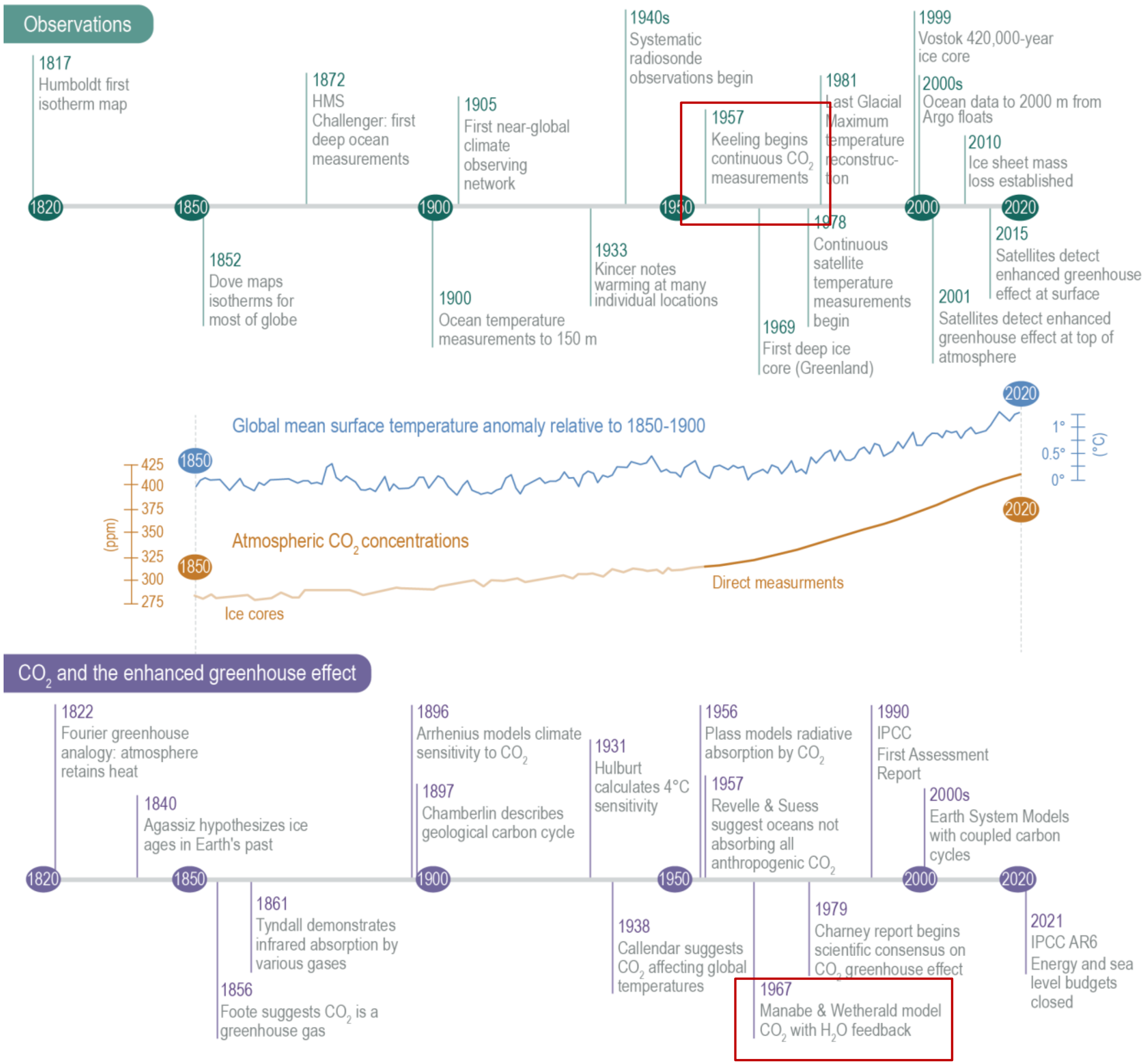
# CHAPTER 8

# CLIMATE CHANGE, FORCINGS AND FEEDBACKS

# Climate Science Milestones



## Observations

**1817** Humboldt first isotherm map

**1852** Dove maps isotherms for most of globe

**1872** HMS Challenger: first deep ocean measurements

**1900** Ocean temperature measurements to 150 m

**1905** First near-global climate observing network

**1933** Kincer notes warming at many individual locations

**1940s** Systematic radiosonde observations begin

**1957** Keeling begins continuous $CO_2$ measurements

**1969** First deep ice core (Greenland)

**1978** Continuous satellite temperature measurements begin

**1981** Last Glacial Maximum temperature reconstruction

**1999** Vostok 420,000-year ice core

**2000s** Ocean data to 2000 m from Argo floats

**2001** Satellites detect enhanced greenhouse effect at top of atmosphere

**2010** Ice sheet mass loss established

**2015** Satellites detect enhanced greenhouse effect at surface

## $CO_2$ and the enhanced greenhouse effect

**1822** Fourier greenhouse analogy: atmosphere retains heat

**1840** Agassiz hypothesizes ice ages in Earth's past

**1856** Foote suggests $CO_2$ is a greenhouse gas

**1861** Tyndall demonstrates infrared absorption by various gases

**1896** Arrhenius models climate sensitivity to $CO_2$

**1897** Chamberlin describes geological carbon cycle

**1931** Hulburt calculates 4°C sensitivity

**1938** Callendar suggests $CO_2$ affecting global temperatures

**1956** Plass models radiative absorption by $CO_2$

**1957** Revelle & Suess suggest oceans not absorbing all anthropogenic $CO_2$

**1967** Manabe & Wetherald model $CO_2$ with $H_2O$ feedback

**1979** Charney report begins scientific consensus on $CO_2$ greenhouse effect

**1990** IPCC First Assessment Report

**2000s** Earth System Models with coupled carbon cycles

**2021** IPCC AR6 Energy and sea level budgets closed

IPCC, 2021

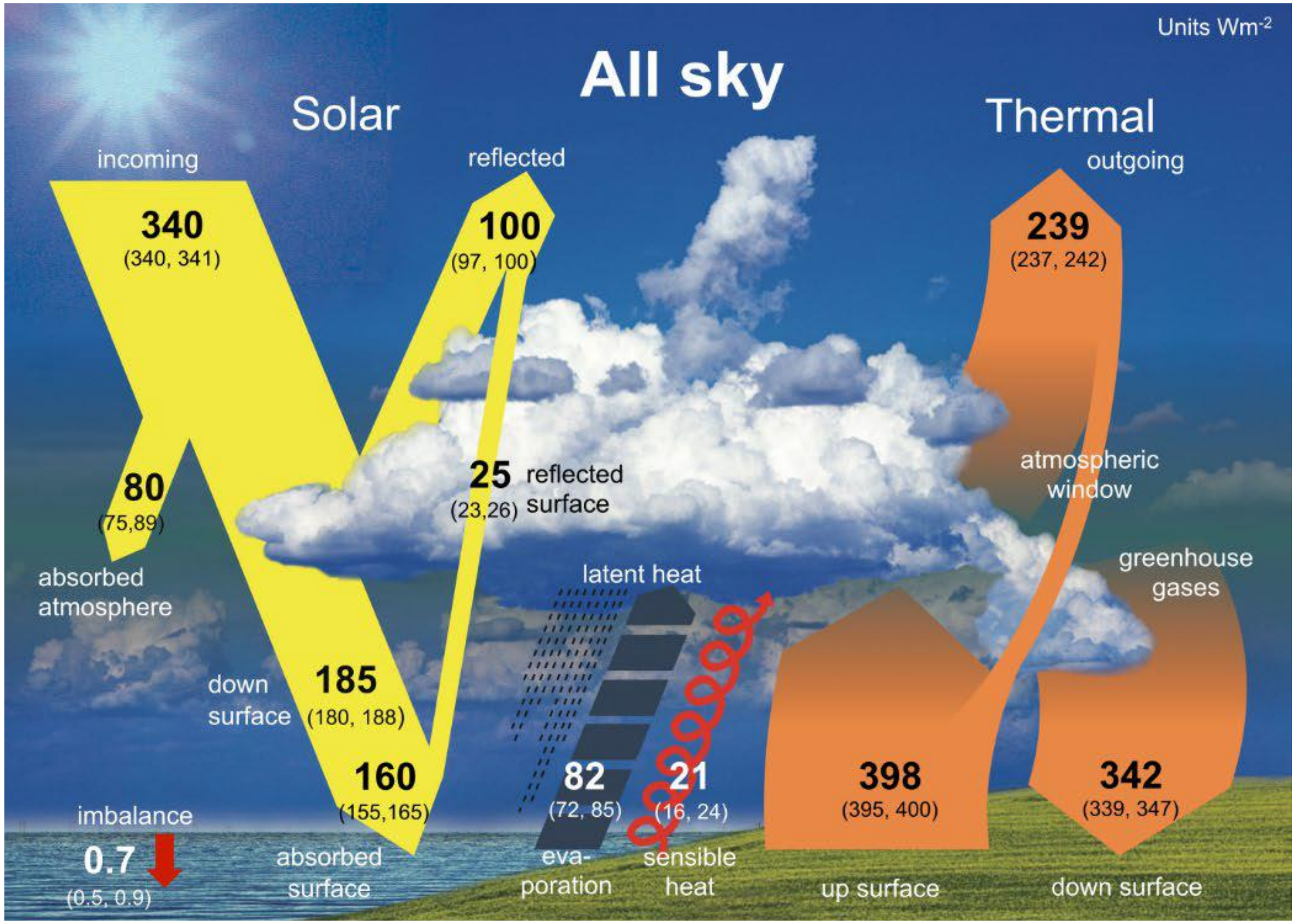
# Global Warming

# 气候变化争议

- ✓ 观测：有没有变暖
- ✓ 归因：变暖是否一定与人类活动有关
- 影响：变暖是否一定不好、有多不好
- 预测：变暖是否会持续/加速
- 应对：我们可否减缓/消除变暖
- 应对：减缓还是适应
- 应对：减缓/适应的手段
- 责任：谁应/多/先买单？

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

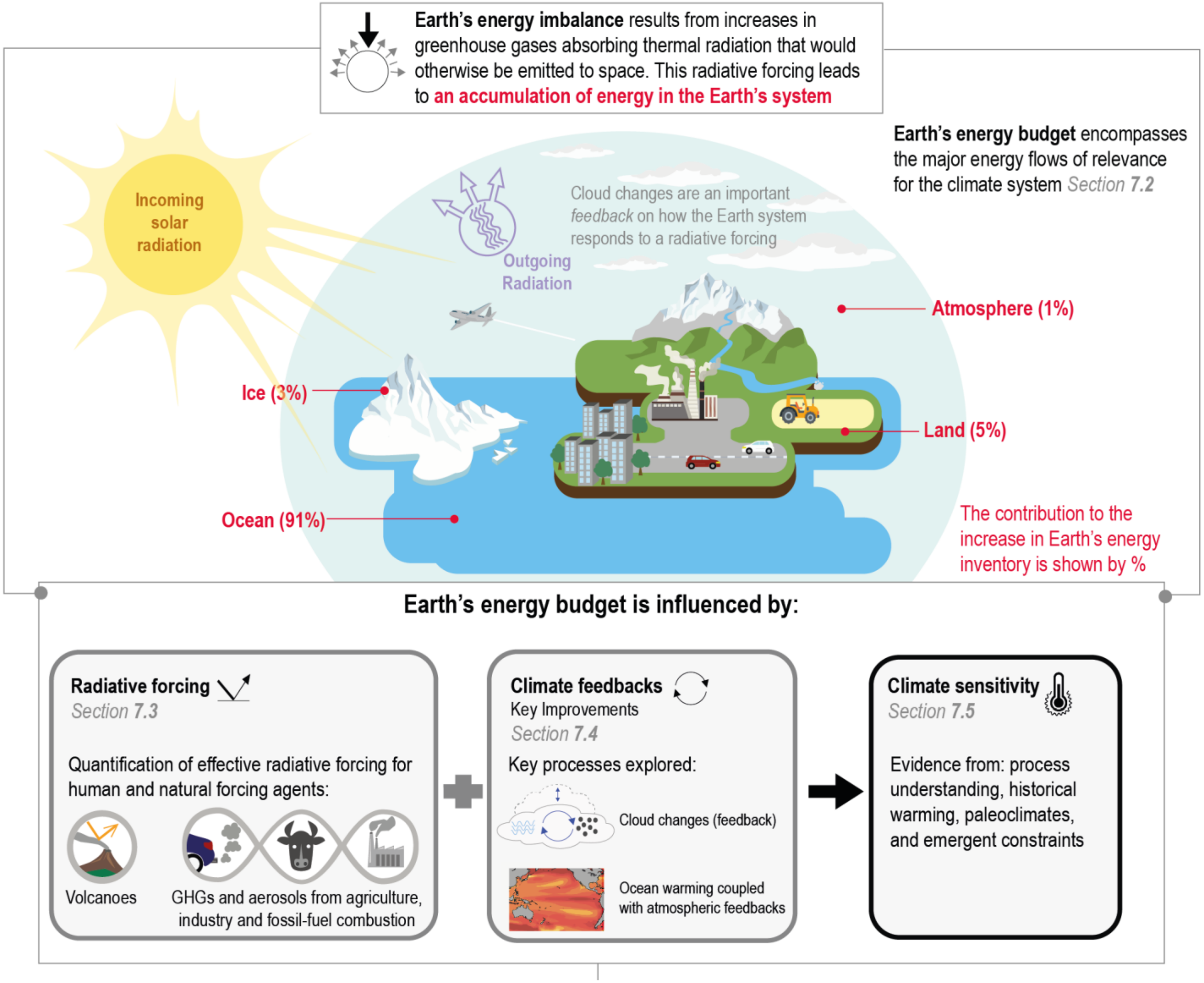
# Earth Energy Budget



IPCC, 2021

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

# How Earth Energy Balance Is Affected by Human



**Earth's energy imbalance** results from increases in greenhouse gases absorbing thermal radiation that would otherwise be emitted to space. This radiative forcing leads to an accumulation of energy in the Earth's system

**Earth's energy budget** encompasses the major energy flows of relevance for the climate system *Section 7.2*

Cloud changes are an important *feedback* on how the Earth system responds to a radiative forcing

The contribution to the increase in Earth's energy inventory is shown by %

**Earth's energy budget is influenced by:**

**Radiative forcing**
*Section 7.3*

Quantification of effective radiative forcing for human and natural forcing agents:

**Climate feedbacks**
Key Improvements
*Section 7.4*

Key processes explored:

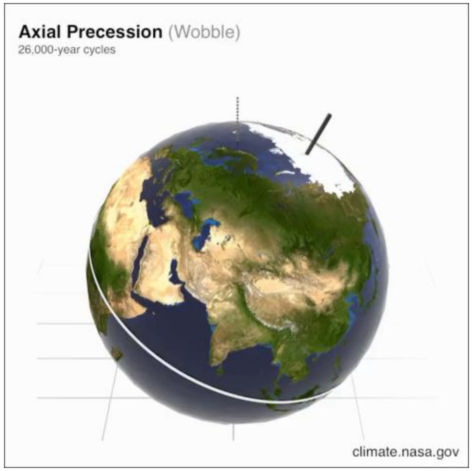
**Climate sensitivity**
*Section 7.5*

Evidence from: process understanding, historical warming, paleoclimates, and emergent constraints

IPCC, 2021

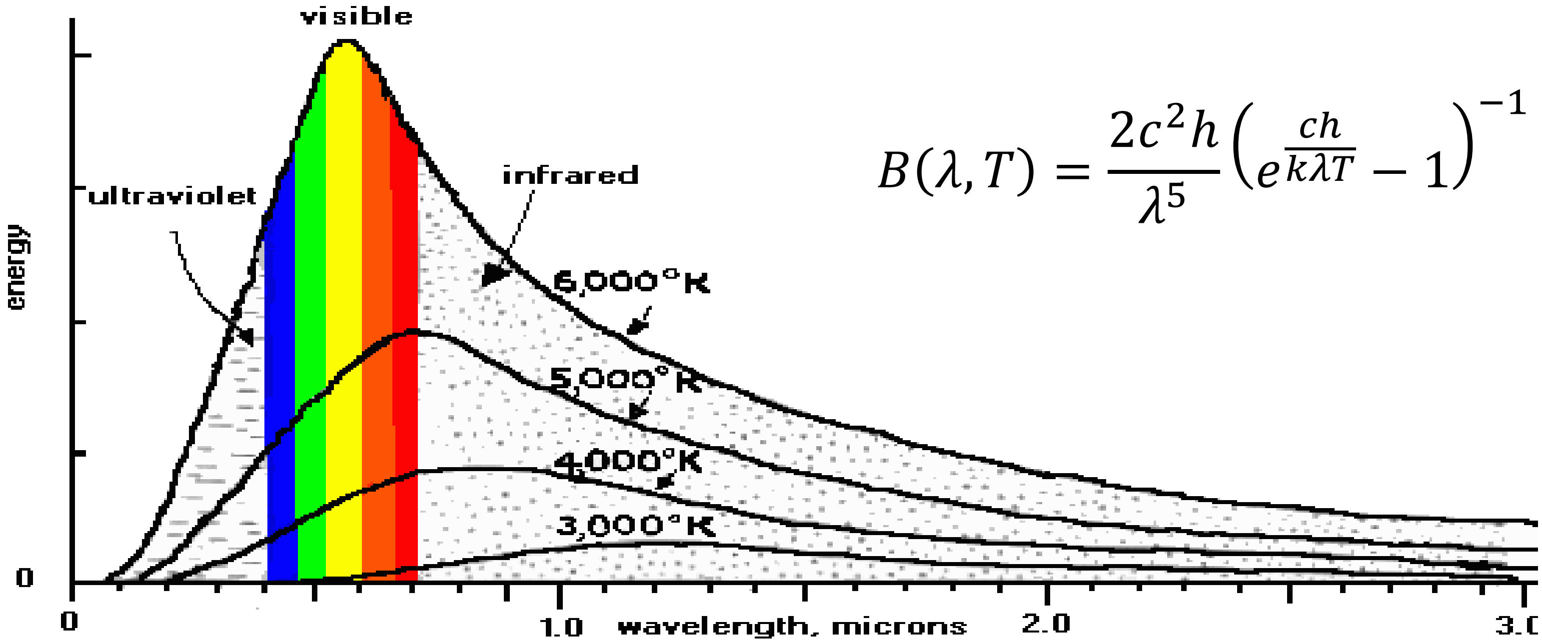
# 影响气候的因子

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



- 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、火山、陨石等）
  - 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、$SF_6$
  - $O_3$（与$NO_x$、CO、VOC相关）
  - 气溶胶：BC、OC、$SO_4^{2-}$、$NO_3^-$、$NH_4^+$、dust
  - 陆面和植被变化
- 反馈过程：热力、动力、碳循环等

# Planck’s Law for Black Body



$$B(\lambda,T)=\frac{2c^2h}{\lambda^5}\left(e^{\frac{ch}{k\lambda T}}-1\right)^{-1}$$

| 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

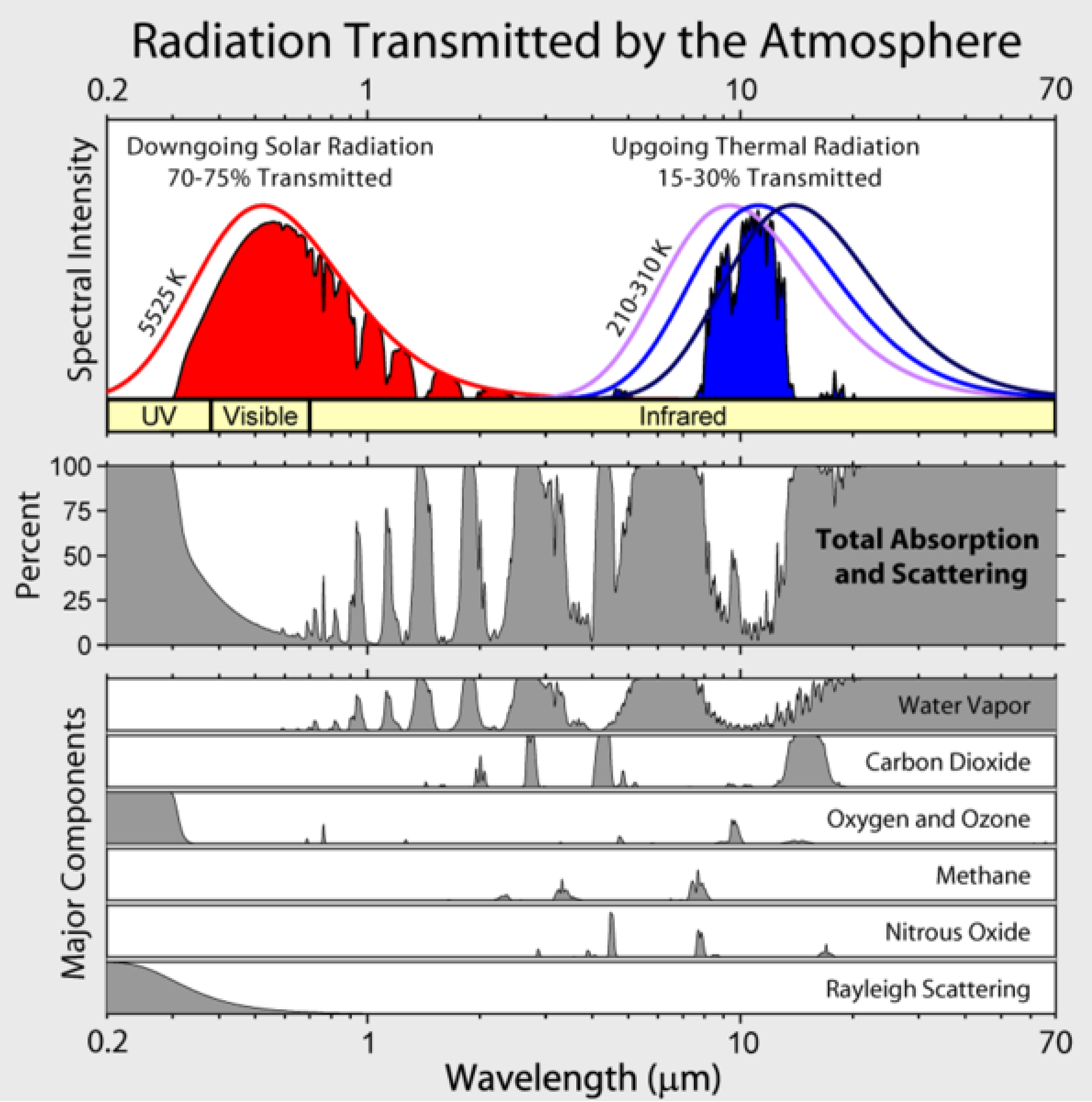
- 吸收：电子能级跃迁（UV/VIS）、原子振动（near IR）、分子转动（IR、microwave）

  特定波长、选择性吸收、组合

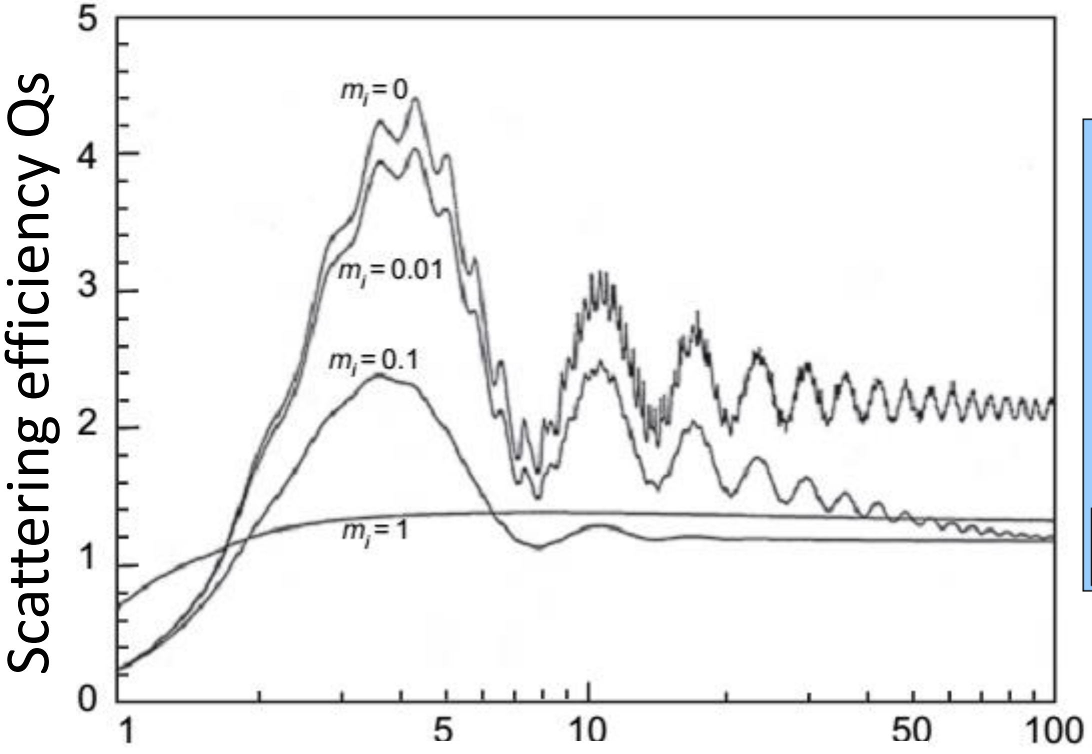
- 谱线增宽：自然增宽（可忽略）、压力增宽、多普勒增宽

- 散射：弹性散射、非弹性散射

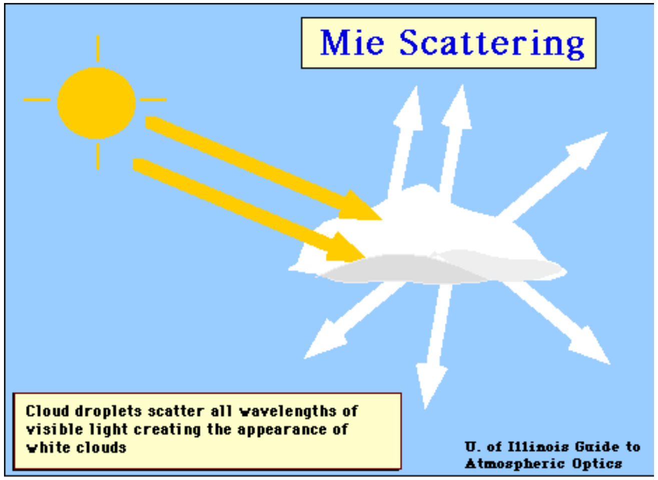
# 大气气体吸收和瑞利散射



# Mie Theory for Atmospheric Scattering



Size parameter $x = 2\pi r/\lambda$

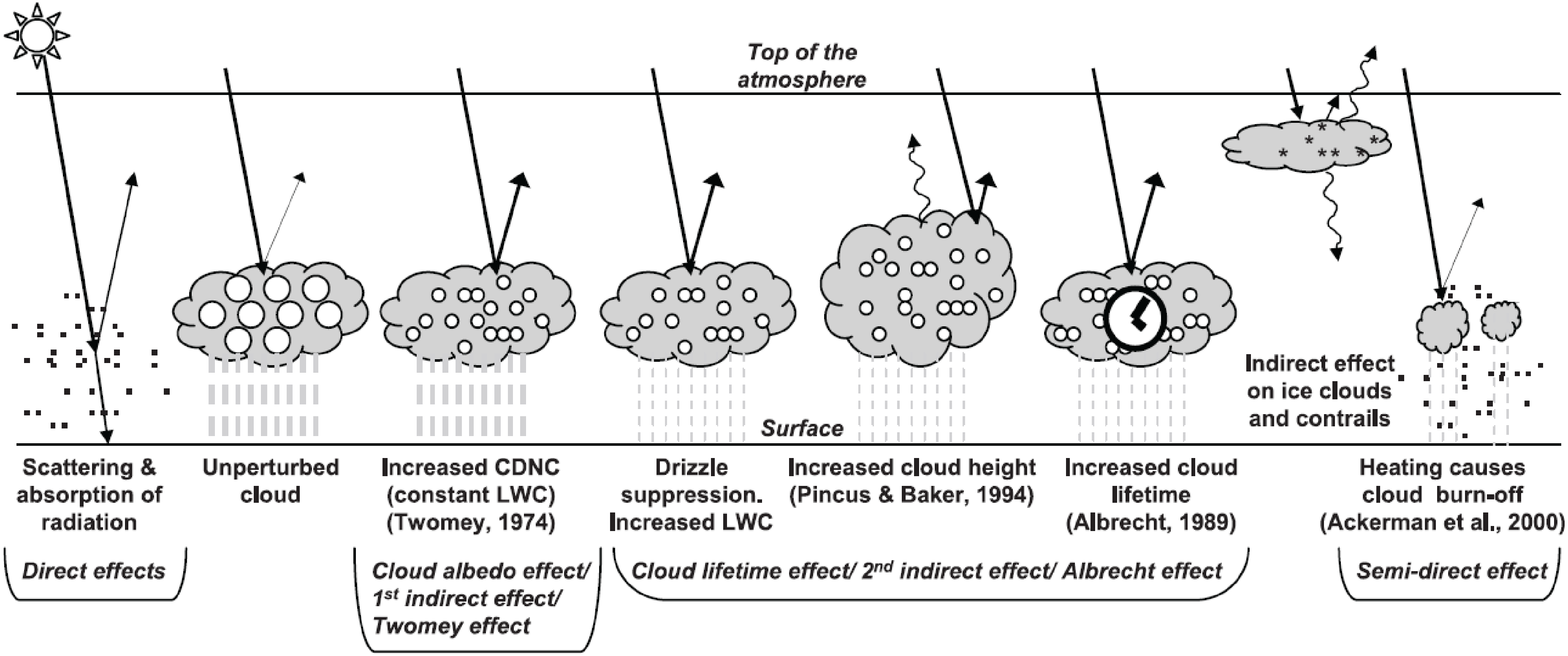


Cloud droplets scatter all wavelengths of visible light creating the appearance of white clouds

