2 fertilization, nutrients
- ‘bottleneck’ feedback (more stratification)

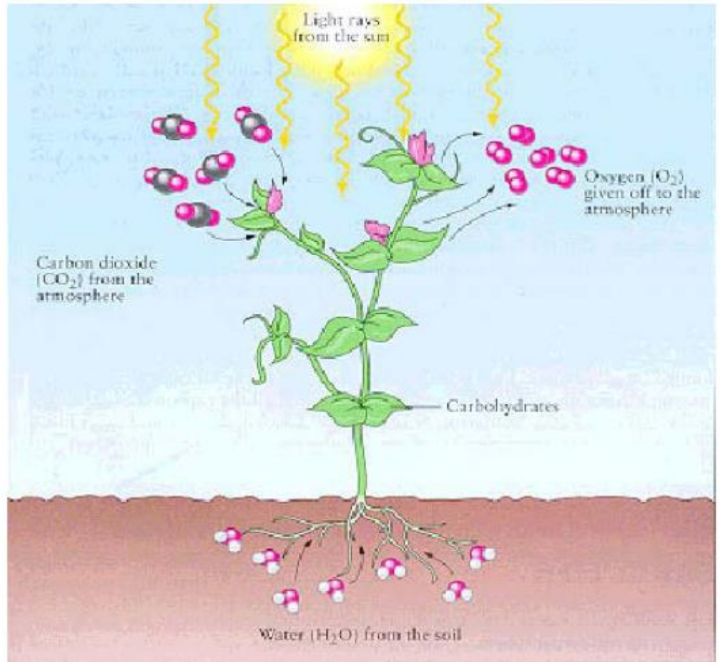
IPCC, 2007

Feedbacks of Terrestrial Carbon Cycle

How do plants process carbon?

Photosynthesis: $CO_2 + H_2O + \text{energy} \rightarrow O_2 + \text{organic C}$

Flux of CO2 from the atmosphere through photosynthesis is 120 billions of metric tons/year



Residence time of carbon in plants ~5 years

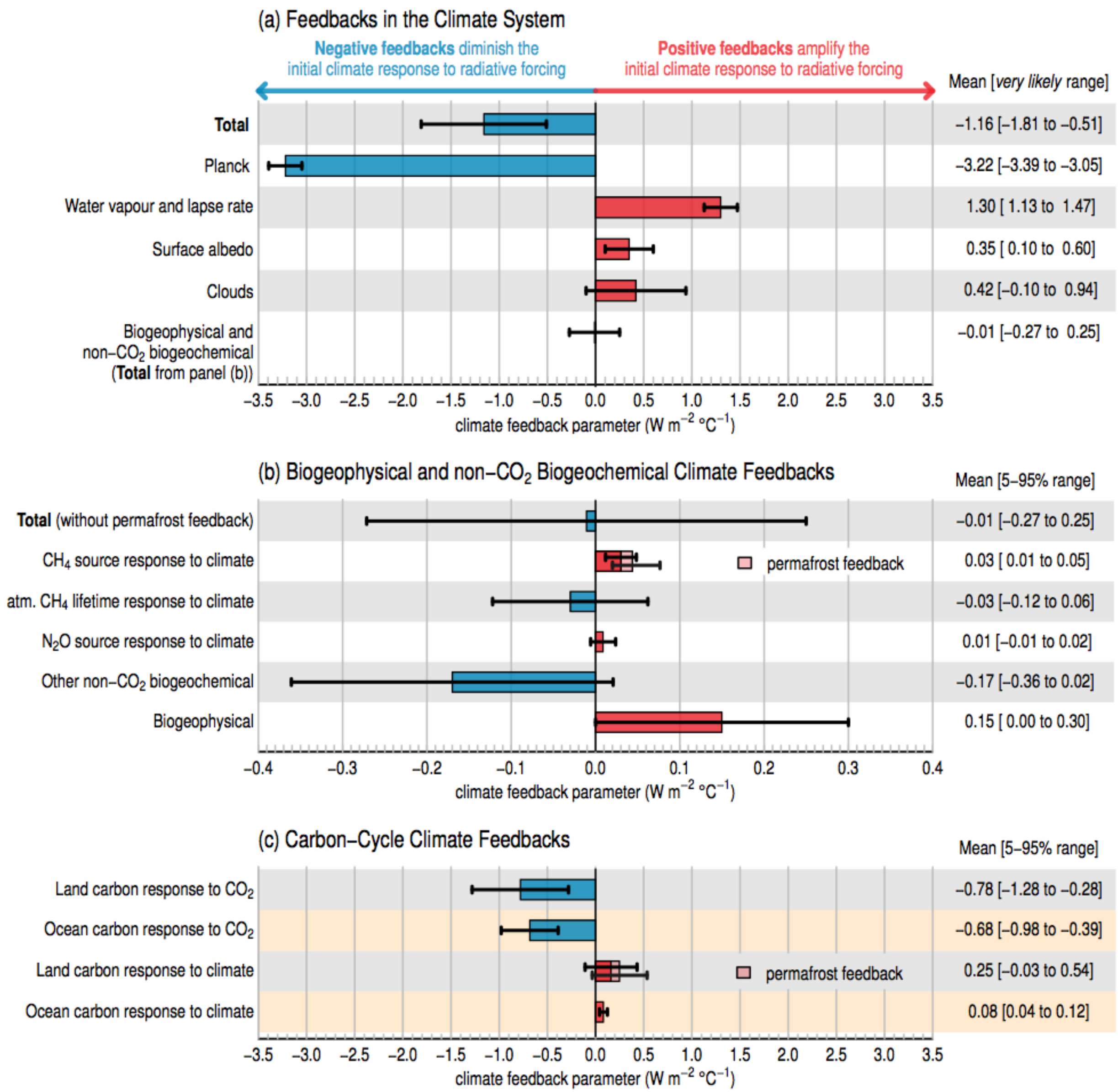
Respiration: $C_6H_{12}O_6 + O_2 \longrightarrow CO_2 + H_2O + \text{energy}$

glucose Oxygen Carbon dioxide water

Flux of CO2 from land plants back to the atmosphere through respiration is 120 billions of metric tons/yr

- Temperature/Precipitation Change
- CO_2 fertilization
- Nutrient limitation, pollution impacts (O_3, etc.)

Summary of Feedbacks



IPCC, 2021