U. of Illinois Guide to Atmospheric Optics

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

# Scattering & Absorption of SW by Aerosols



IPCC, 2007

# Radiative Forcing: Terminology

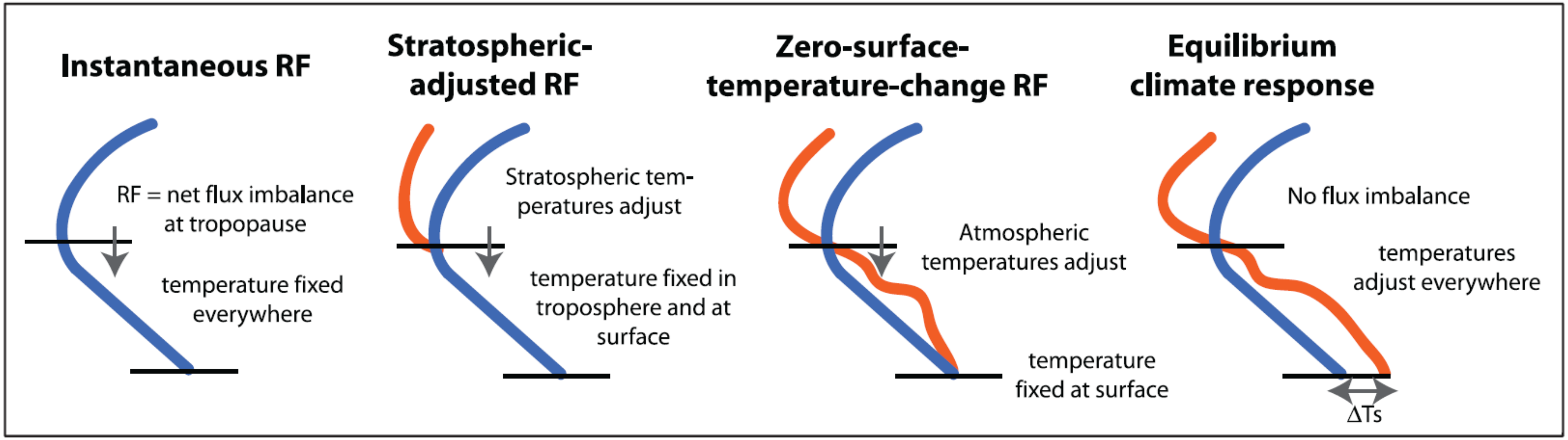
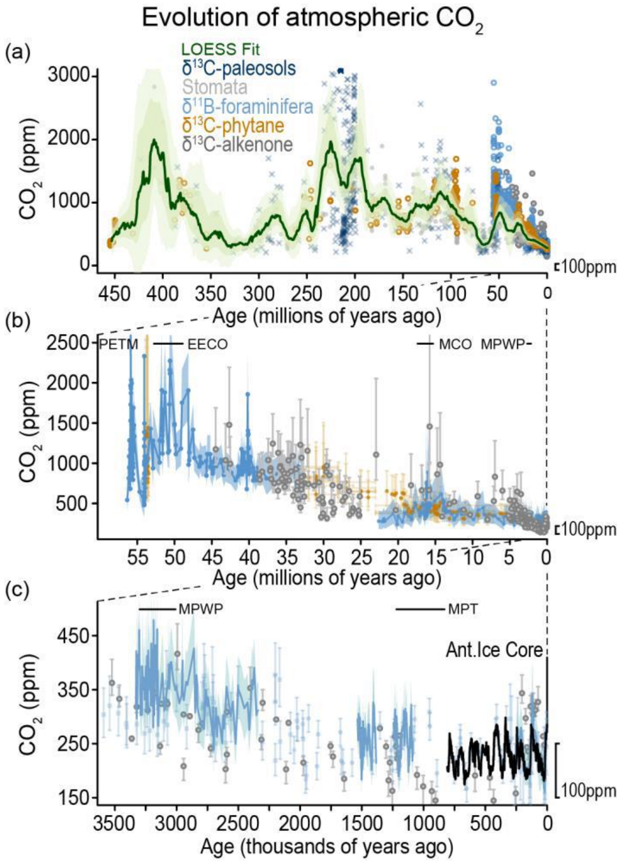


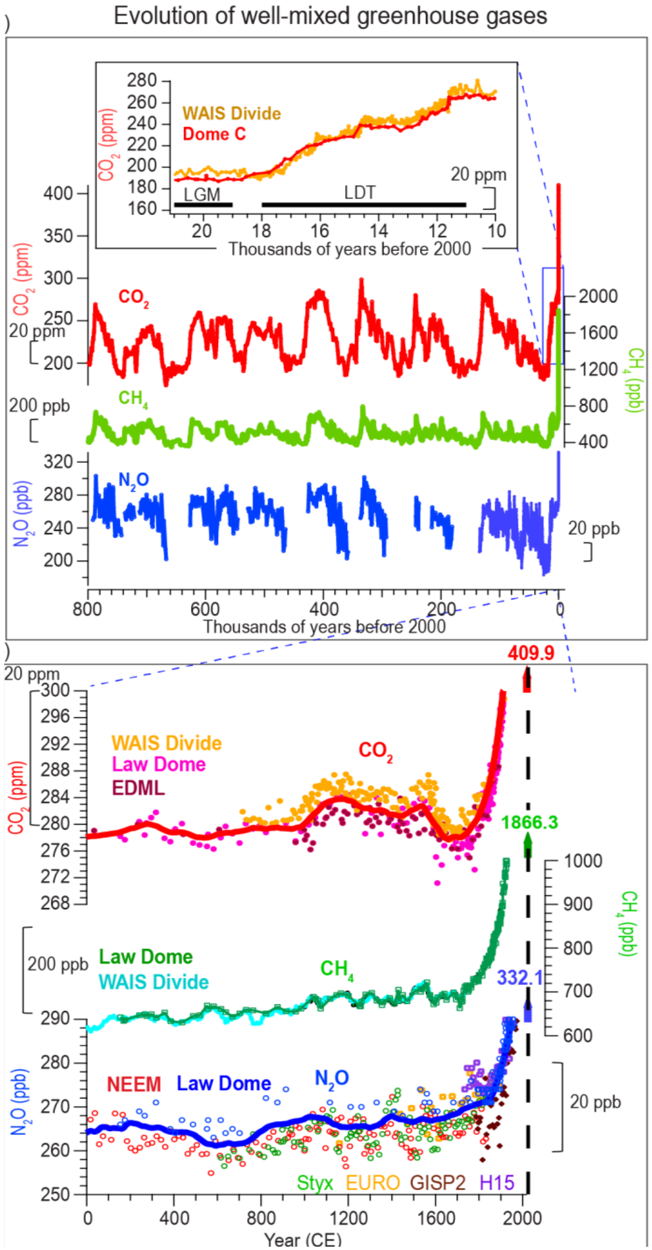
**Figure 2.2.** *Schematic comparing RF calculation methodologies. Radiative forcing, defined as the net flux imbalance at the tropopause, is shown by an arrow. The horizontal lines represent the surface (lower line) and tropopause (upper line). The unperturbed temperature profile is shown as the blue 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 ($\Delta T_s$).*

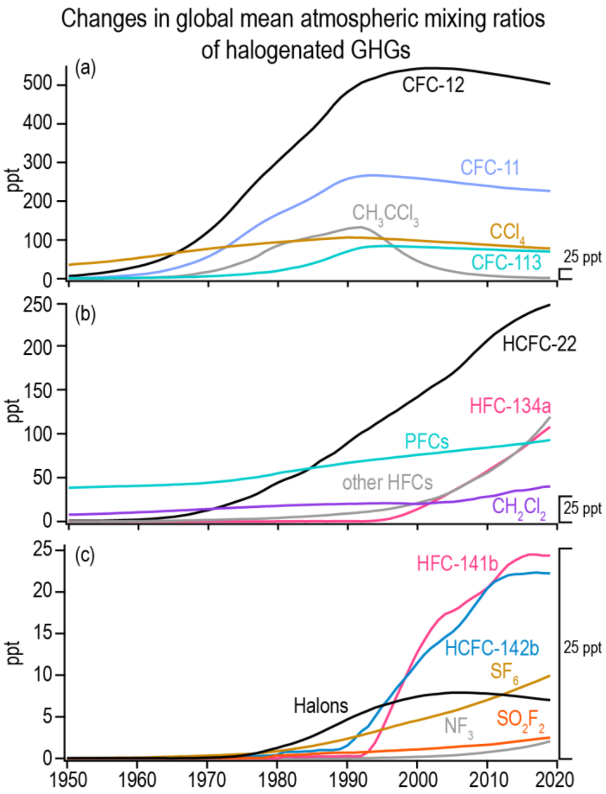
IPCC, 2007

# Trends in Long-lived GHGs Concentrations

**$[CO_2]$ in 2023: 419.3 ppm**





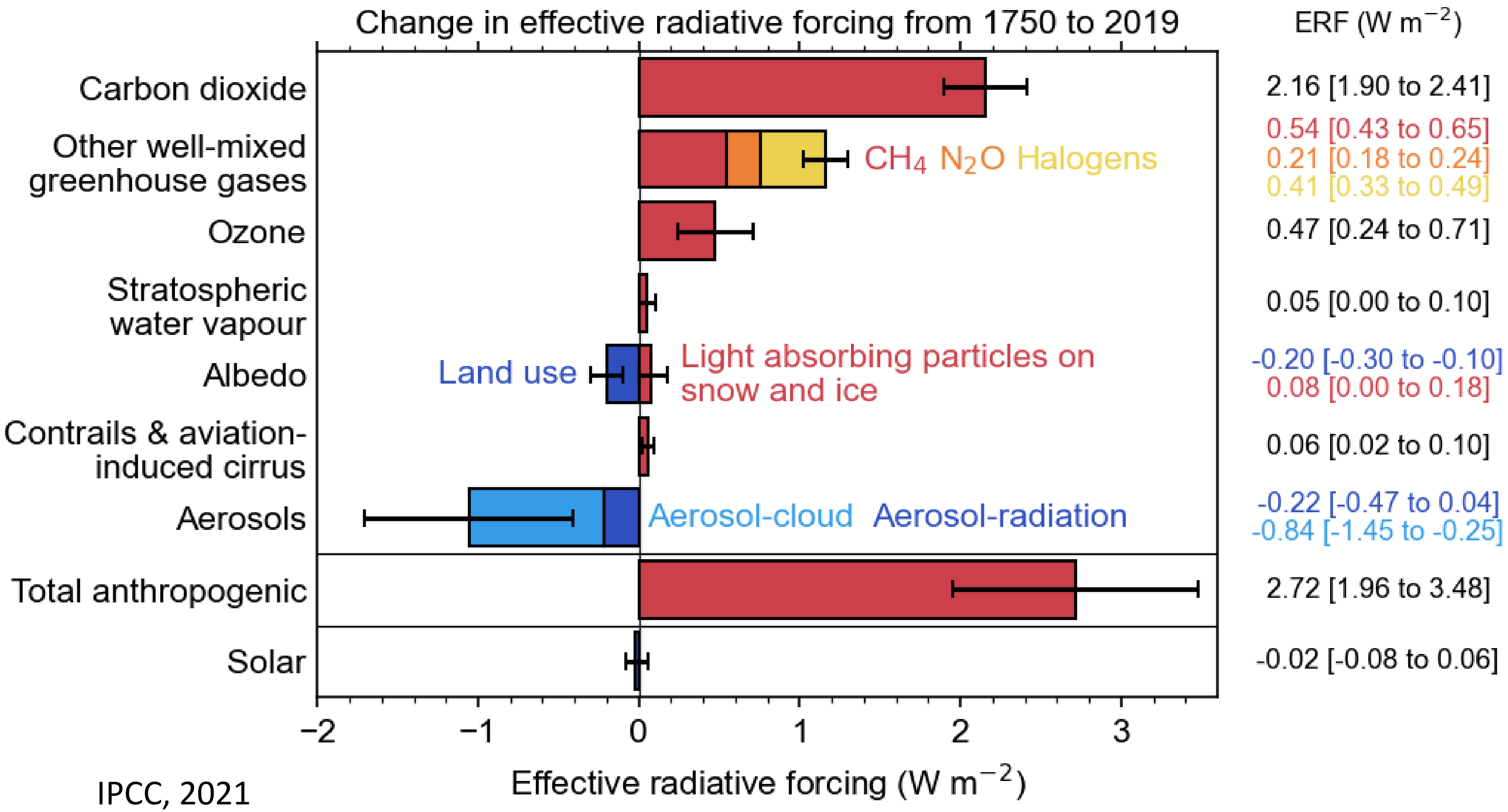


IPCC, 2021

# Effective Radiative Forcing

**What is ERF?**

**[Concentration based]**

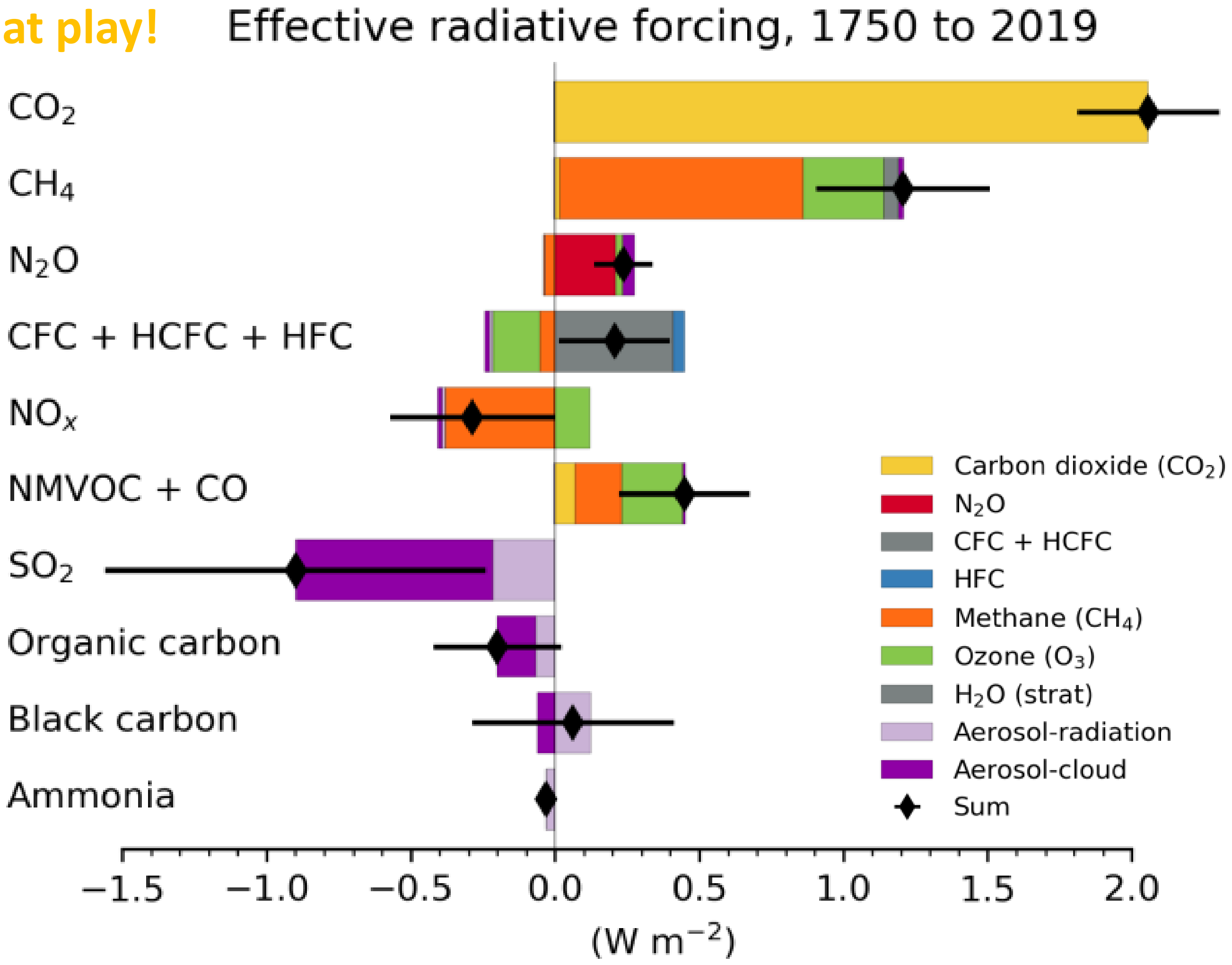


IPCC, 2021

# Effective Radiative Forcing

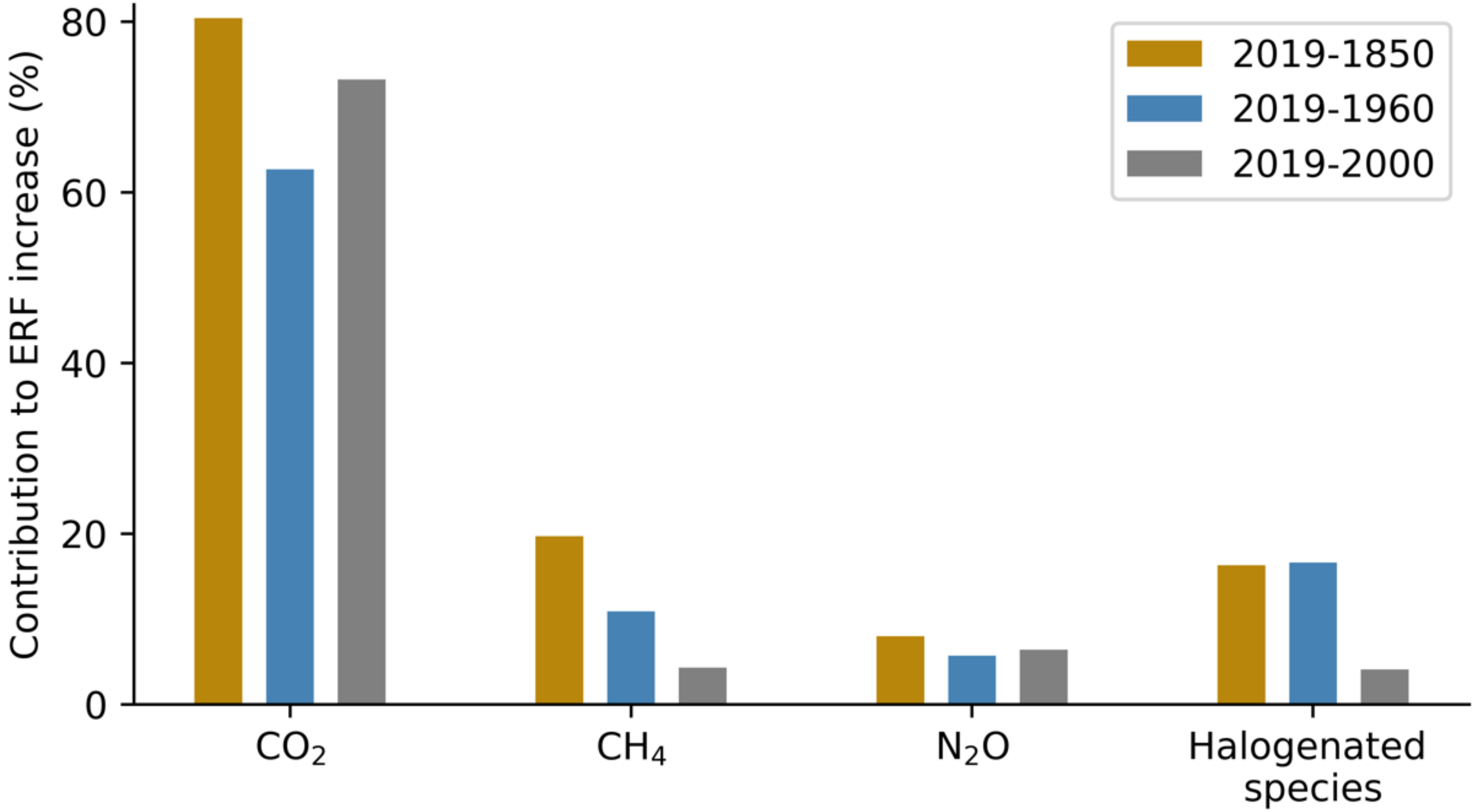
**Climate-chemistry interactions at play!**

**[Emission based]**



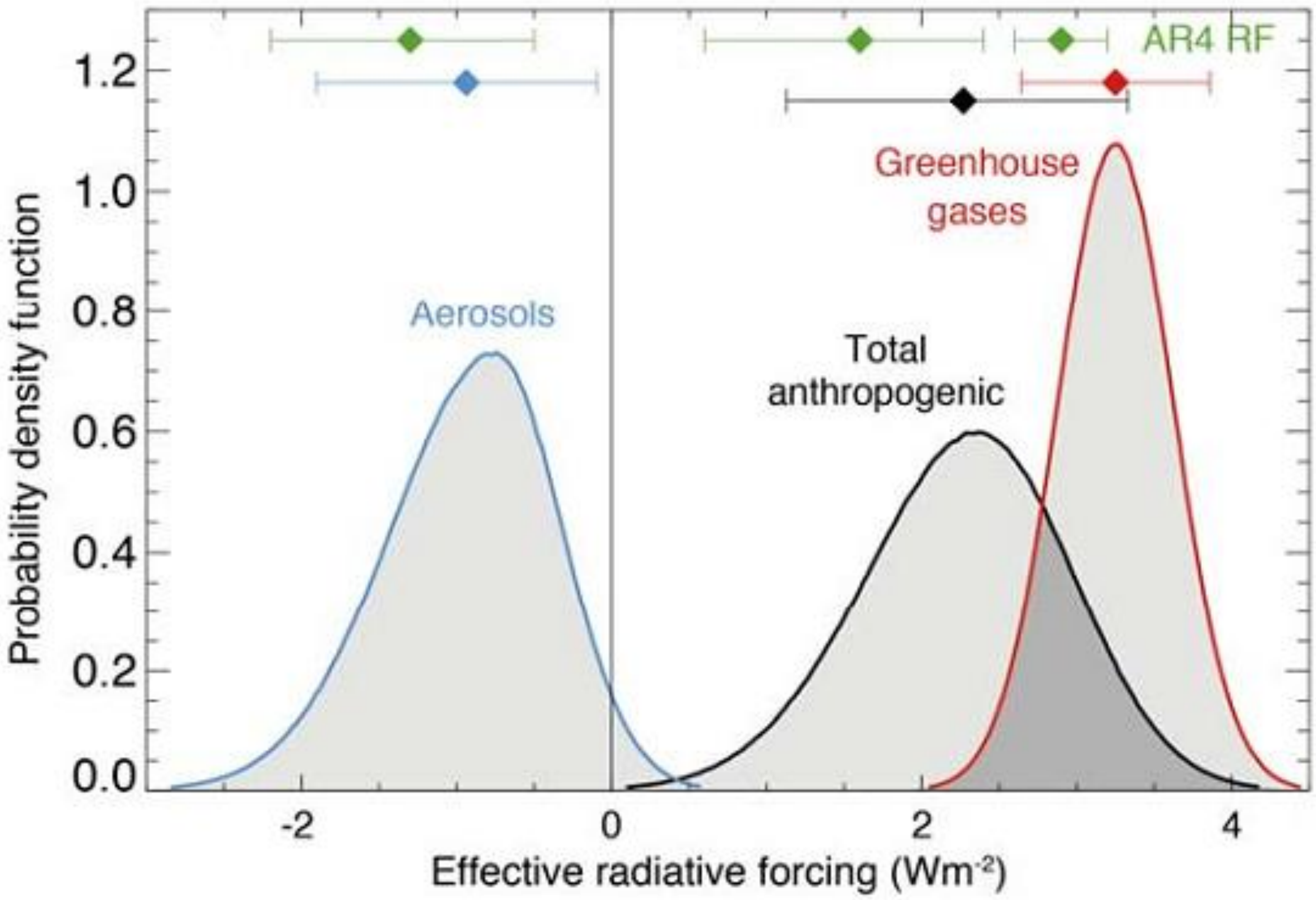
IPCC, 2021

# Contributions of Long-lived GHGs to Total ERF



IPCC, 2013

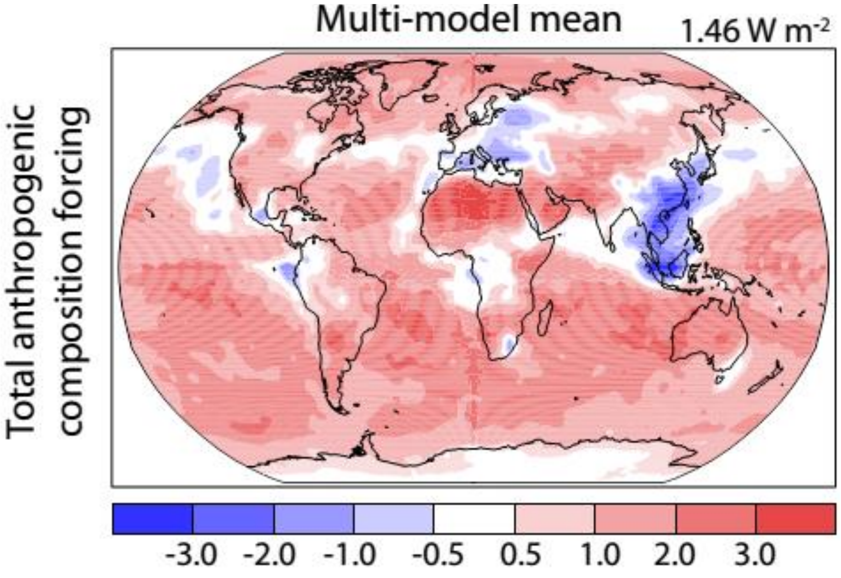
# Effective Radiative Forcing



IPCC, 2013

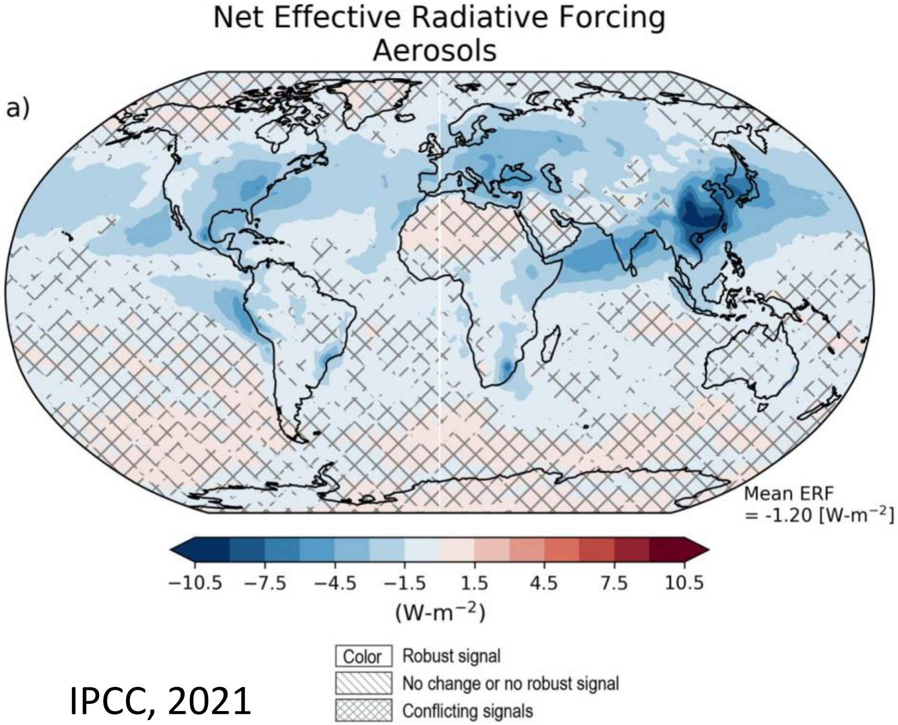
# Radiative Forcing: Spatial Distribution

**Total RF: 1850–2000**



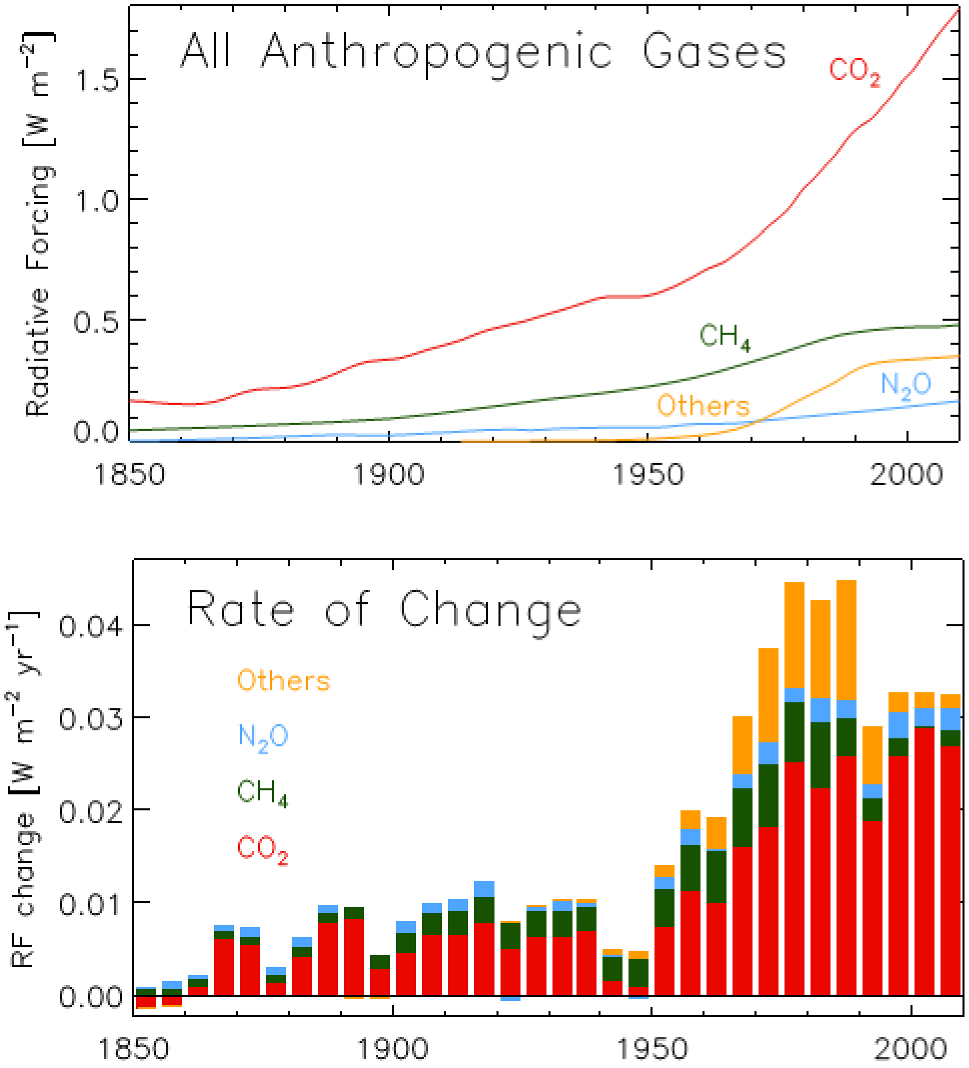
IPCC, 2013

**Aerosol ERF: 1850–[1995-2014 mean]**



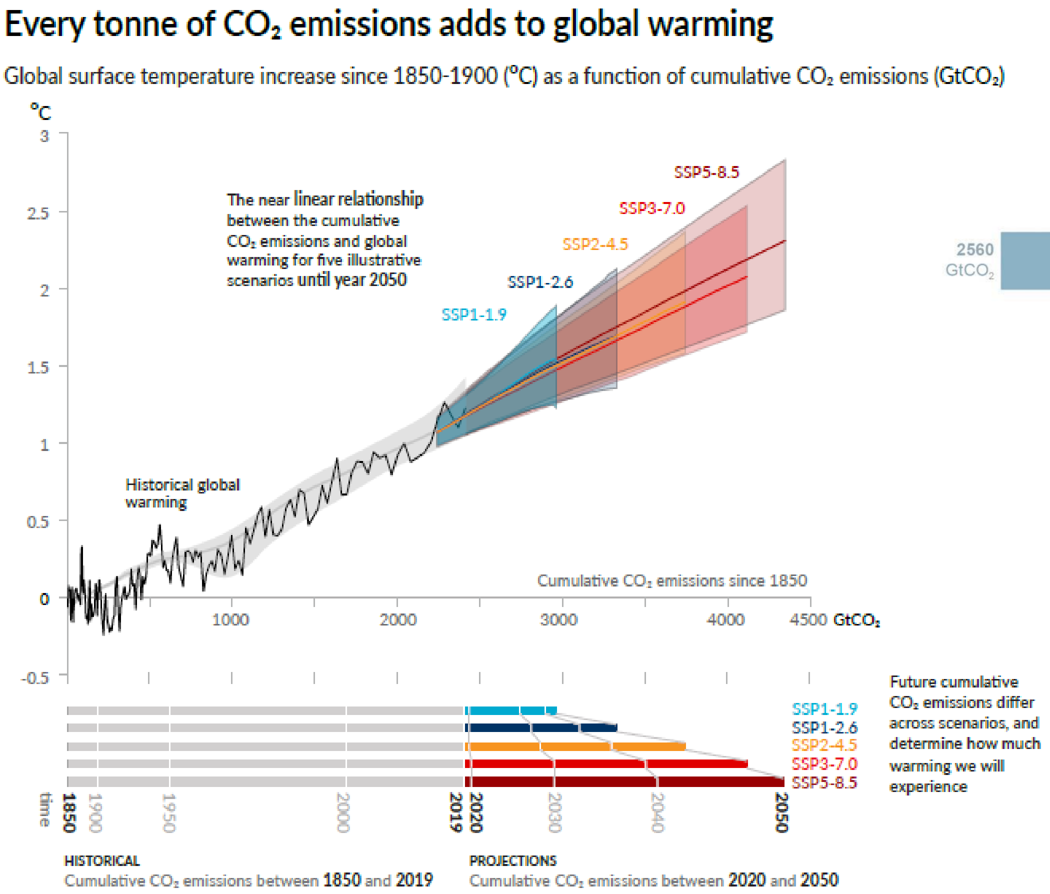
IPCC, 2021

# Trends in Long-lived GHG Radiative Forcing

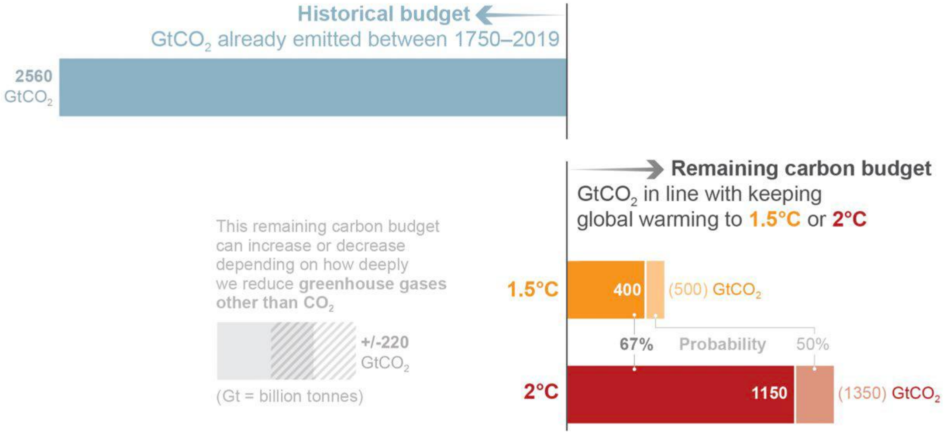


IPCC, 2013

# Cumulative $CO_2$ Emissions and Warming

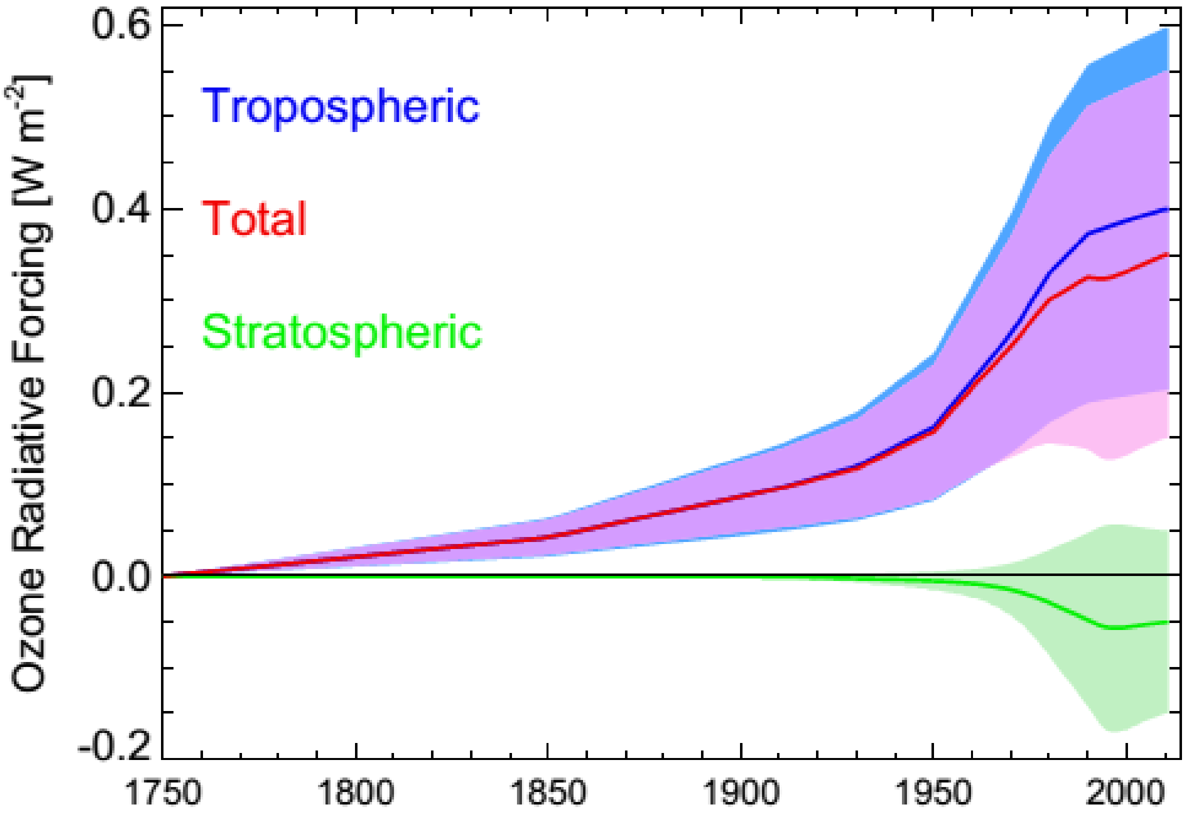


## Carbon budget



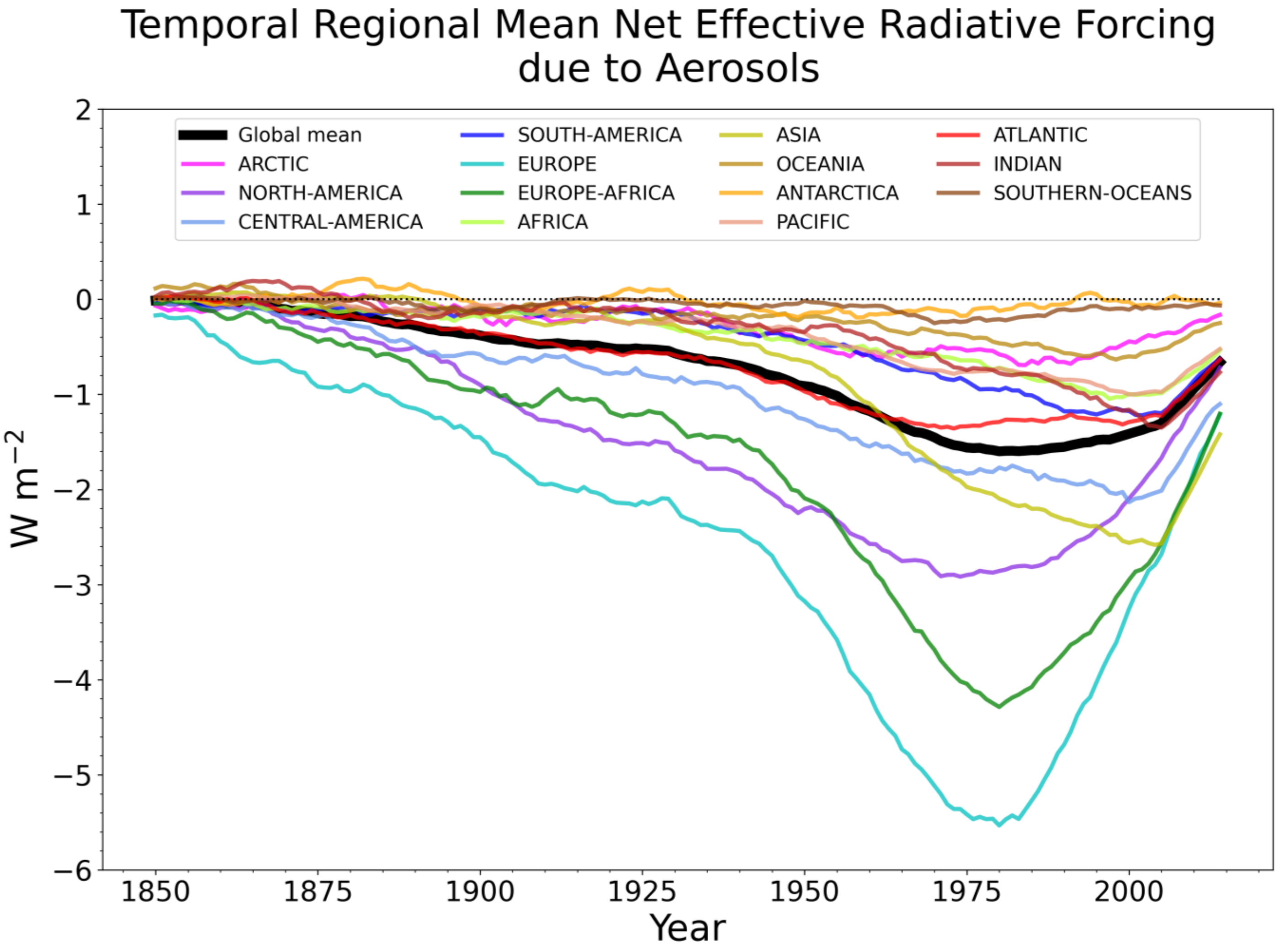
IPCC, 2021

# Ozone Radiative Forcing



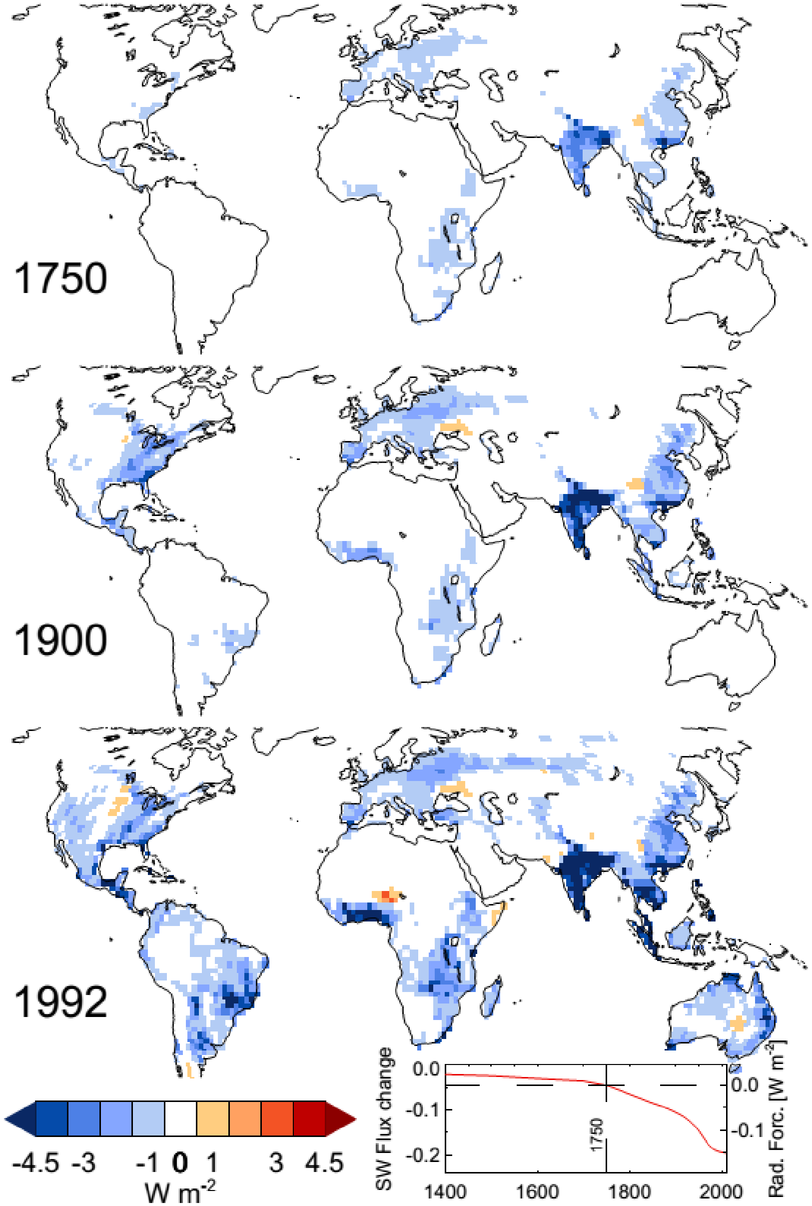
**IPCC, 2013**

# Aerosol Effective Radiative Forcing



IPCC, 2021

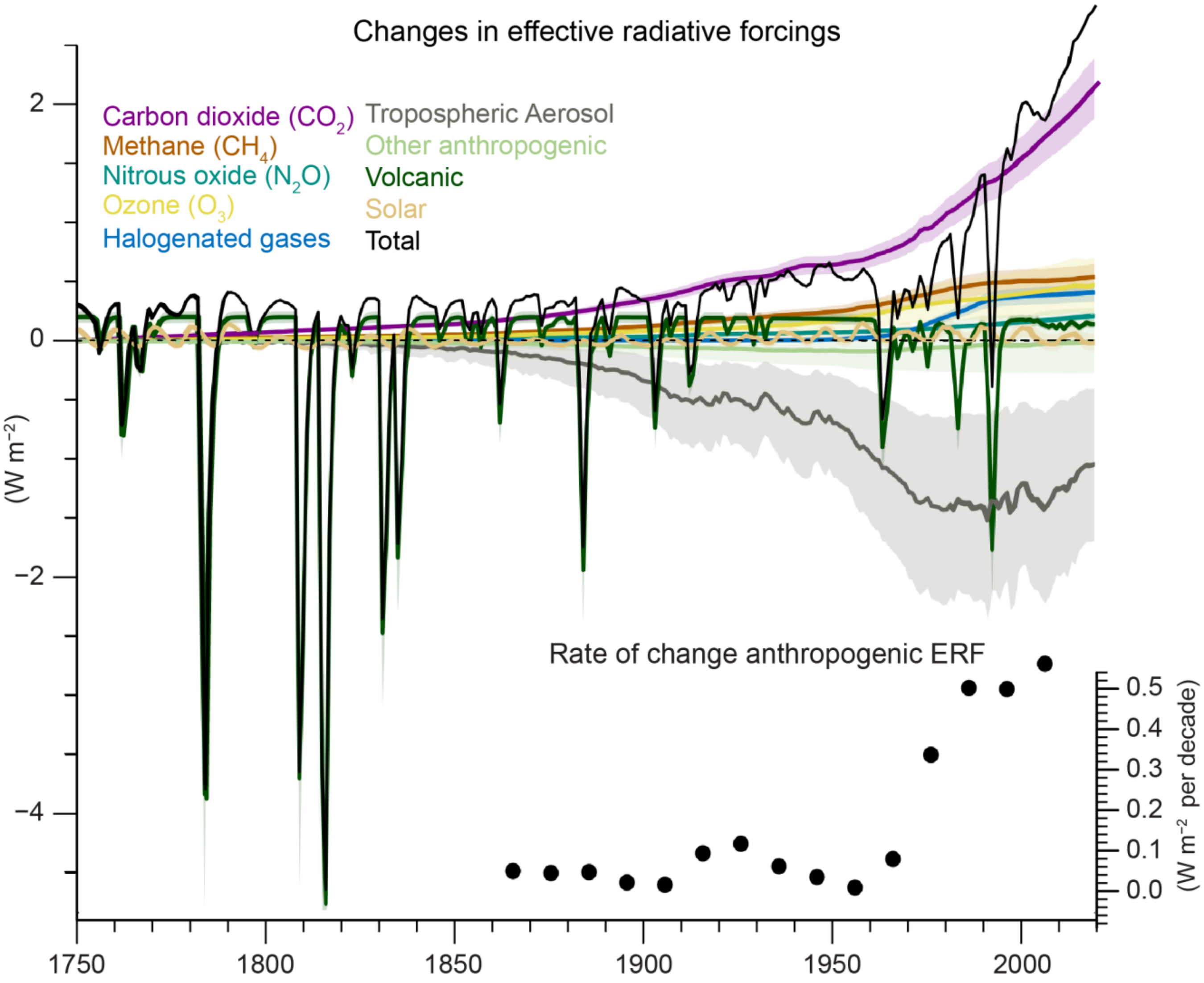
# LUC-related Surface Albedo Radiative Forcing



**Effects already occurred in 1750**

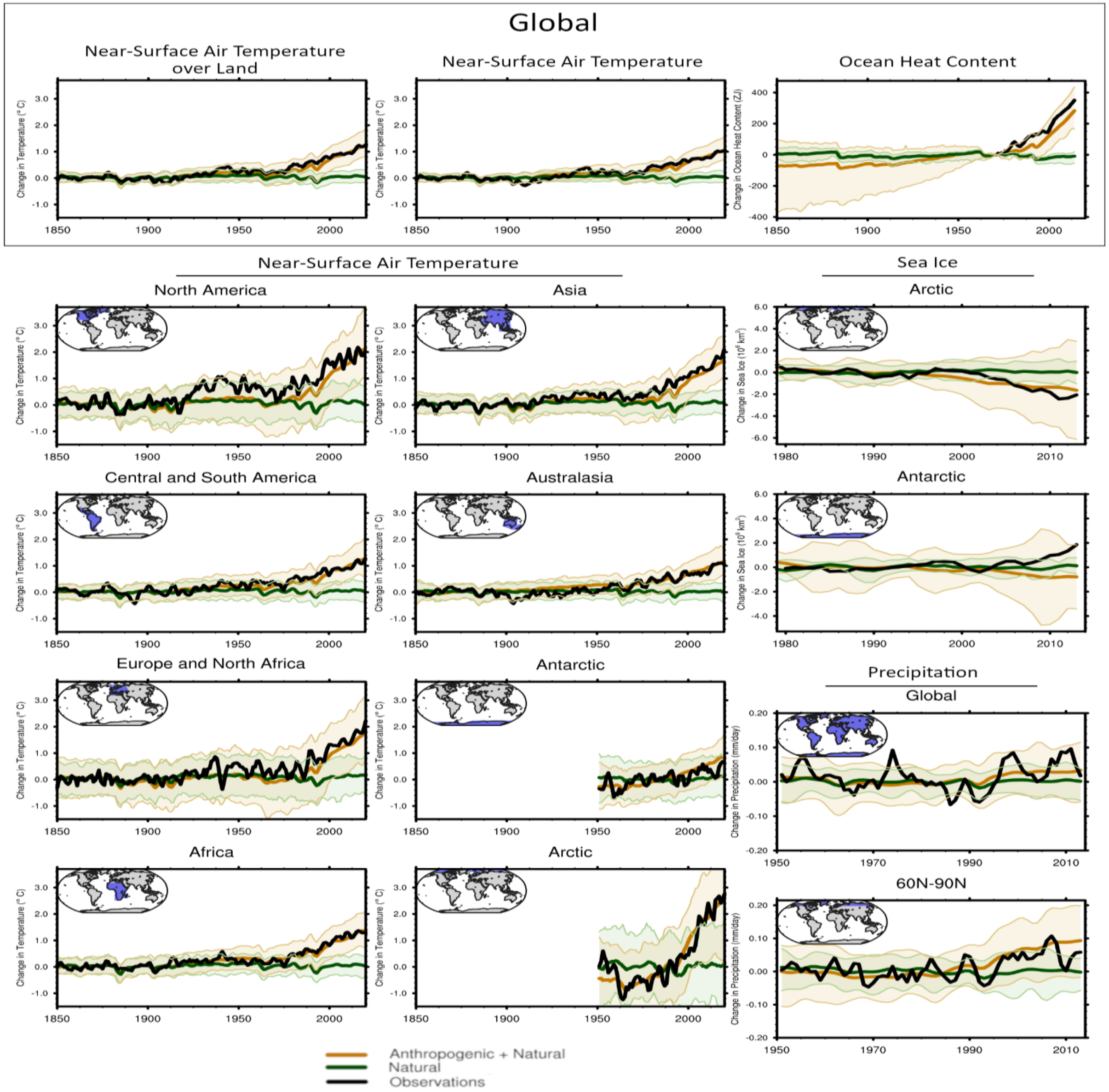
IPCC, 2013

# Effective Radiative Forcing



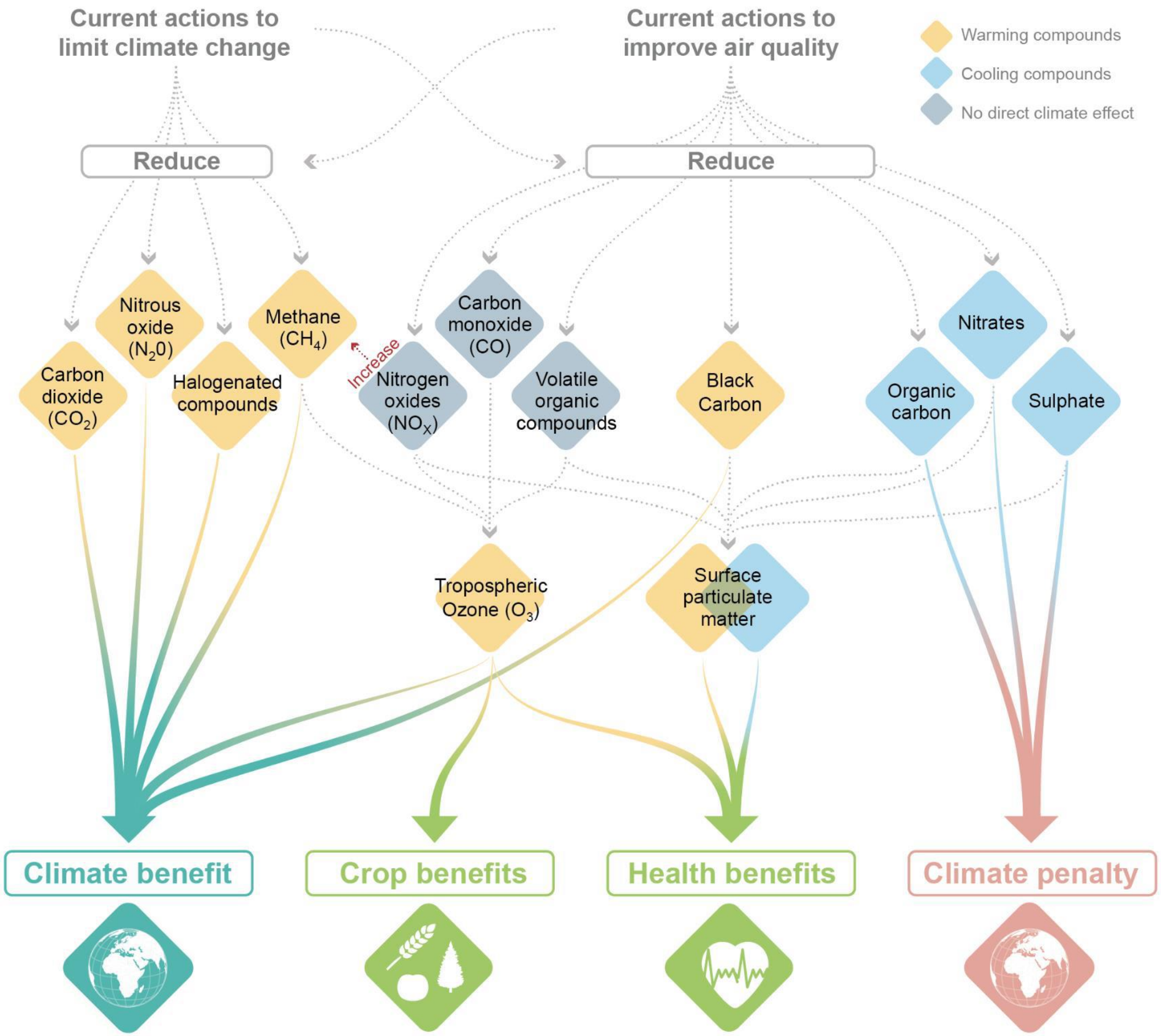
IPCC, 2021

# Modeled Anthropogenic versus Natural Impacts



IPCC, 2021

# Effects of Pollution Control on Climate: Climate-Pollution Nexus



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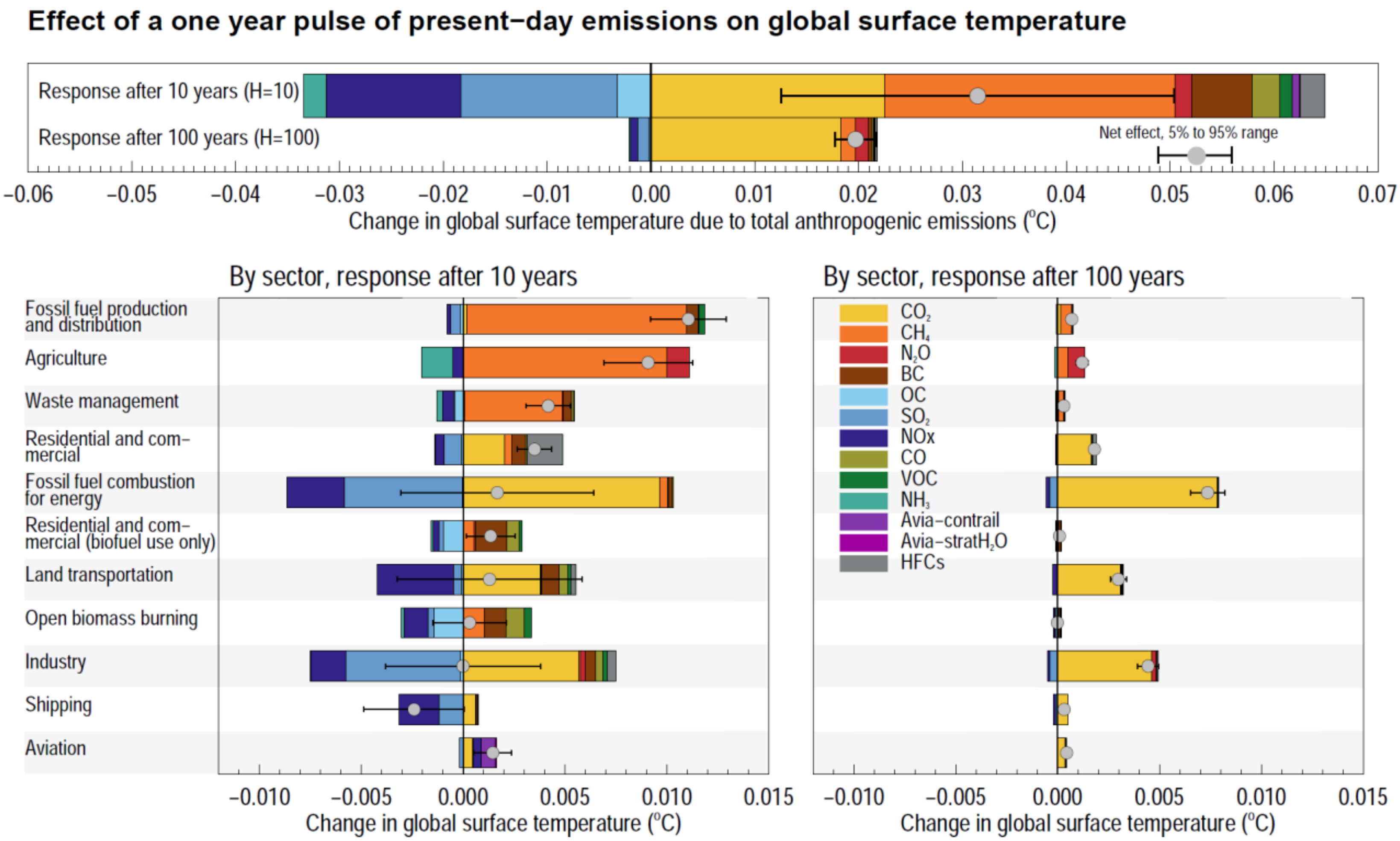
# Temperature Response to Perturbed Emissions

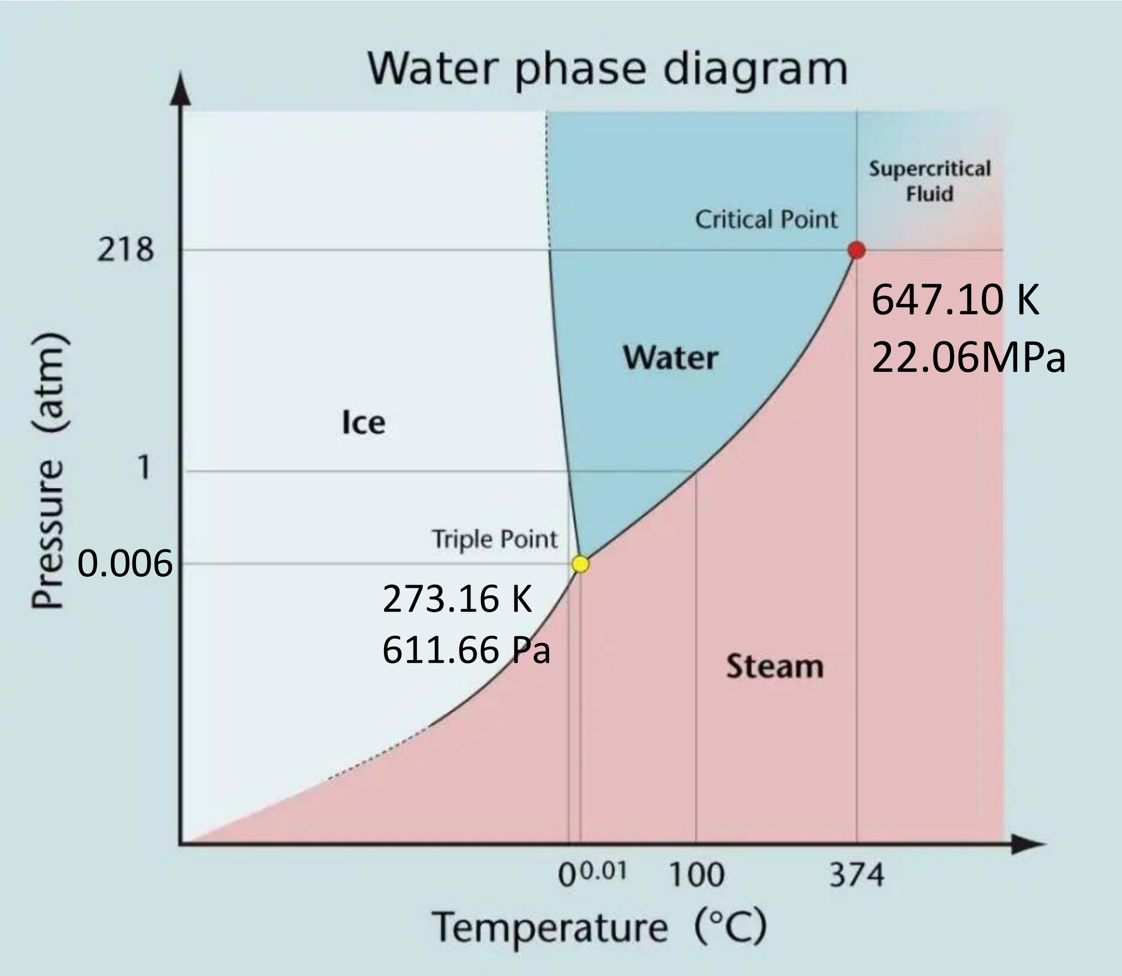


IPCC, 2021

# 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

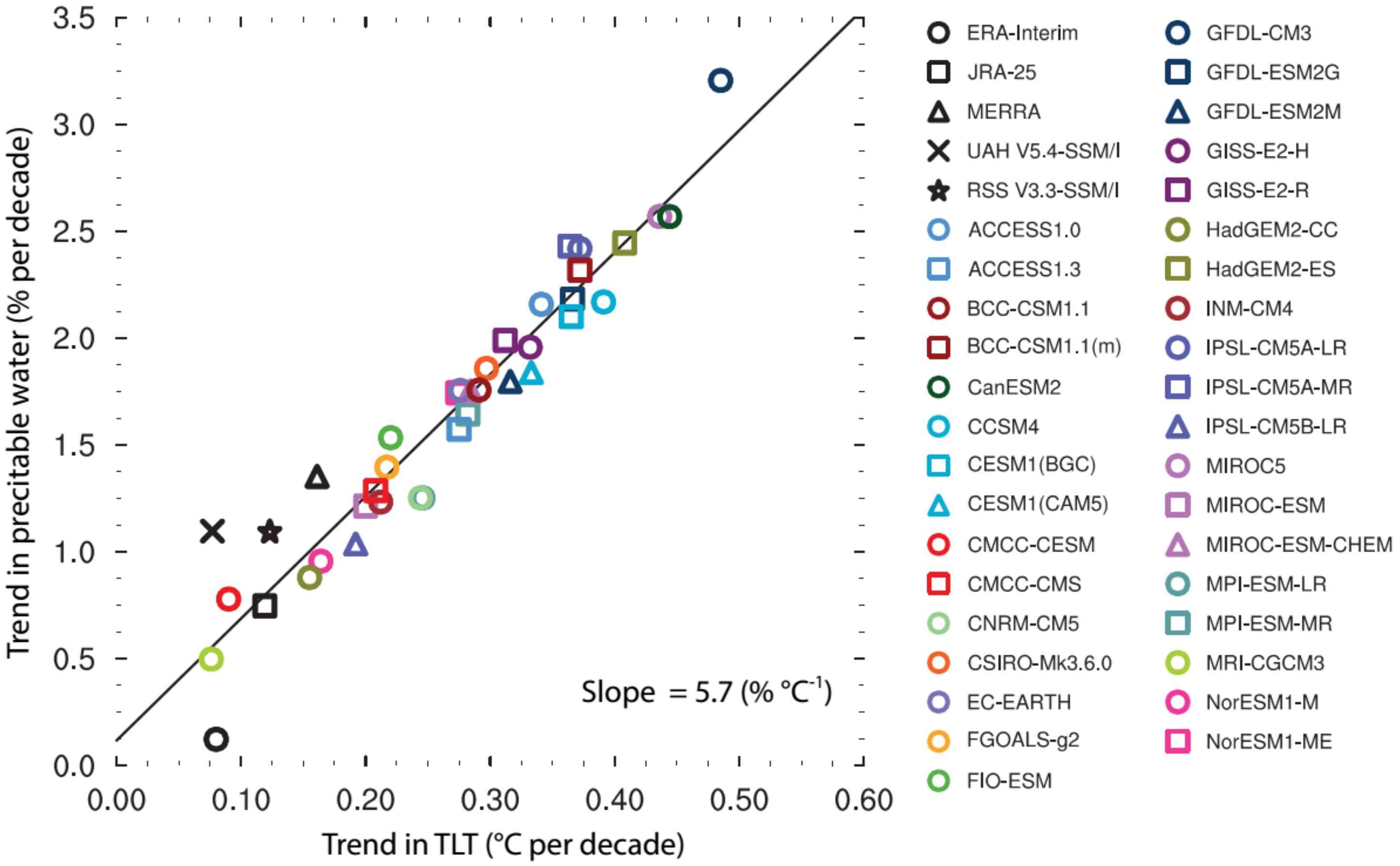


**Clausius–Clapeyron Eq.:**

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

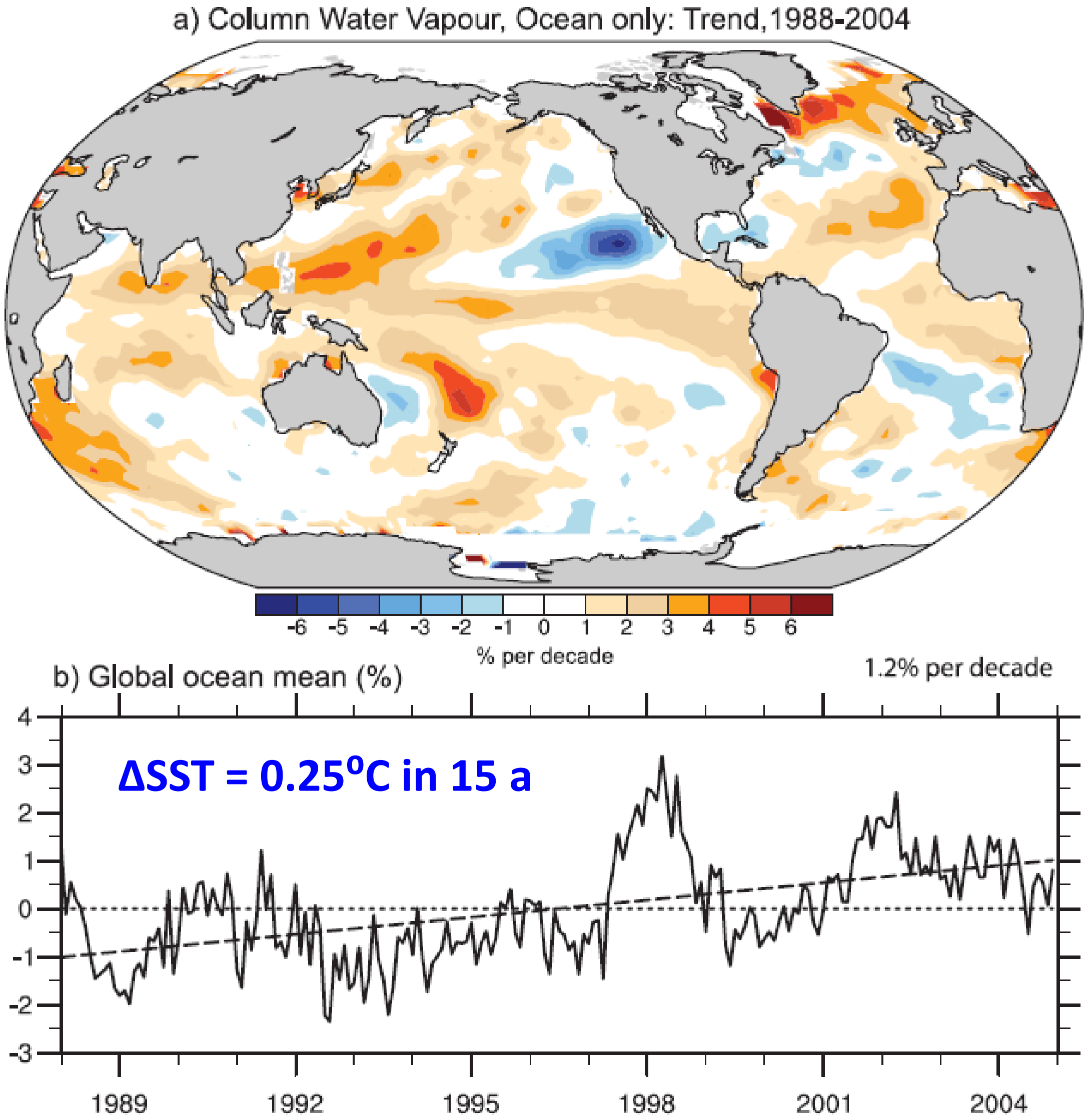
**With constant RH** $\mathbf{T} \uparrow \rightarrow \mathbf{H_2O} \uparrow \rightarrow$ **GH effect** $\uparrow \rightarrow \mathbf{T} \uparrow$

# Water Vapor Increase Driven by Warming



IPCC, 2013

# Water Vapor Change: 1988-2004

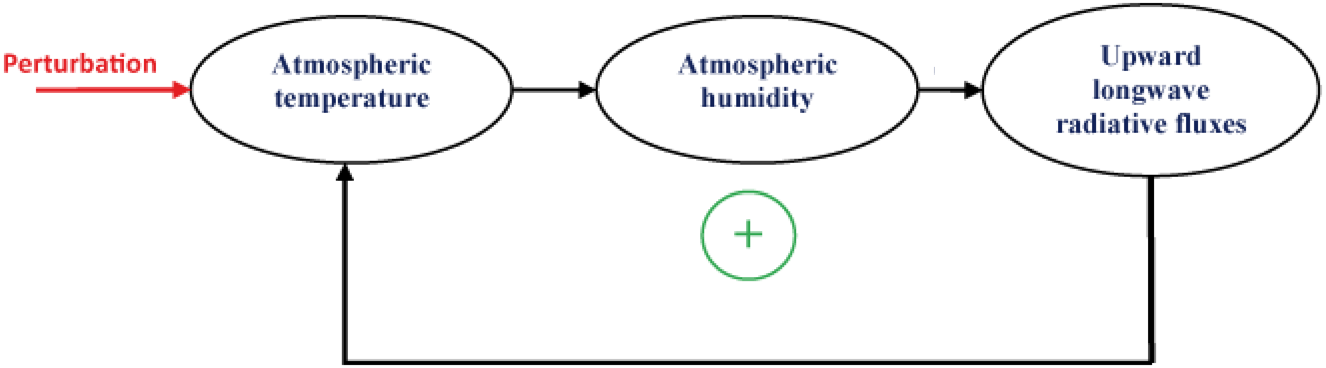


ΔSST = 0.25°C in 15 a

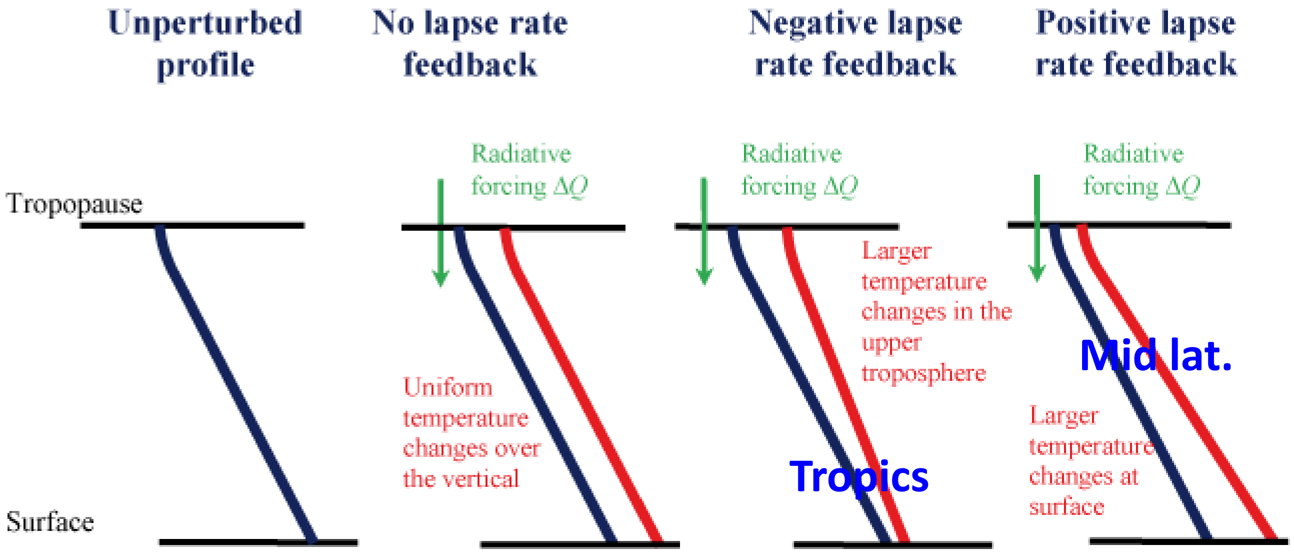
IPCC, 2007

# Water Vapor – Lapse Rate Feedback

**Water vapor feedback**



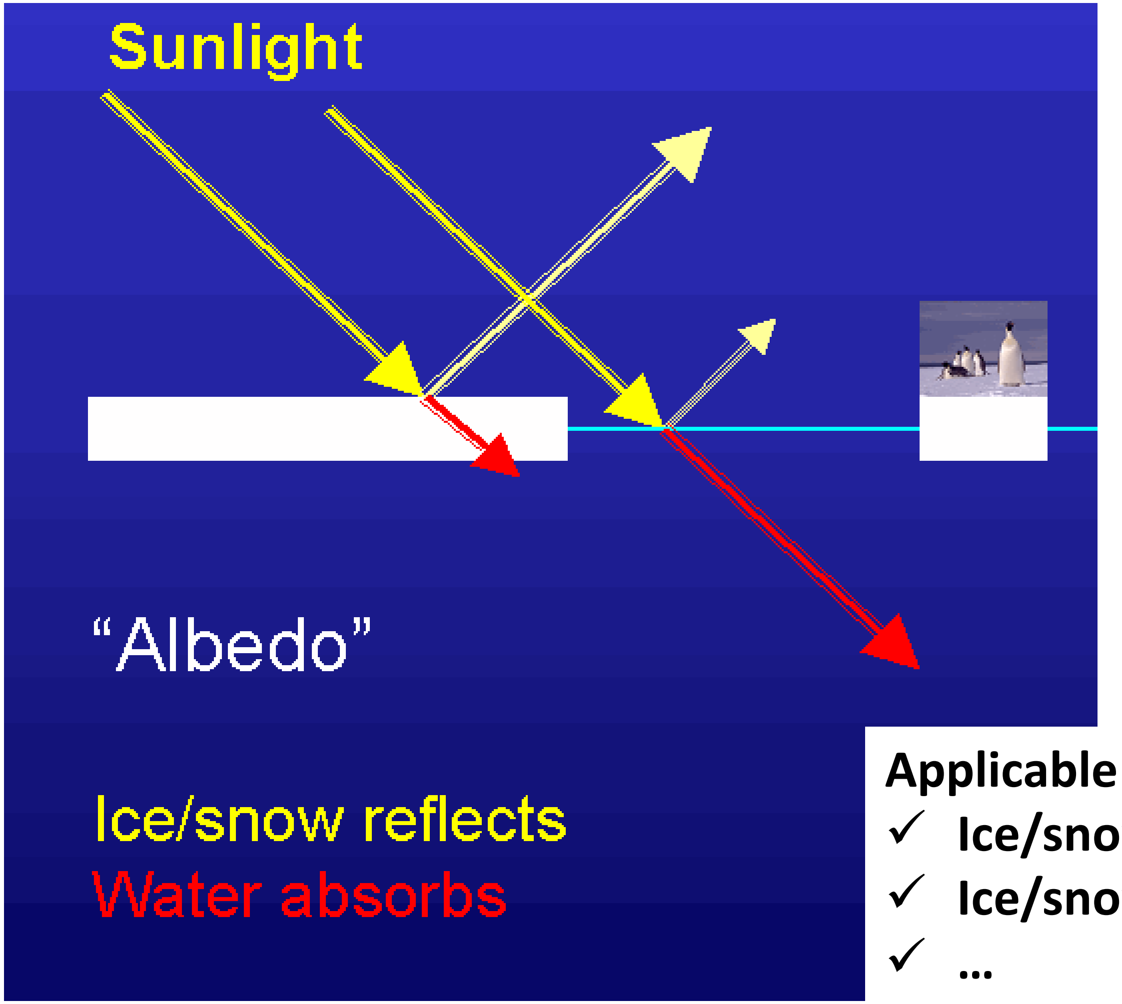
**Lapse rate feedback**



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

IPCC, 2007

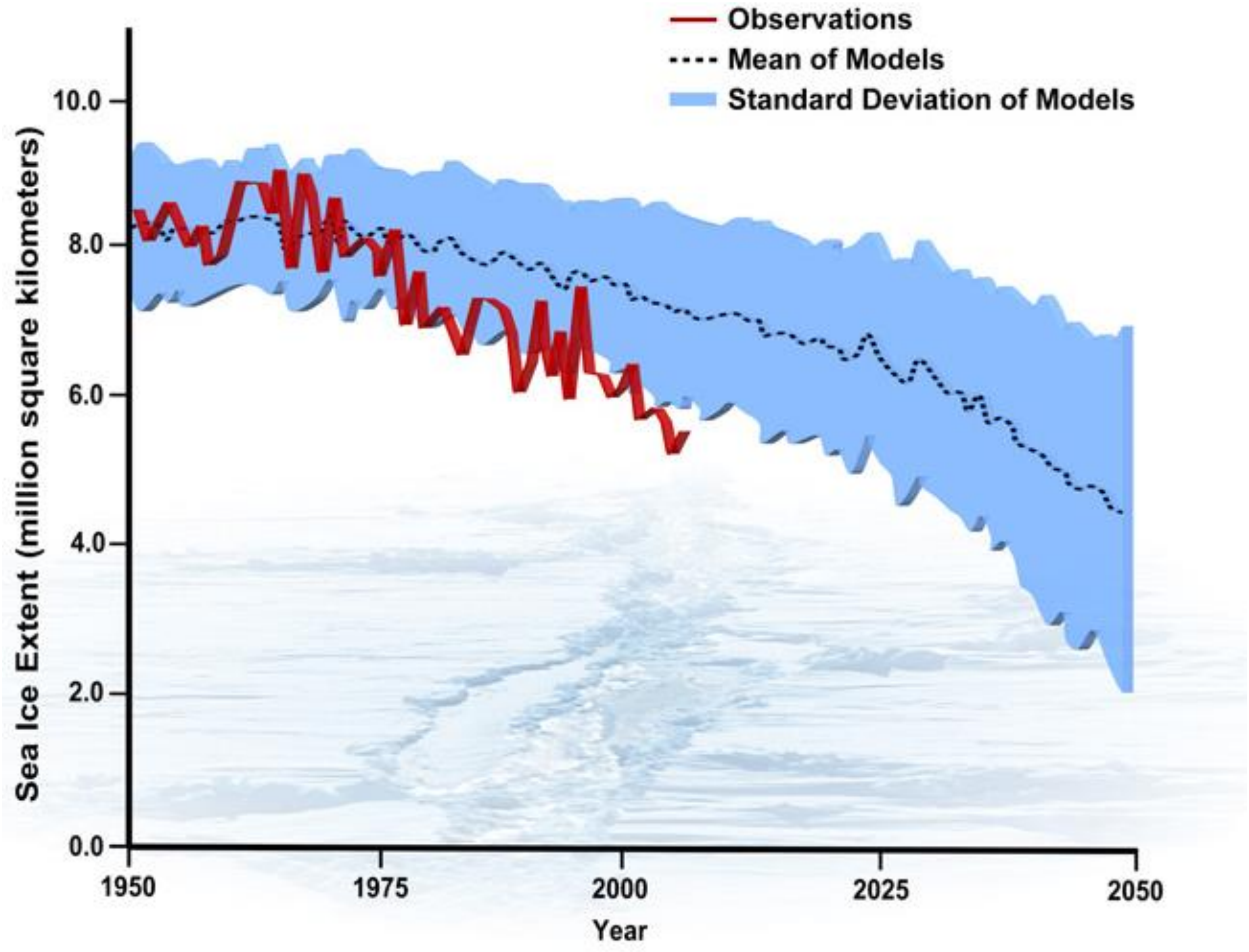
# Ice Albedo Feedback



**Applicable to:**
- ✓ Ice/snow vs. water
- ✓ Ice/snow vs. land/veg.
- ✓ …

**T ↑ => Ice ↓ => Albedo ↓ => T ↑**

# Changes in Polar Ice



Stroeve et al. [2007]

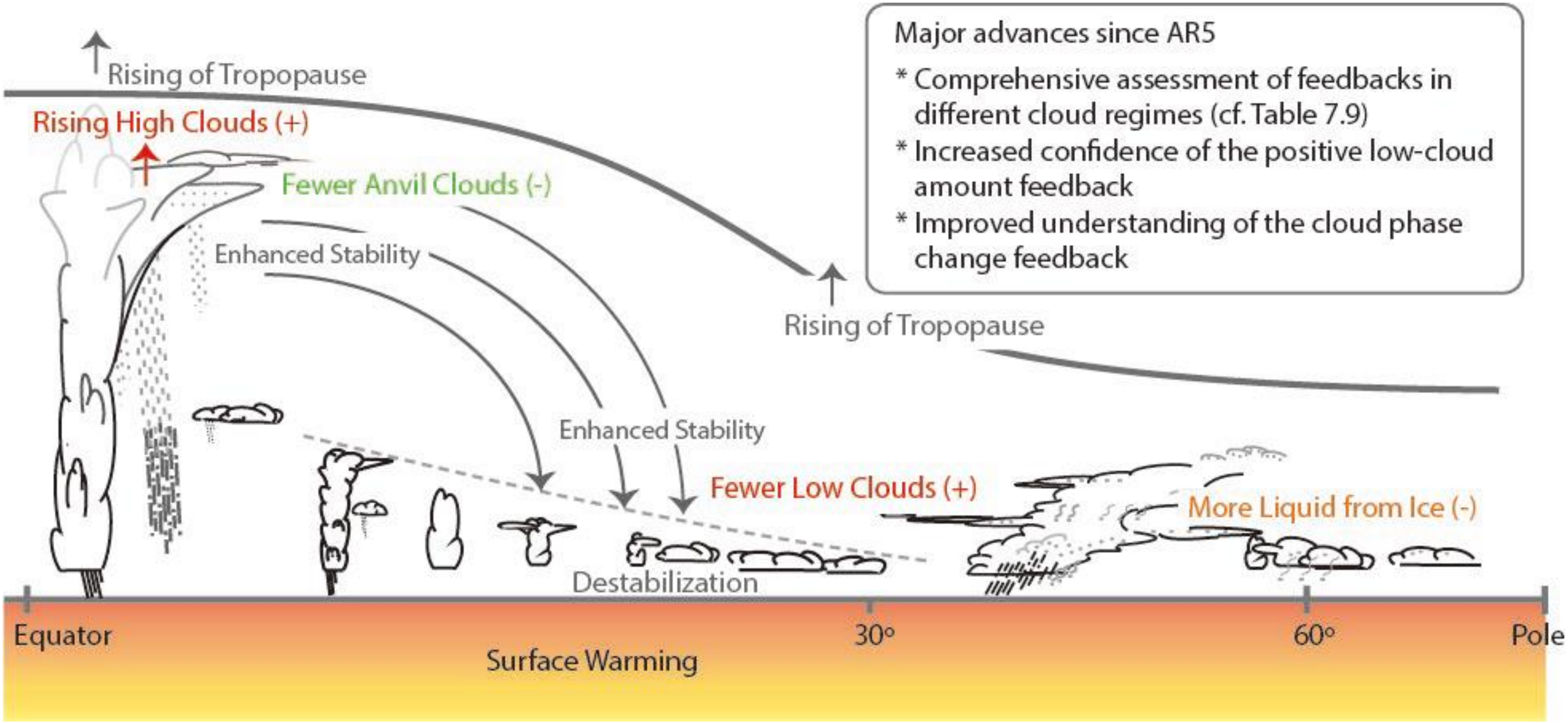
# Cloud Types and Radiative Effects

Changes in CRF are extremely difficult to quantify, leading to large uncertainty in current estimates

- ✓ 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
- ✓ Mid-level clouds: liquid/ice mixed
- ✓ Polar clouds in different seasons?

How to affect clouds: height, fraction, thickness, droplet size, phase (liquid/ice/mixed), lifetime

# Changes in Cloud

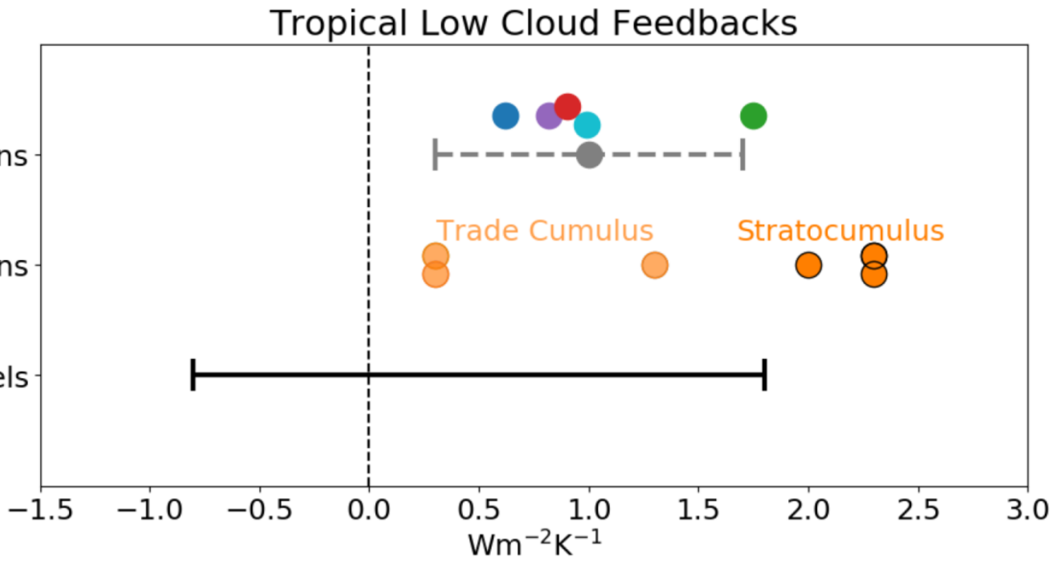


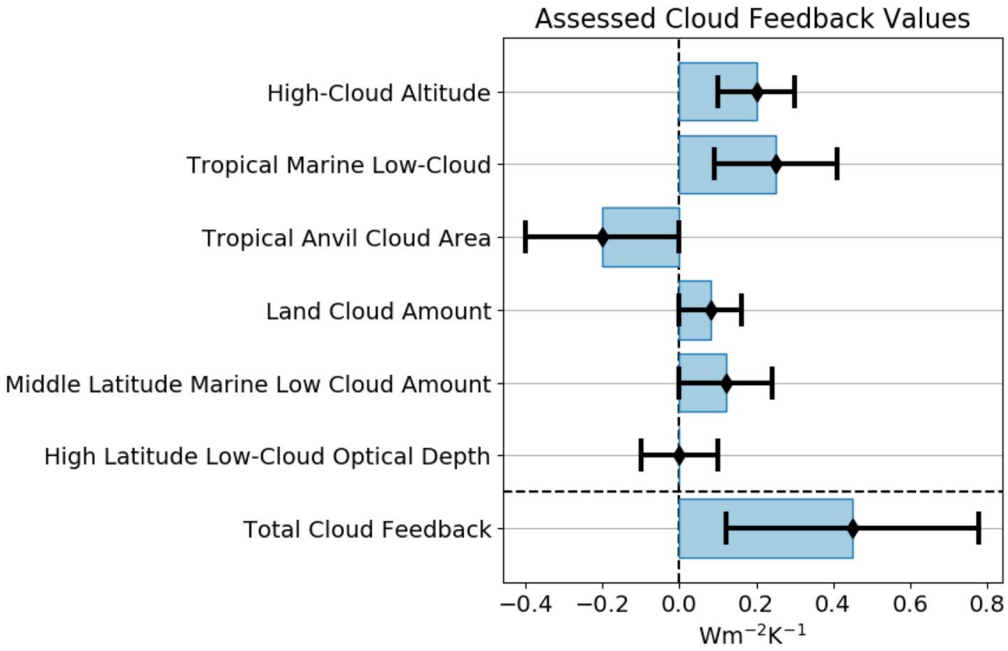
Major advances since AR5

- * Comprehensive assessment of feedbacks in different cloud regimes (cf. Table 7.9)
- * Increased confidence of the positive low-cloud amount feedback
- * Improved understanding of the cloud phase change feedback

IPCC, 2021

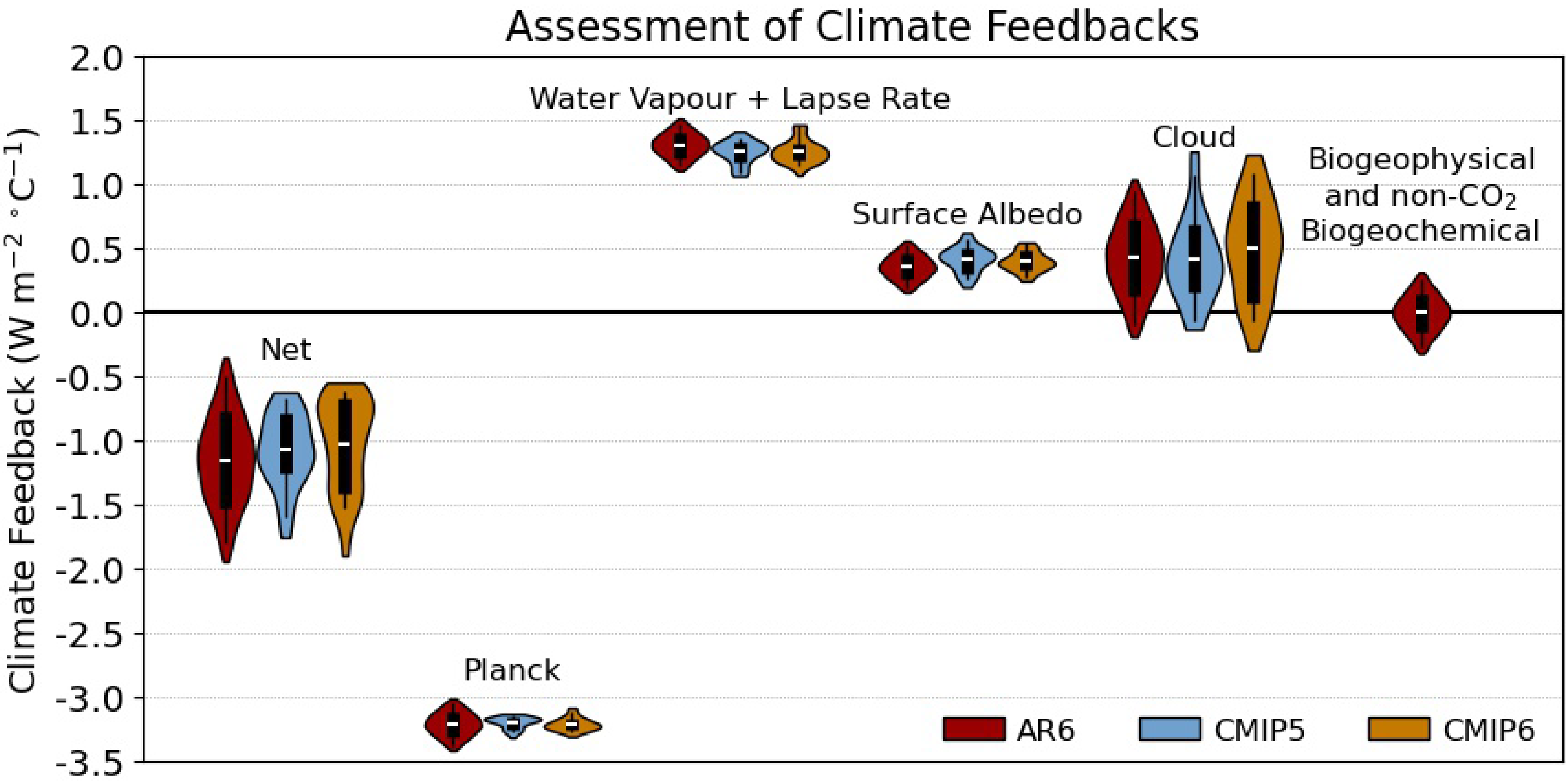
# Cloud Feedbacks





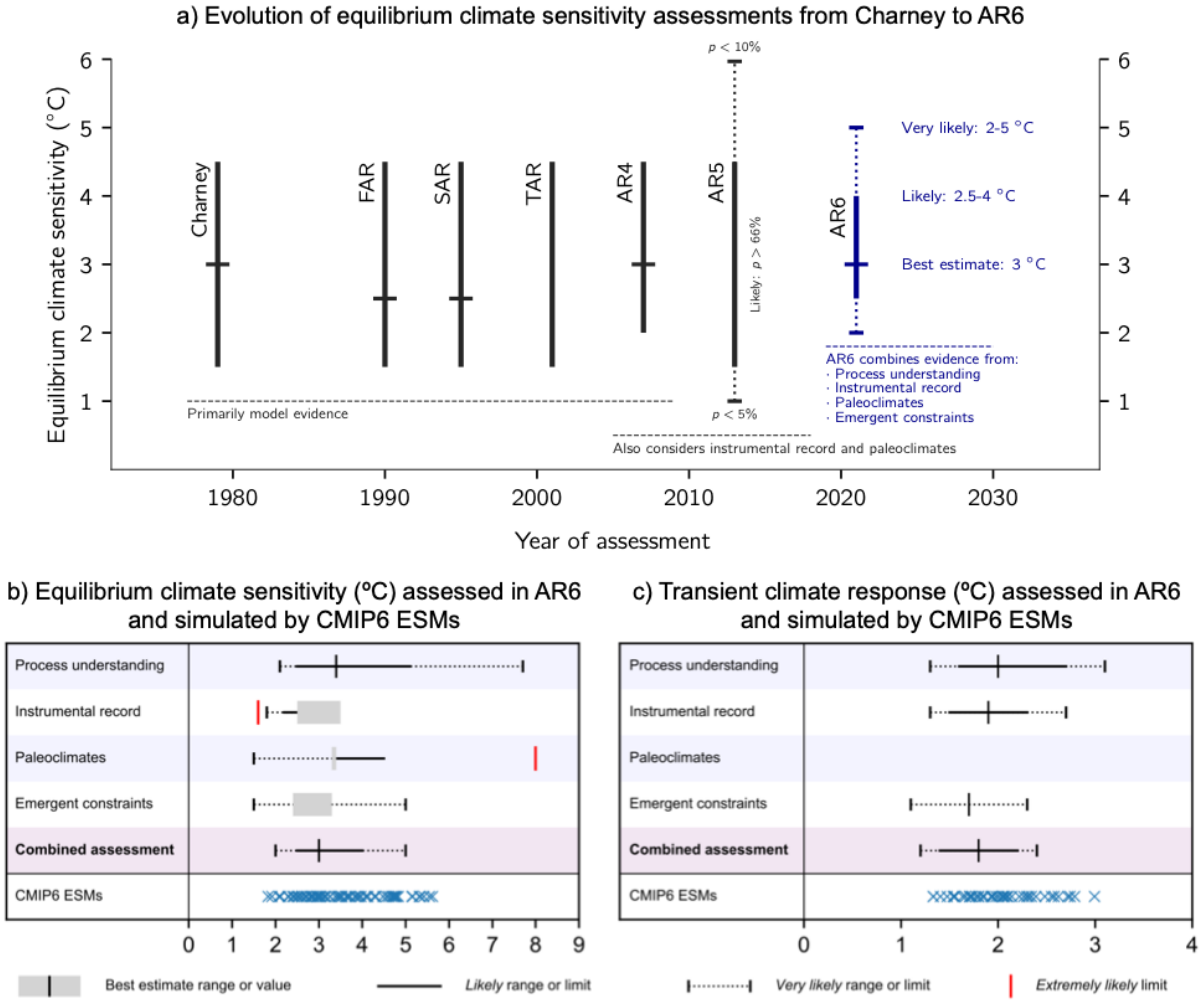
Sherwood et al., 2020 RoG

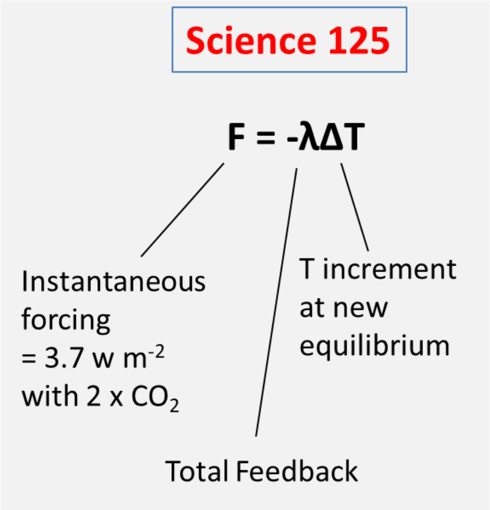
# Summary of Feedbacks



IPCC, 2021

# Climate Sensitivity





**Science 125**

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

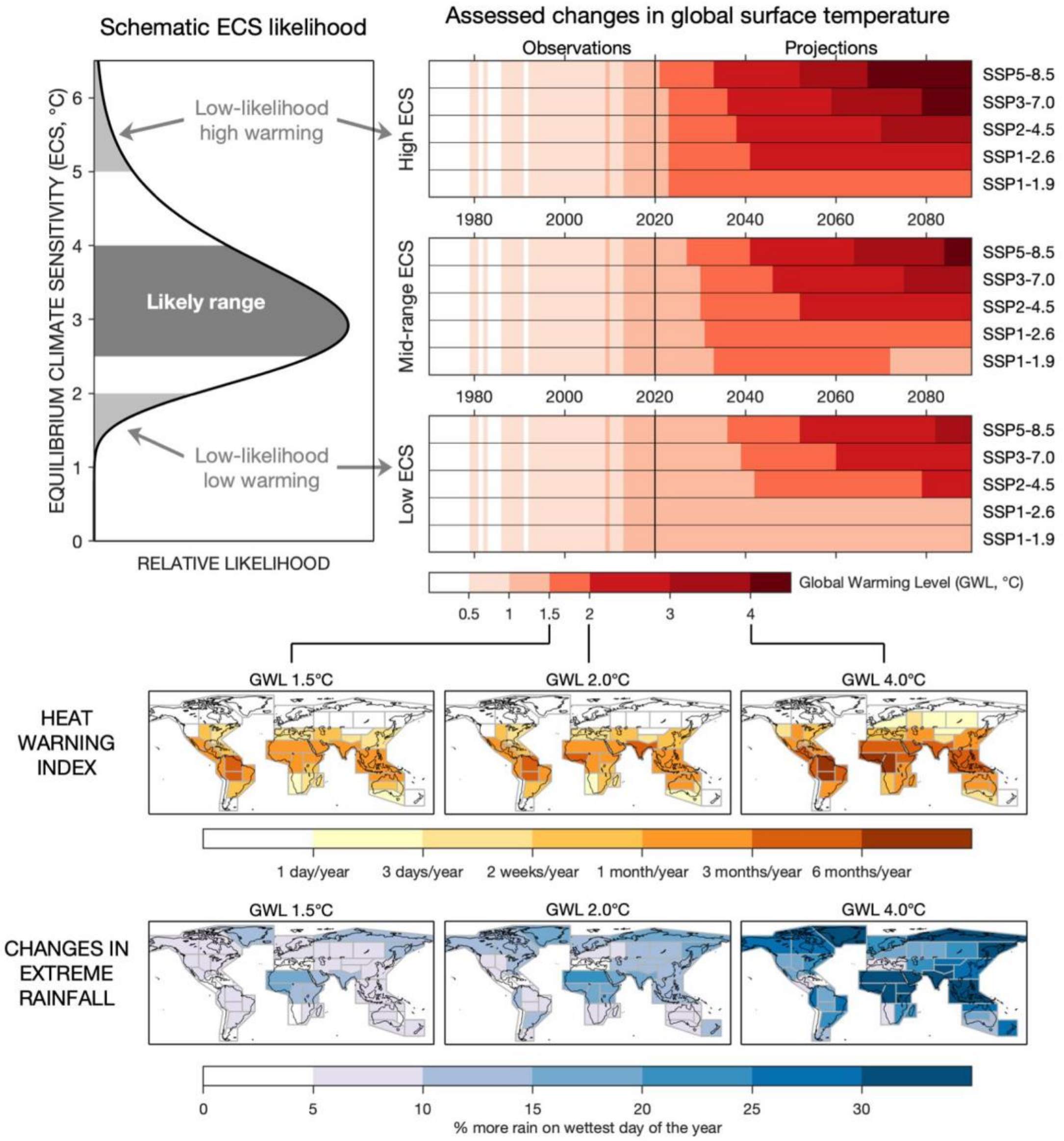
Instantaneous forcing = 3.7 w m$^{-2}$ with 2 x $CO_2$

T increment at new equilibrium

Total Feedback

IPCC, 2021

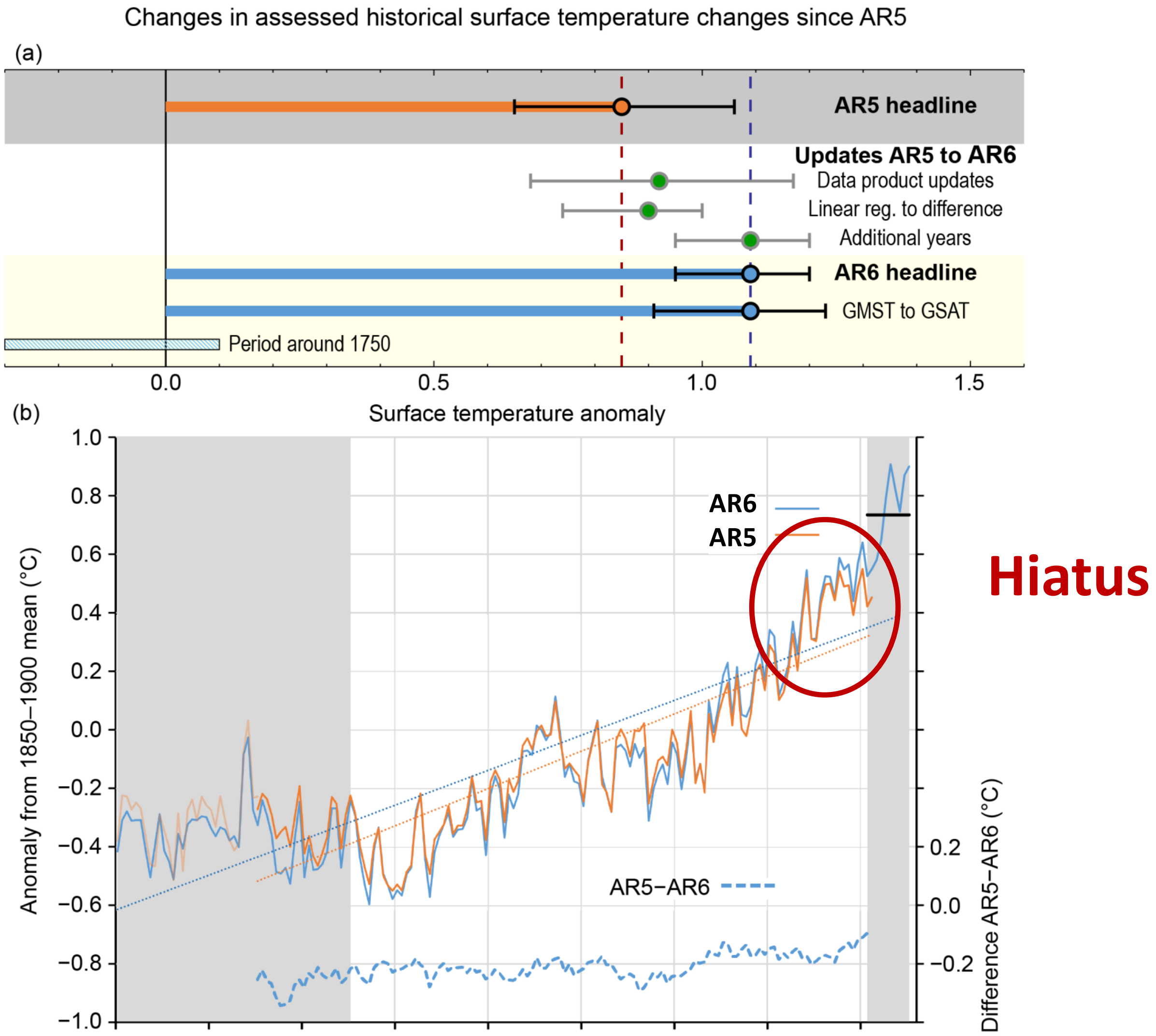
# Climate Sensitivity and Warming



IPCC, 2021

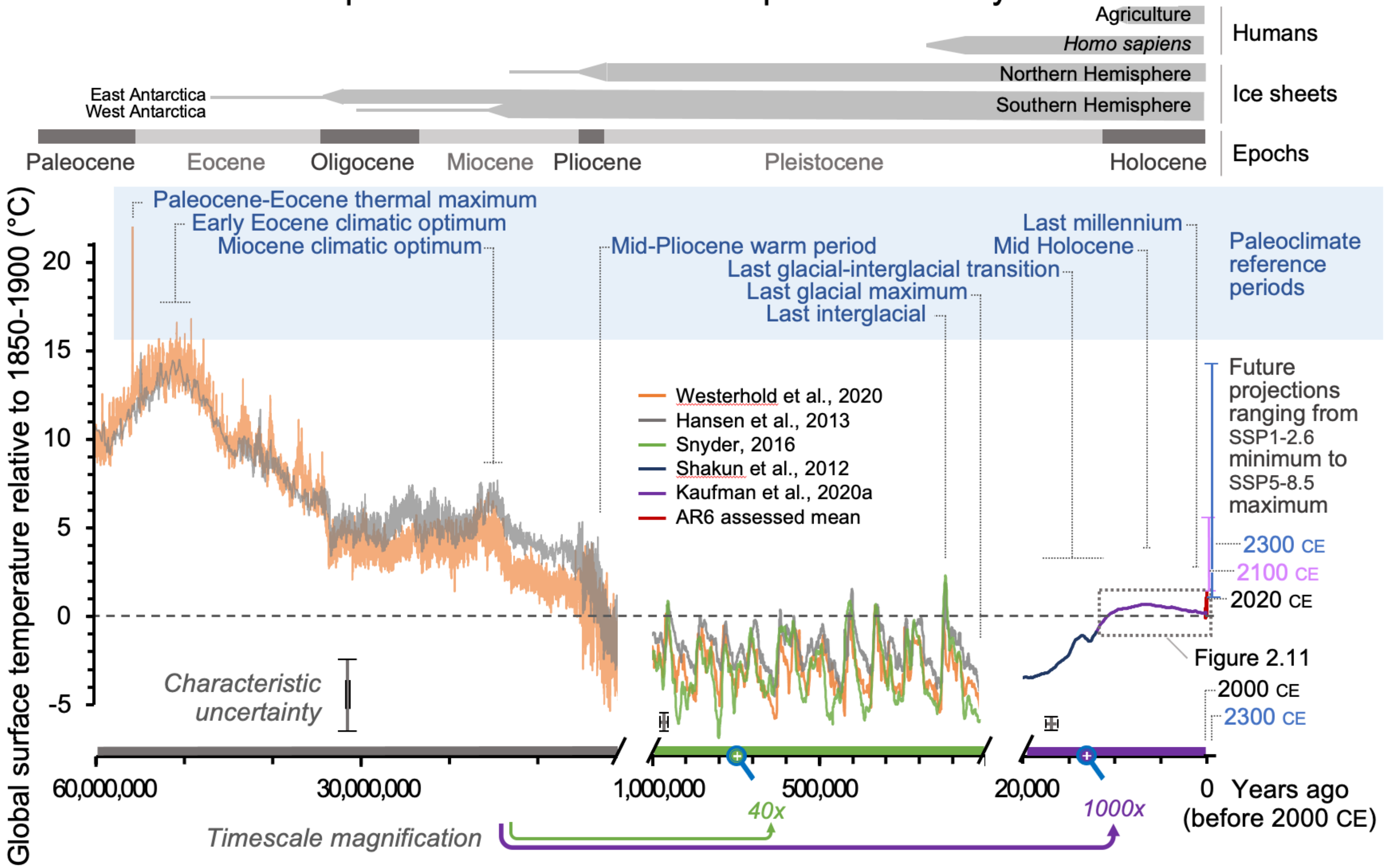
# Past Climate Change

# Global Temperature Anomaly: 1850-2020



IPCC, 2021

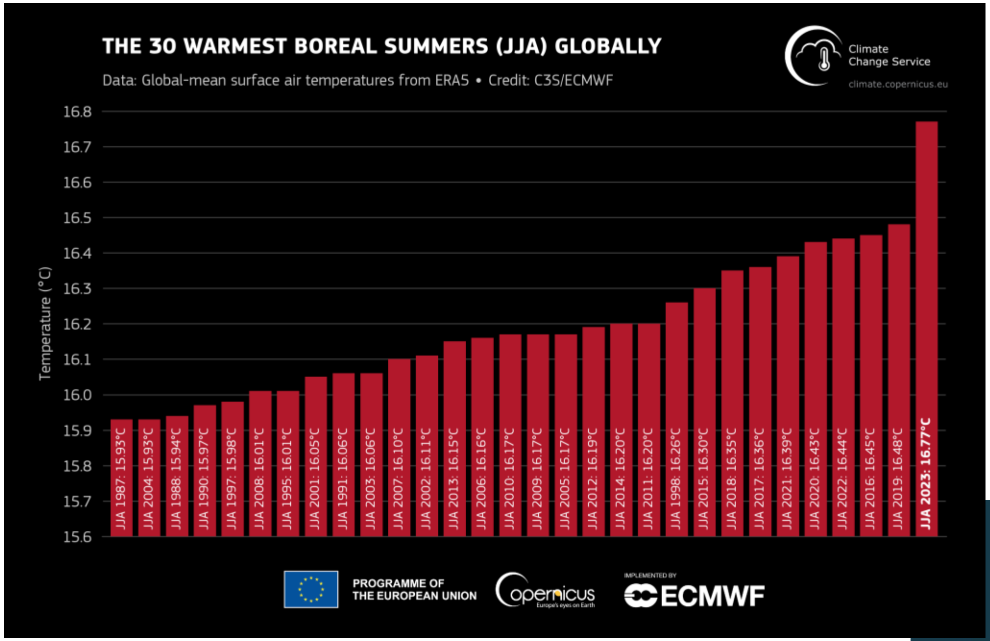
# Global Temperature Evolution


Global temperature evolution over the past 60 million years

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

IPCC, 2021

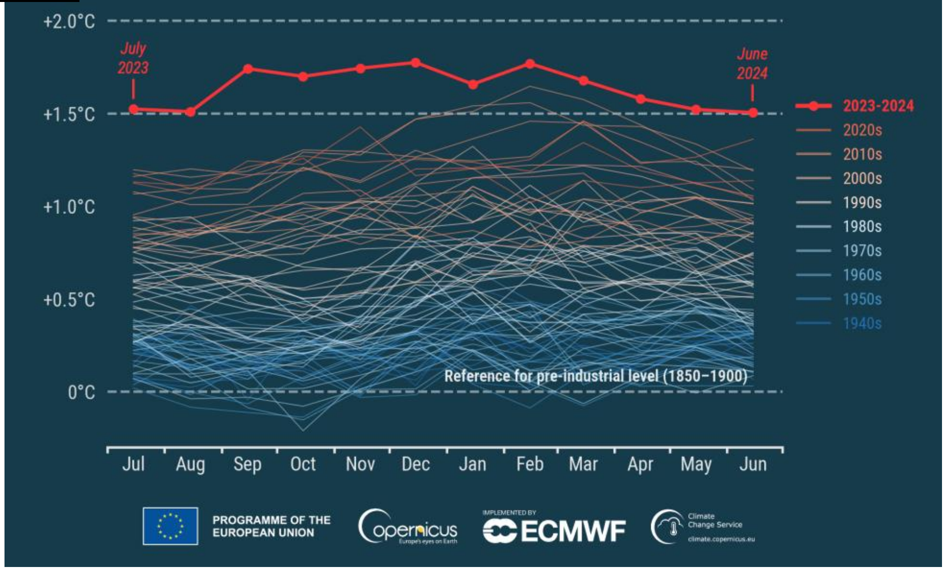
# Global Temperature in 2023 and 2024



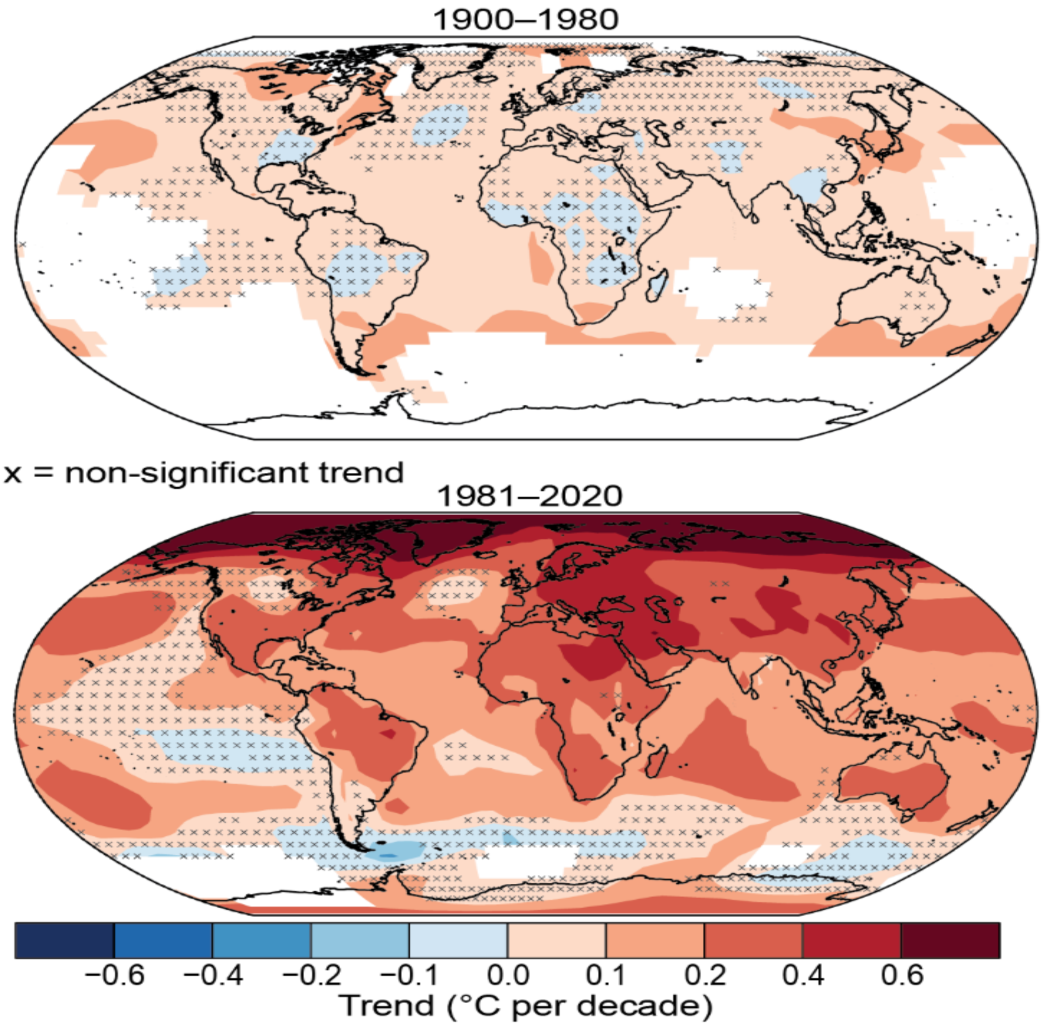
**June 2024 was warmer globally than any previous June in the data record**, with an average ERA5 surface air temperature of 16.66° C, 0.67° C above the 1991-2020 average for June and 0.14° C above the previous high set in June 2023.

**Monthly global surface temperature increase above pre-industrial**

Data: ERA5 1940–2024 • Reference period: 1850-1900 • Credit: C3S/ECMWF



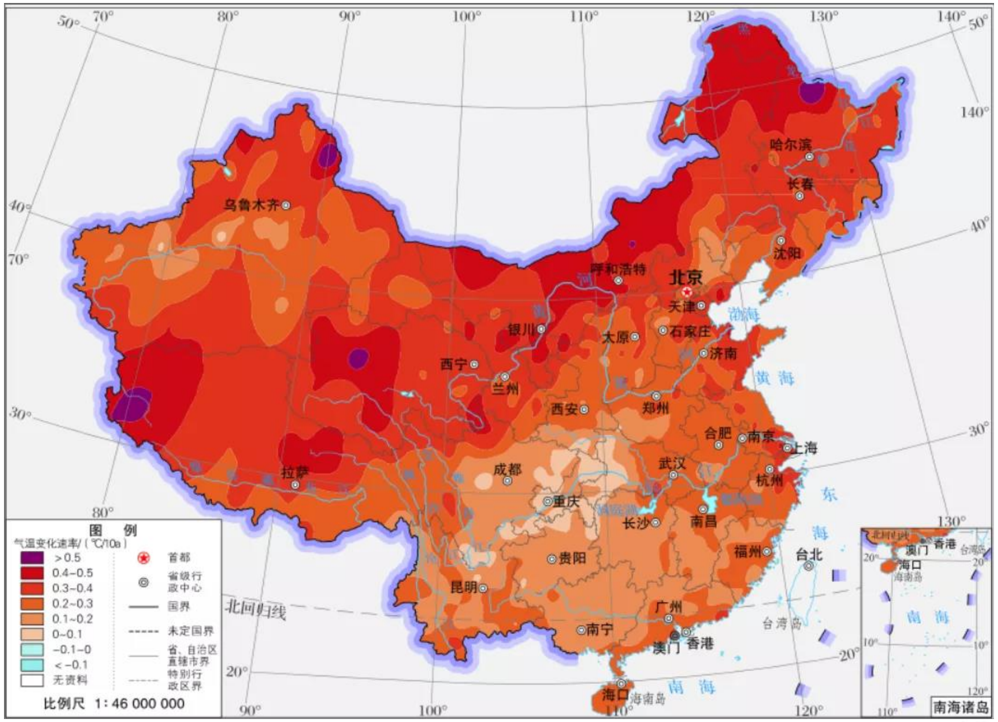
# Global Temperature Anomaly: 1850-2020



IPCC, 2021

**Jim Hansen: ΔT variability and biodiversity?**

# China Temperature Anomaly: 1901-2020

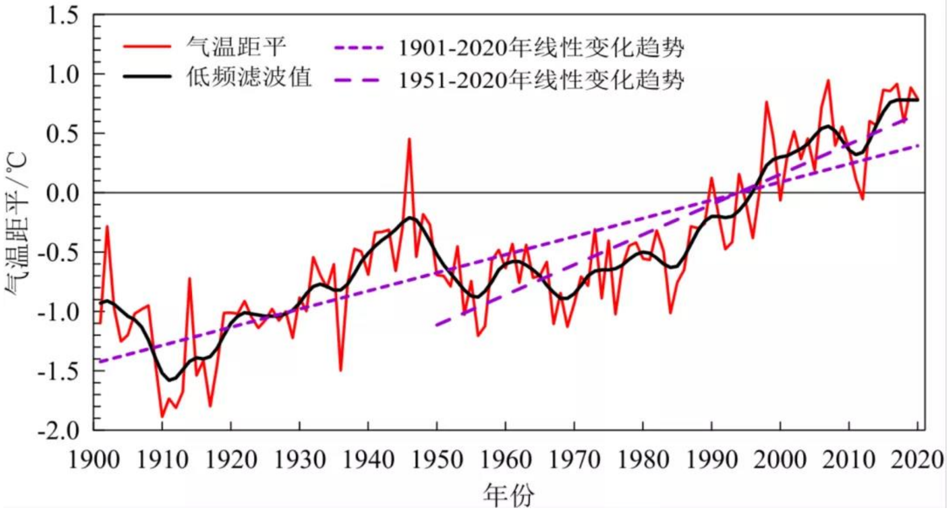


中国气候变化蓝皮书（2021）

- ➢ 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。

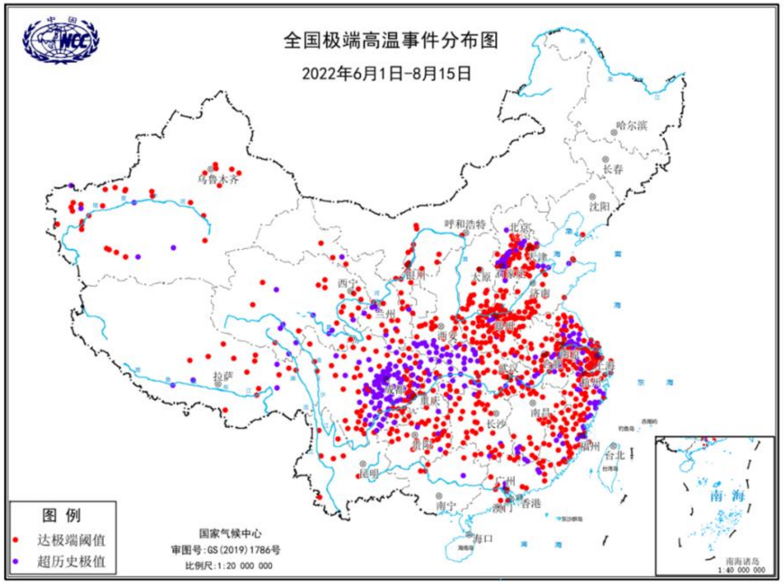
中国气候变化蓝皮书（2024）

- ➢ 2023年，我国地表平均气温较常年值偏高0.84℃，为1901年以来的最暖年份

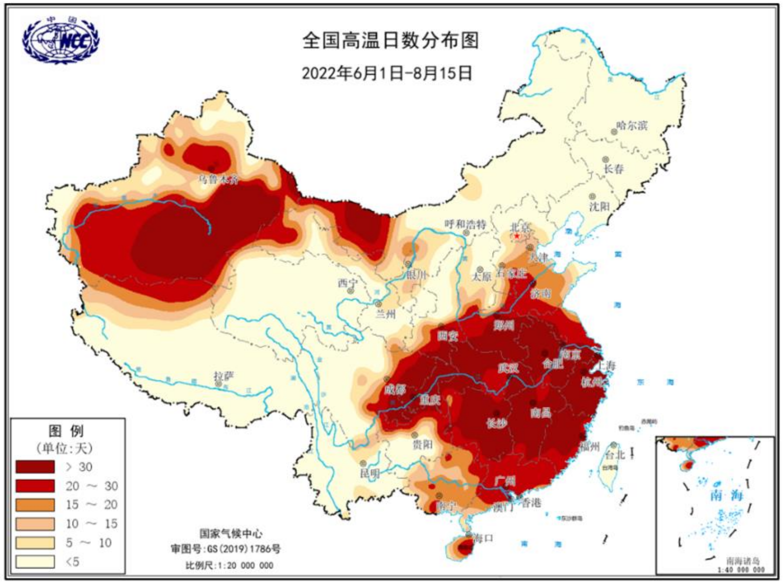


# Heatwave in 2022 in China

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）

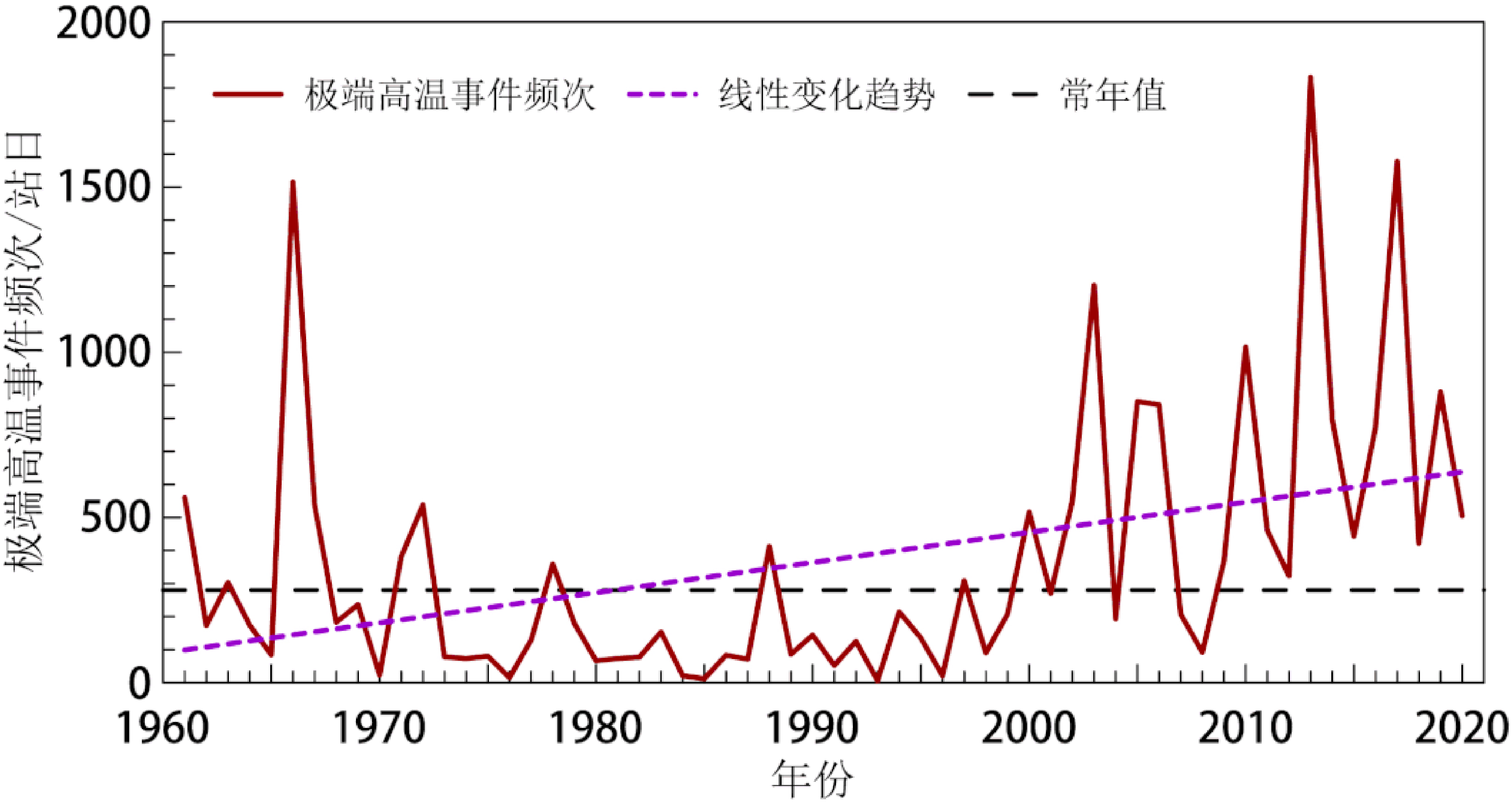


鄱阳湖提前进入枯水期

**国家气候中心：**

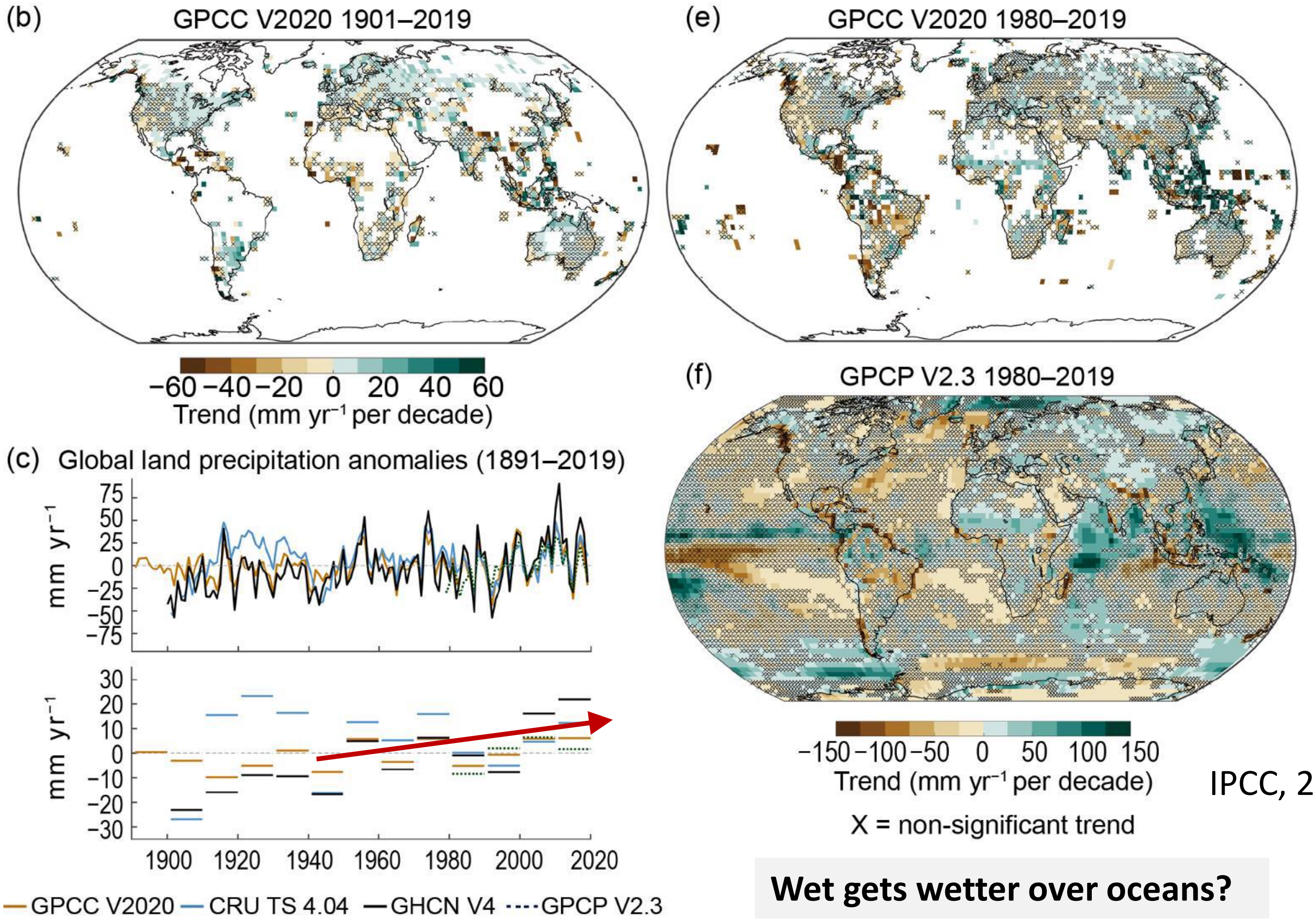
综合考虑高温热浪事件的平均强度、影响范围和持续时间，从今年6月13日开始至8月17日的区域性高温事件**综合强度已达到1961年有完整气象观测记录以来最强**

# China Extreme Weather Changes



中国气候变化蓝皮书（2021）

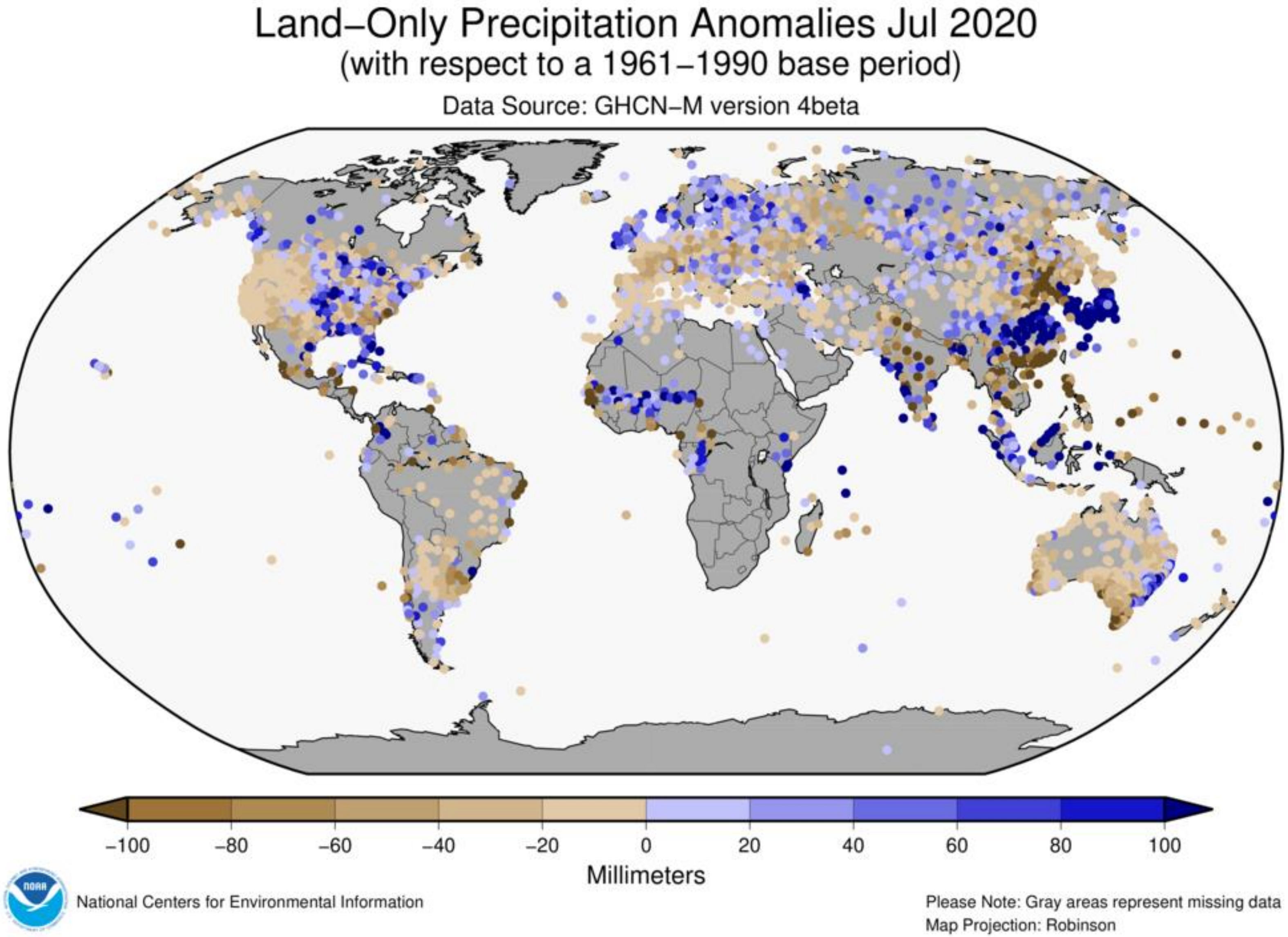
# Global Precipitation Anomaly: 1901–2019



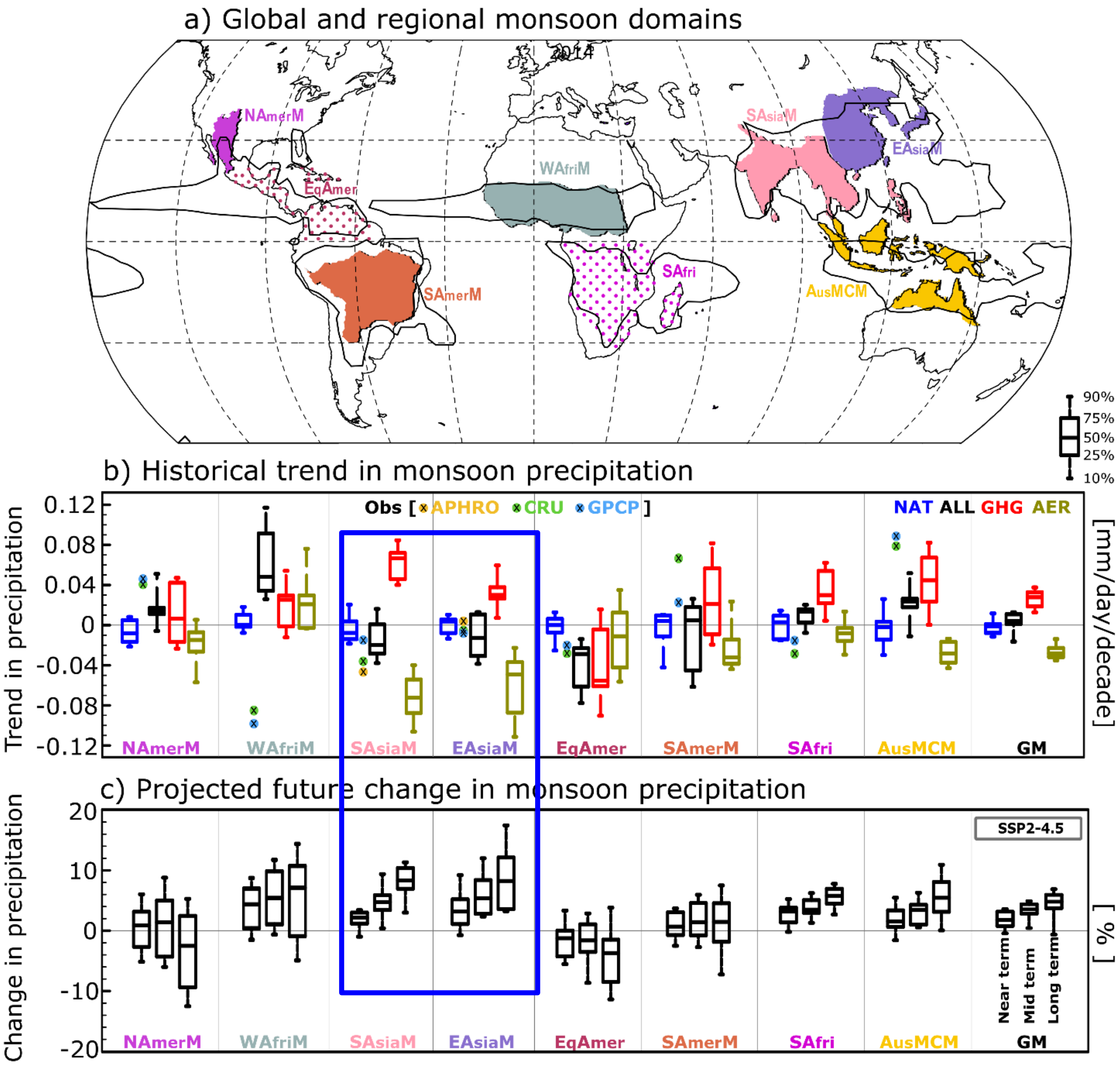
IPCC, 2021

**Wet gets wetter over oceans?**

# Global Precipitation Anomaly



# Changes in Global Monsoon Precipitation



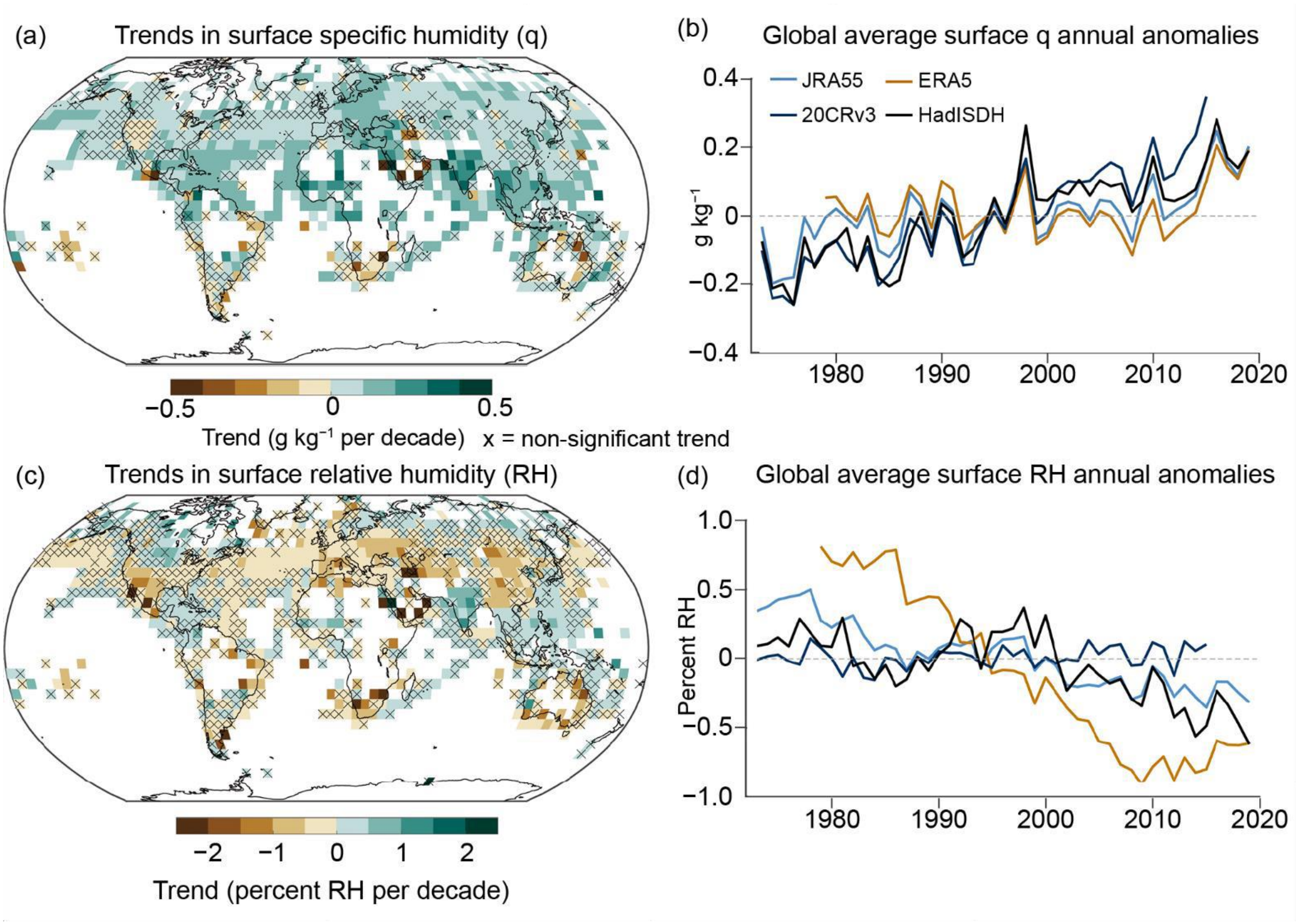
a) Global and regional monsoon domains

b) Historical trend in monsoon precipitation

c) Projected future change in monsoon precipitation

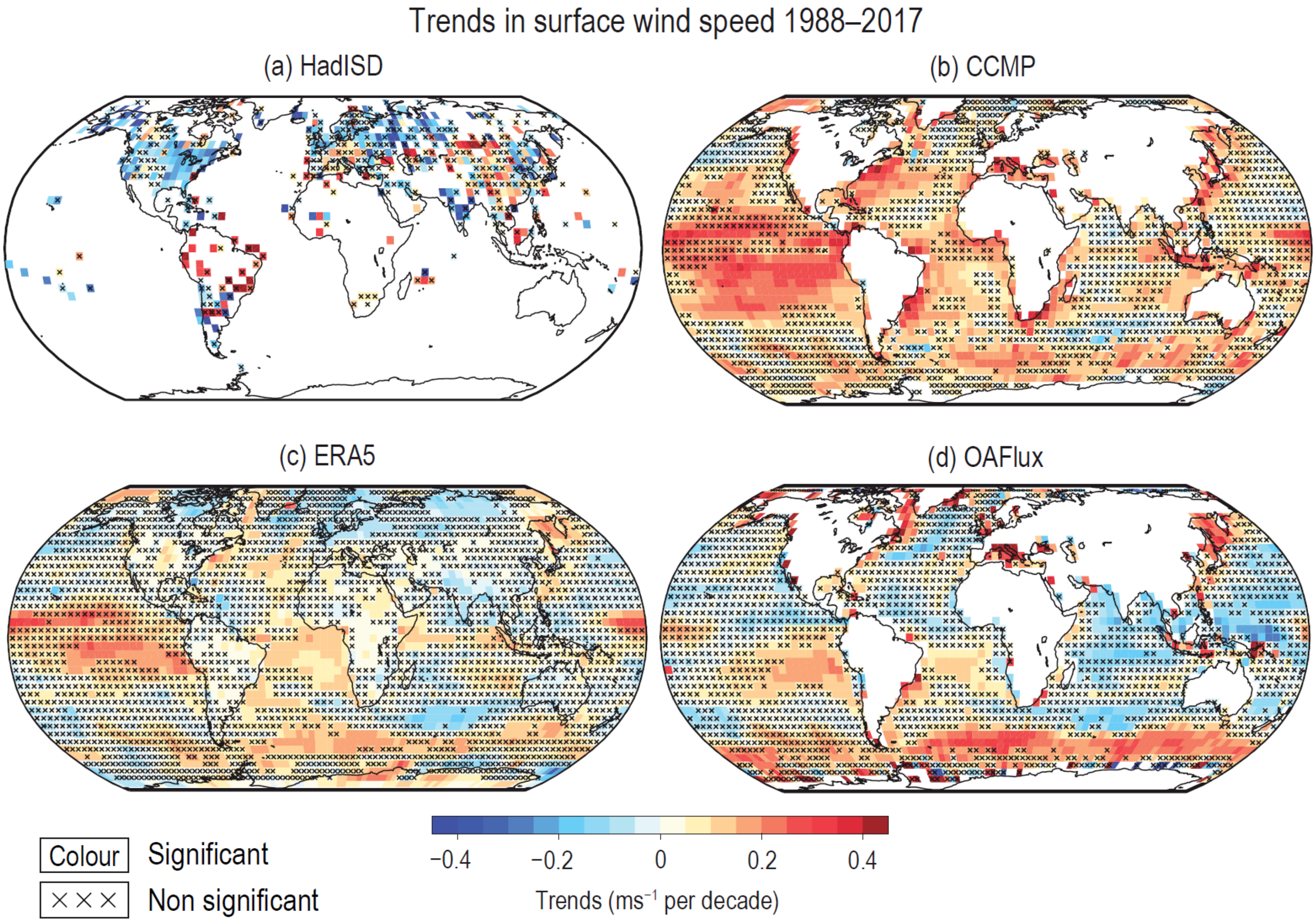
IPCC, 2021

# Humidity Change: 1973–2019



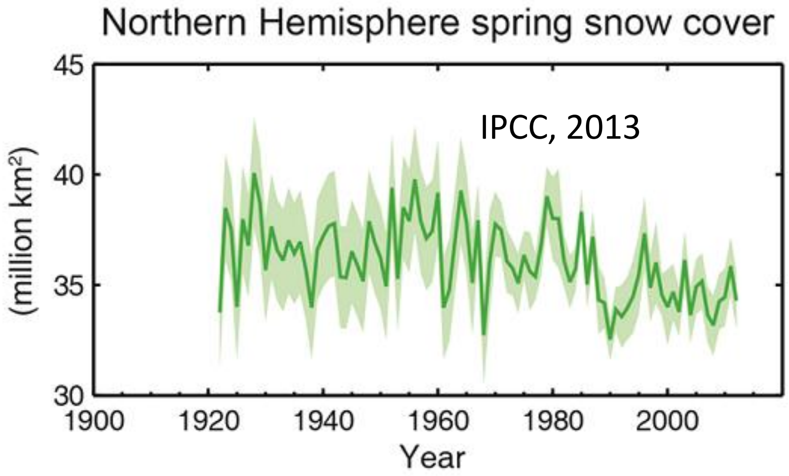
IPCC, 2021

# Surface Wind Speed Change: 1988–2017

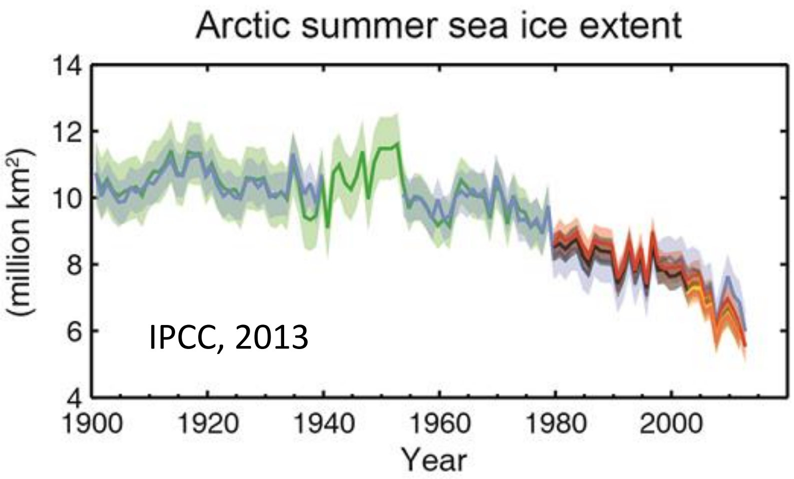


IPCC, 2021

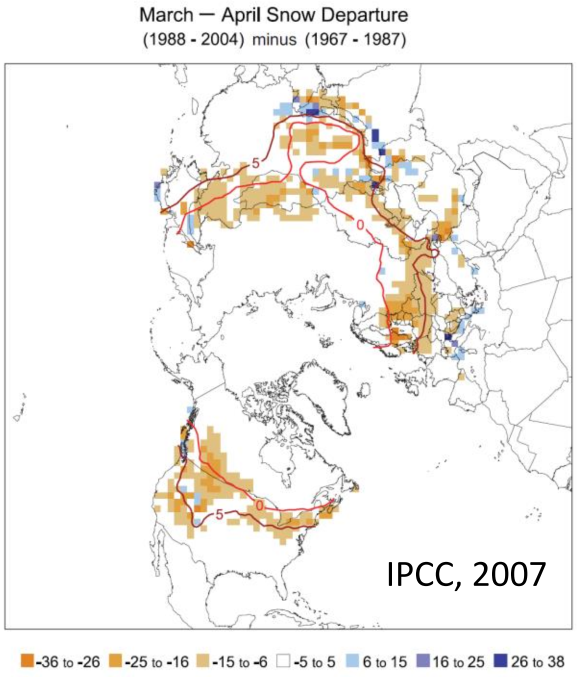
# Changes in Cryosphere and Its Components



IPCC, 2013



IPCC, 2013



IPCC, 2007

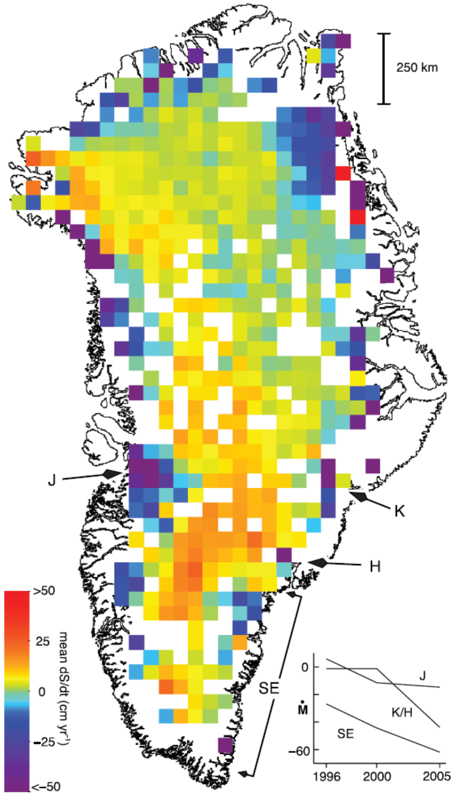
天山乌鲁木齐河源1号冰川

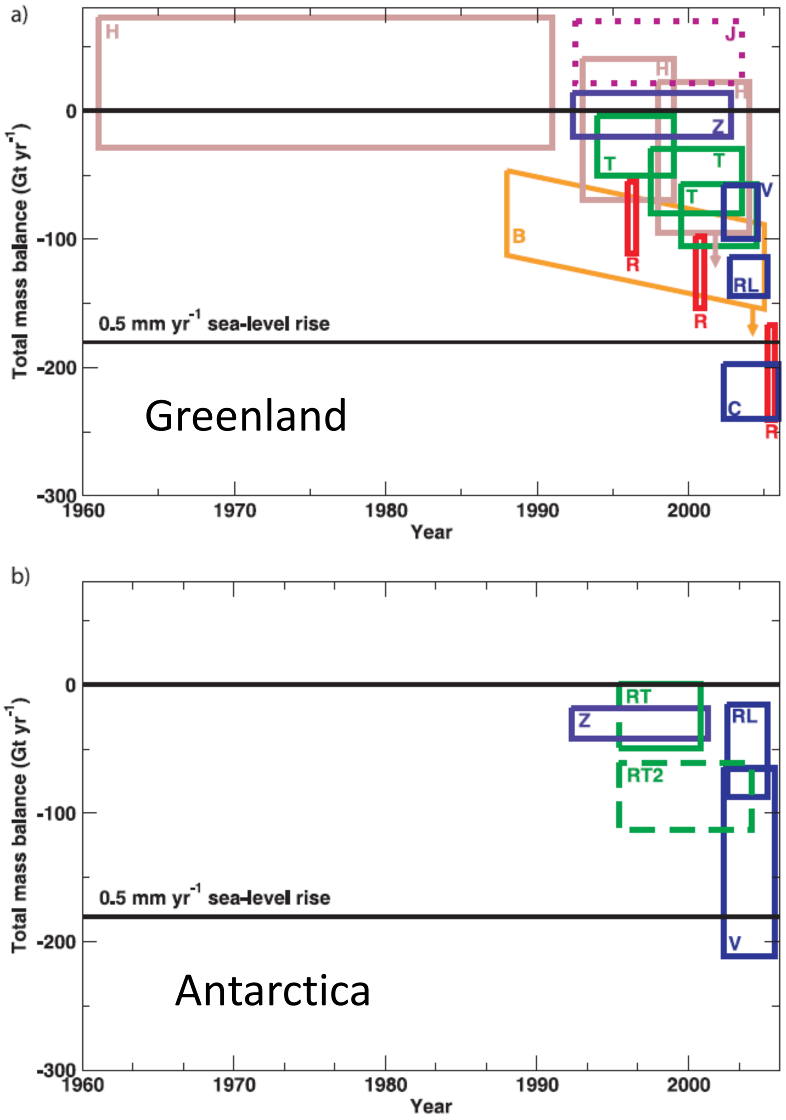
中国气候变化蓝皮书（2021）

# Changes in Greenland and Antarctic Ice Sheets

Total mass change

Height change



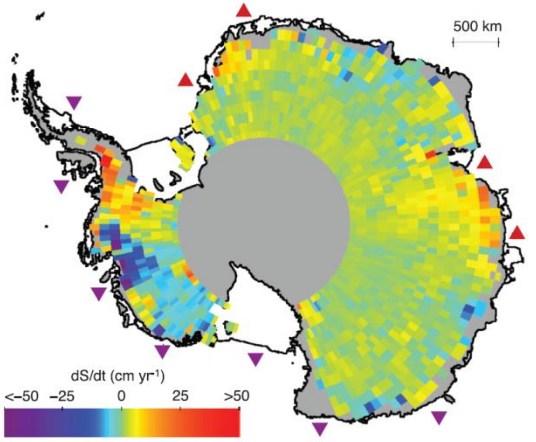


Greenland

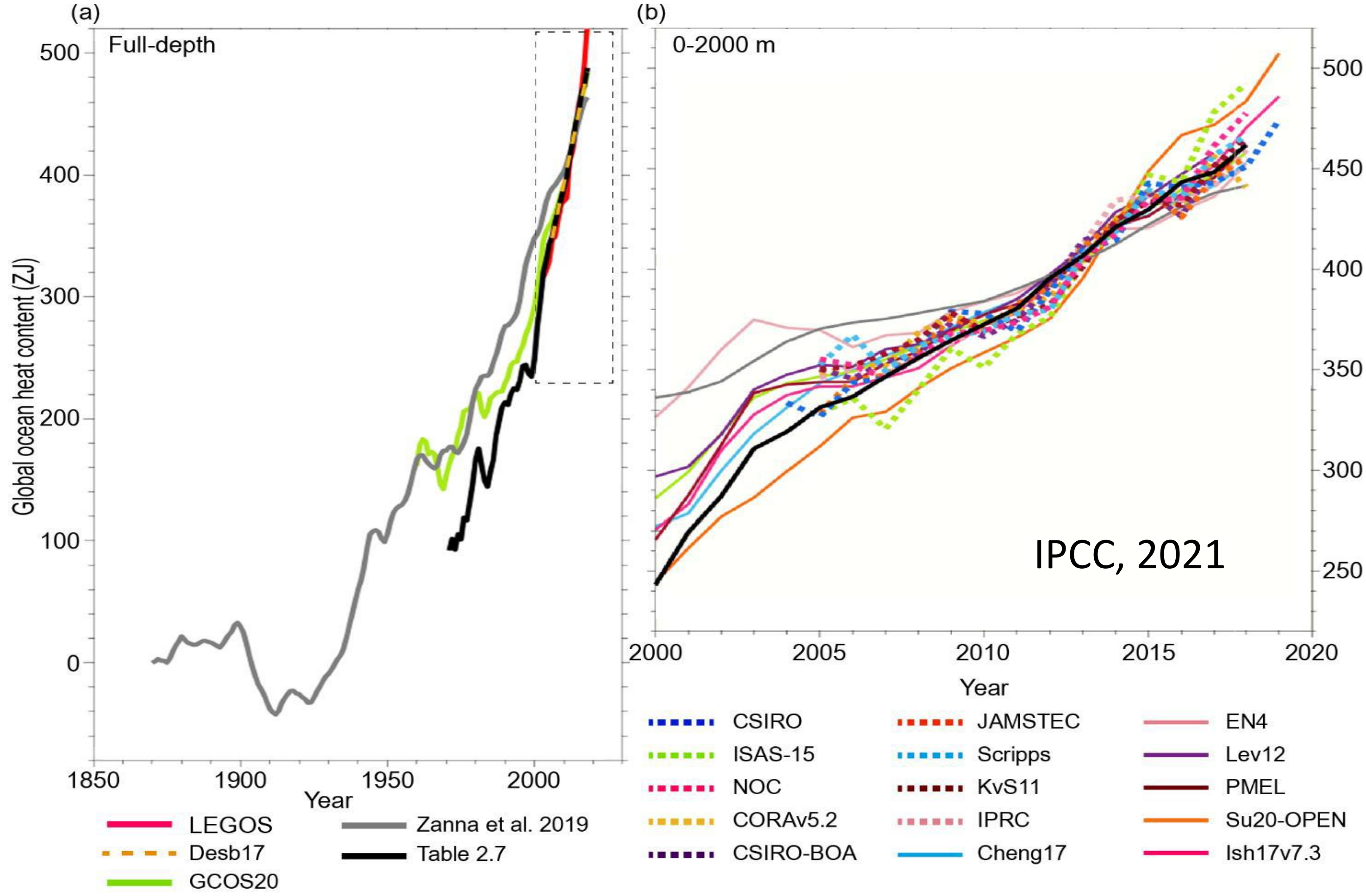
Antarctica

IPCC, 2013

Height change



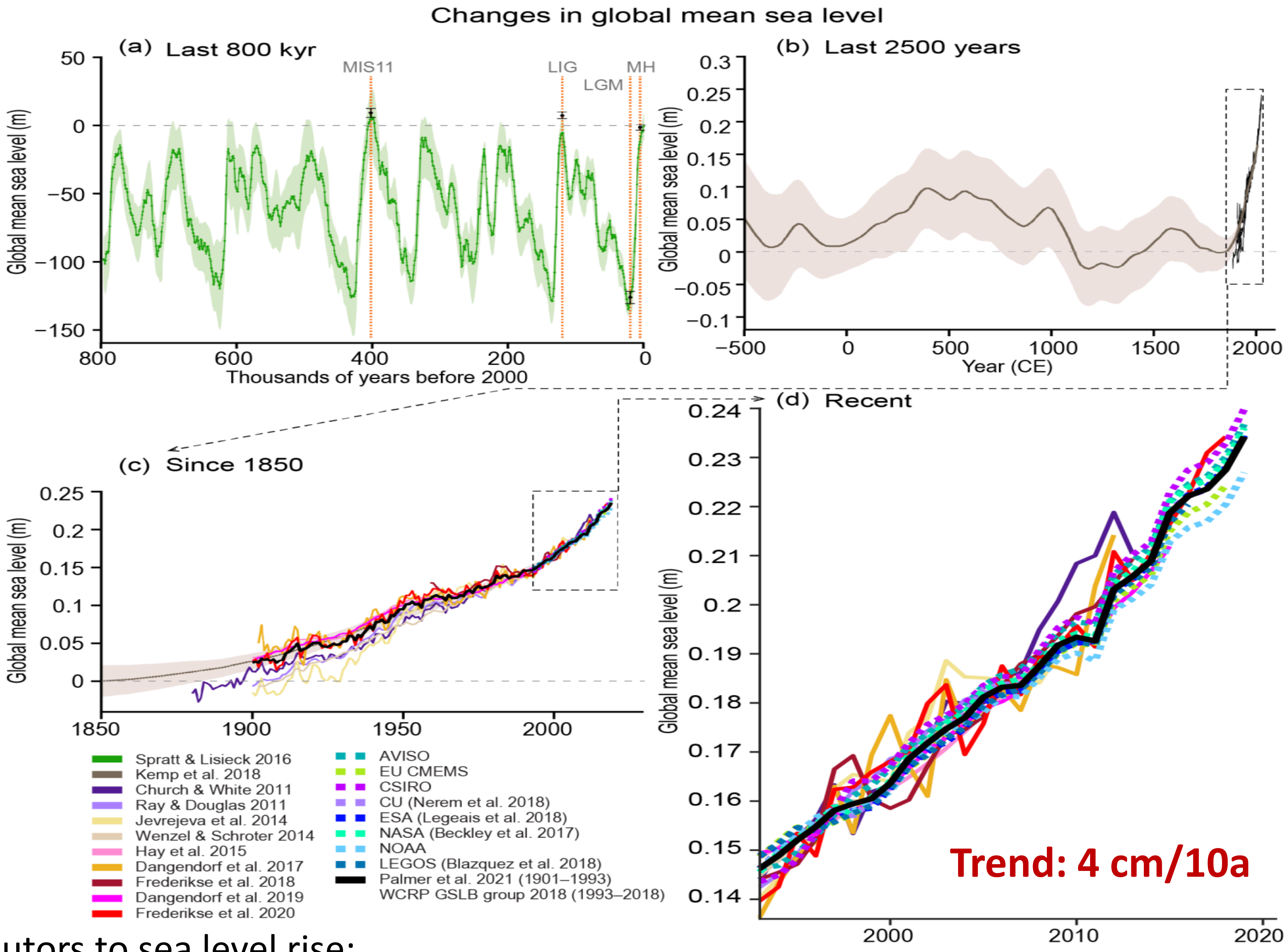
# Ocean Heat Content Change



IPCC, 2021

- ➢ 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

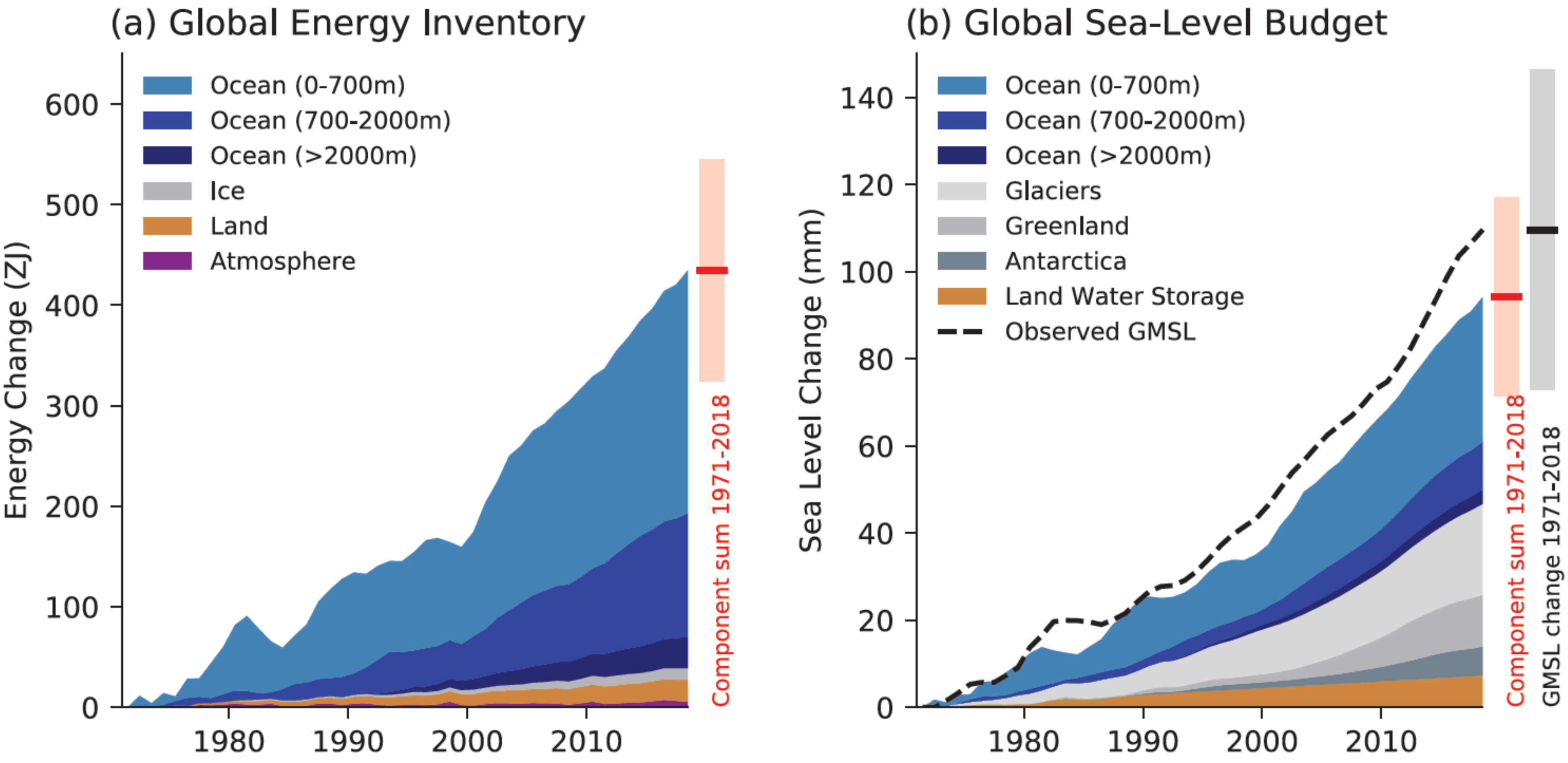


**Trend: 4 cm/10a**

Contributors to sea level rise:
https://youtu.be/Q15gTMXjwCc

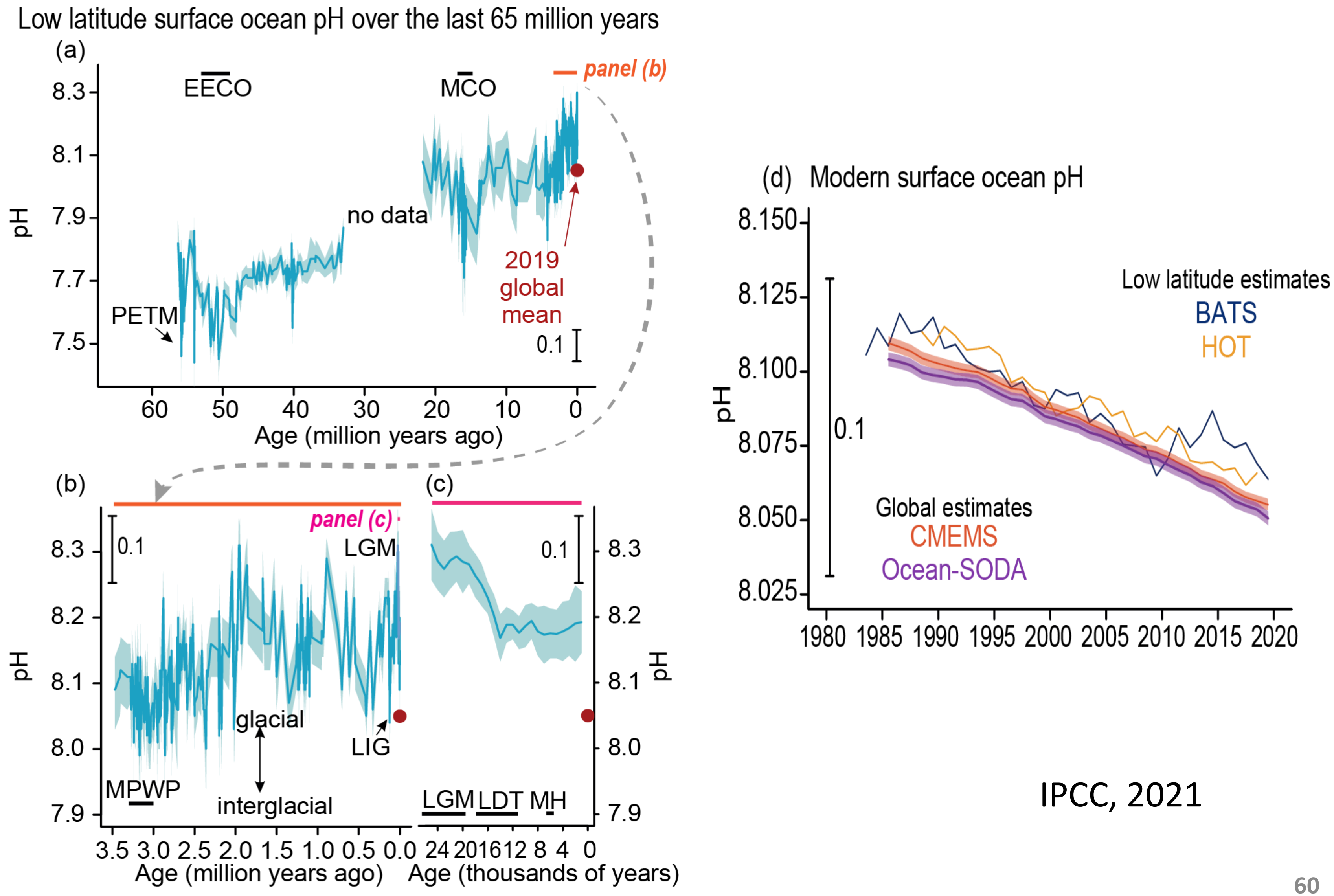
IPCC, 2021

# Sea Level Rise and Its Causes



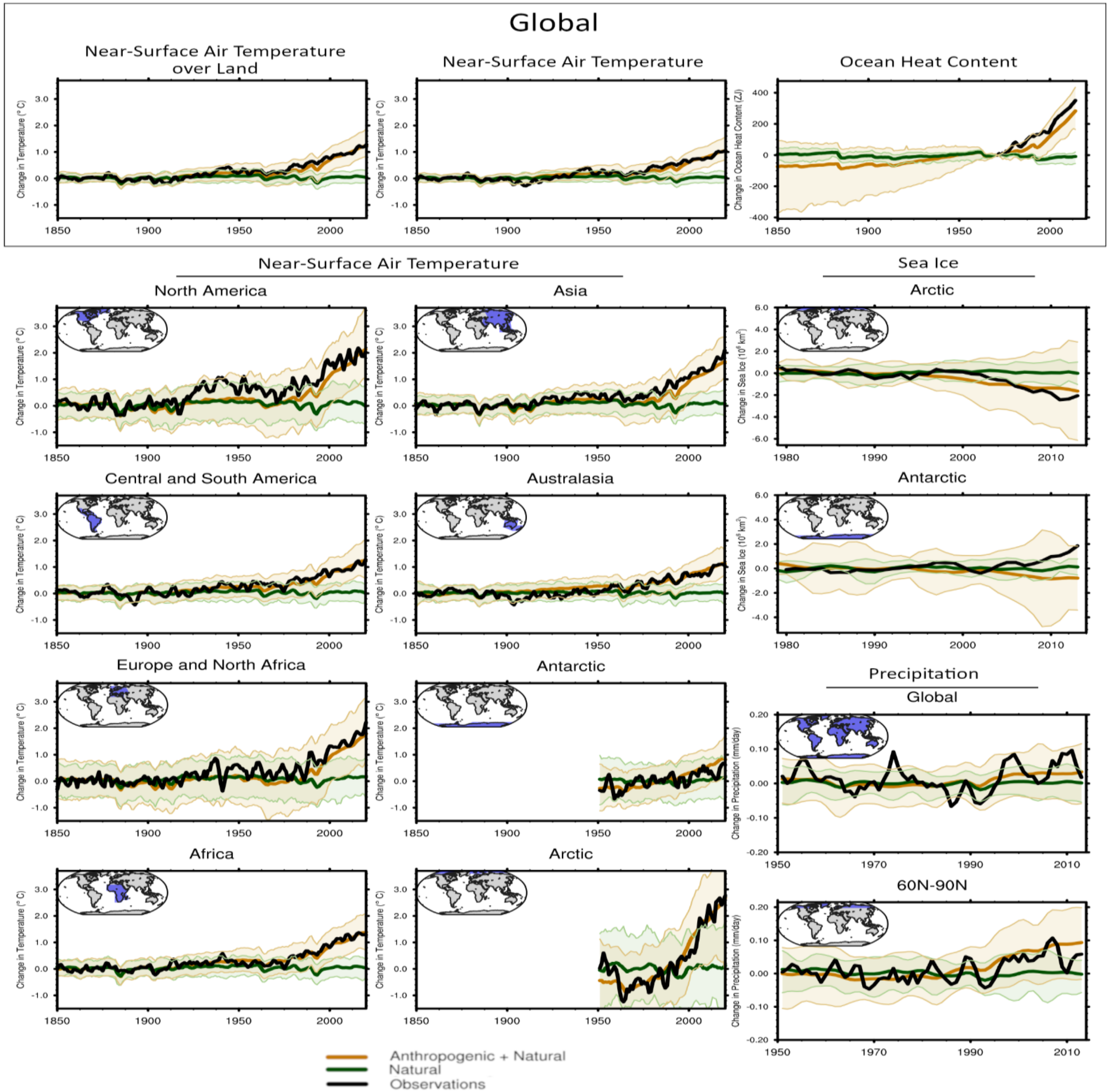
IPCC, 2021

# Changes in Ocean pH



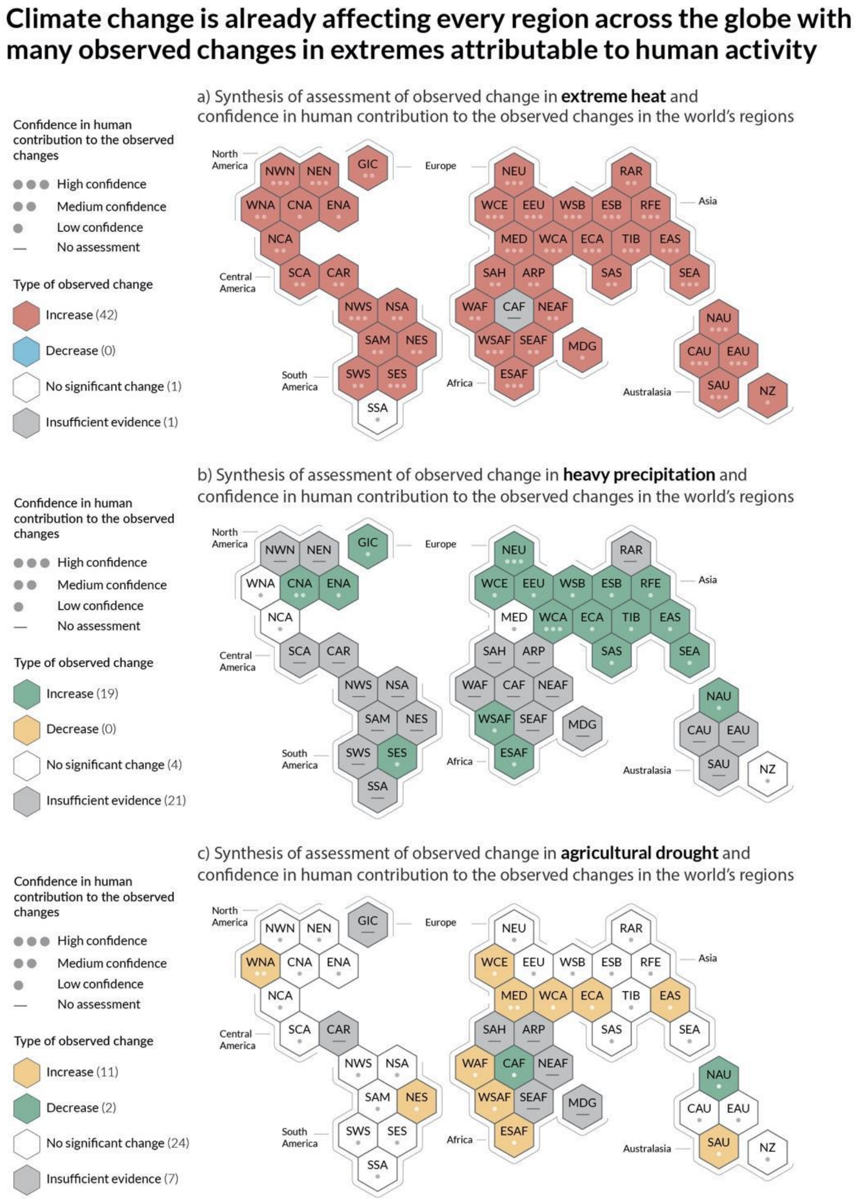
IPCC, 2021

# Modeled Anthropogenic versus Natural Impacts



IPCC, 2021

# Changes in Climate Extremes and Attribution


Climate change is already affecting every region across the globe with many observed changes in extremes attributable to human activity

a) Synthesis of assessment of observed change in **extreme heat** and confidence in human contribution to the observed changes in the world's regions

b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions

c) Synthesis of assessment of observed change in **agricultural drought** and confidence in human contribution to the observed changes in the world's regions

**Extreme heat**

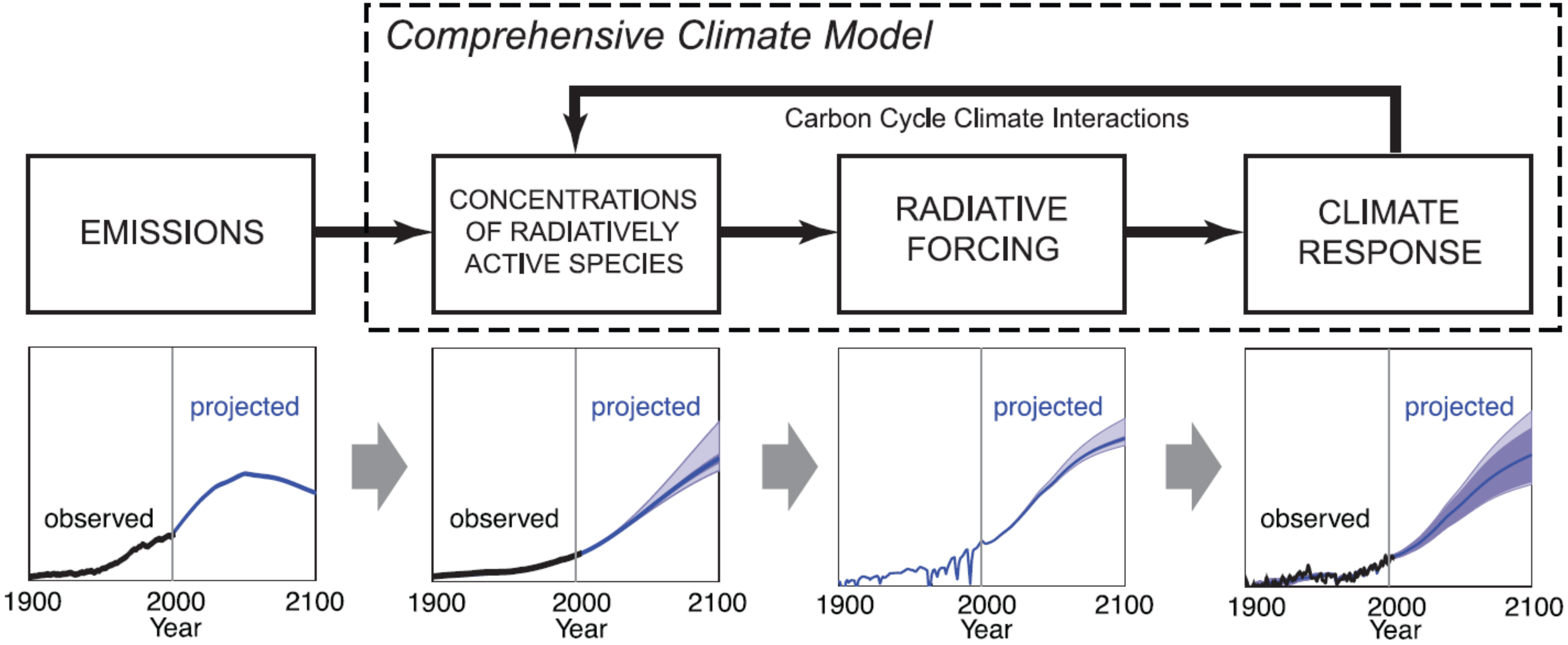
**Heavy prec.**

**Agri. drought**

IPCC, 2021

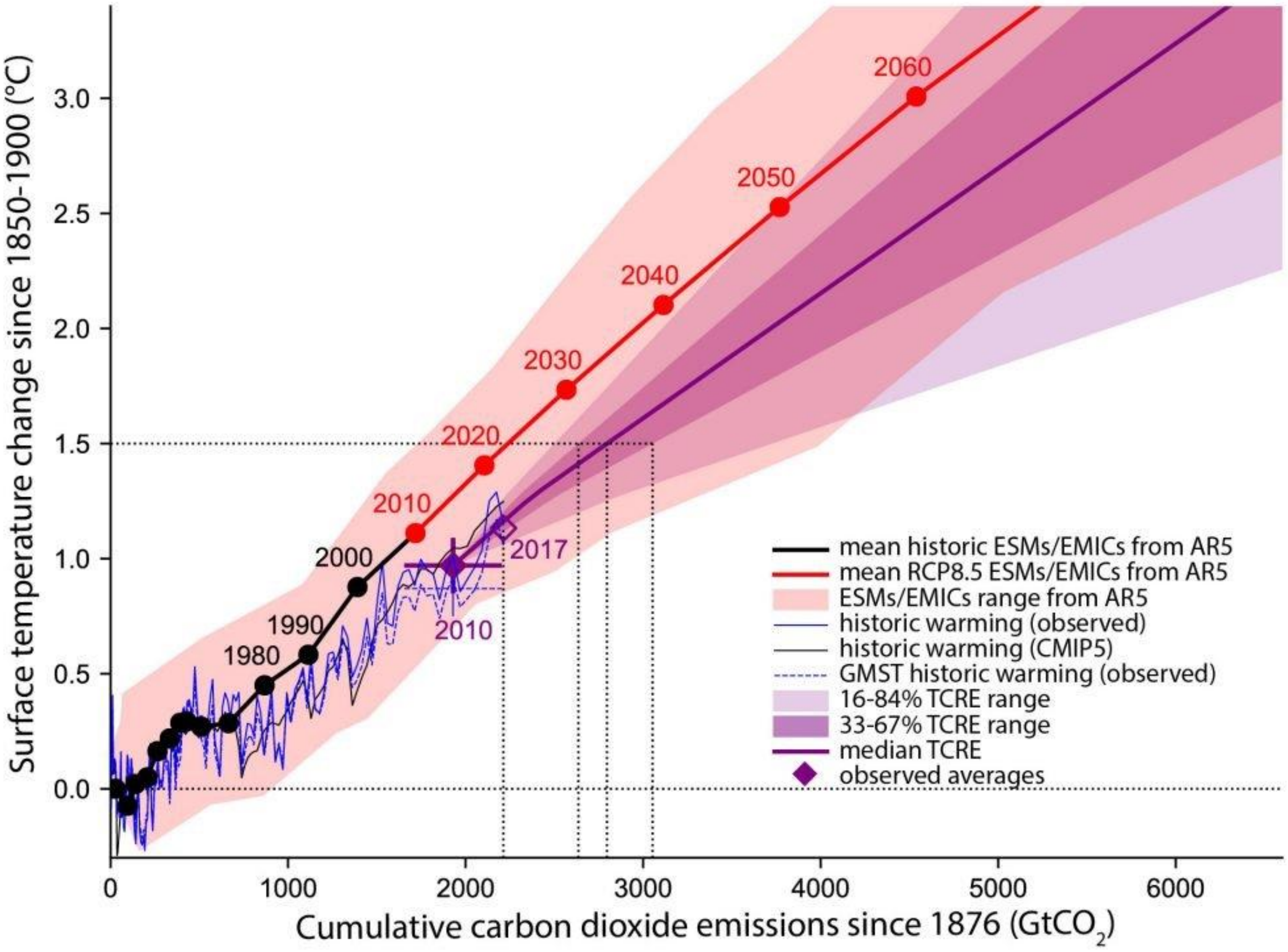
# Future Climate Change Projections

# Future Climate Change: From Emissions to Climate



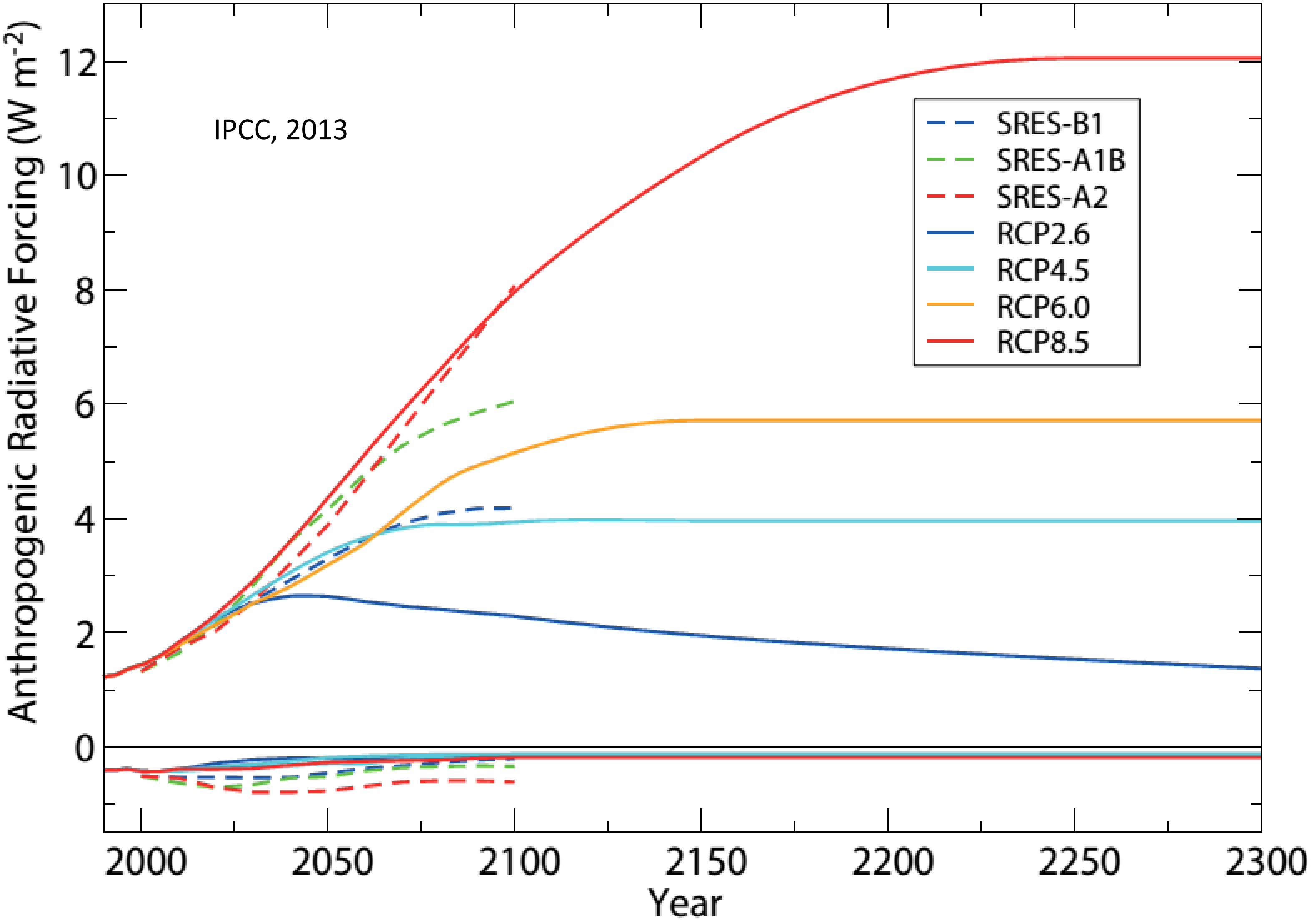
IPCC, 2013

# Projected GHG Emissions versus Temperature Rise

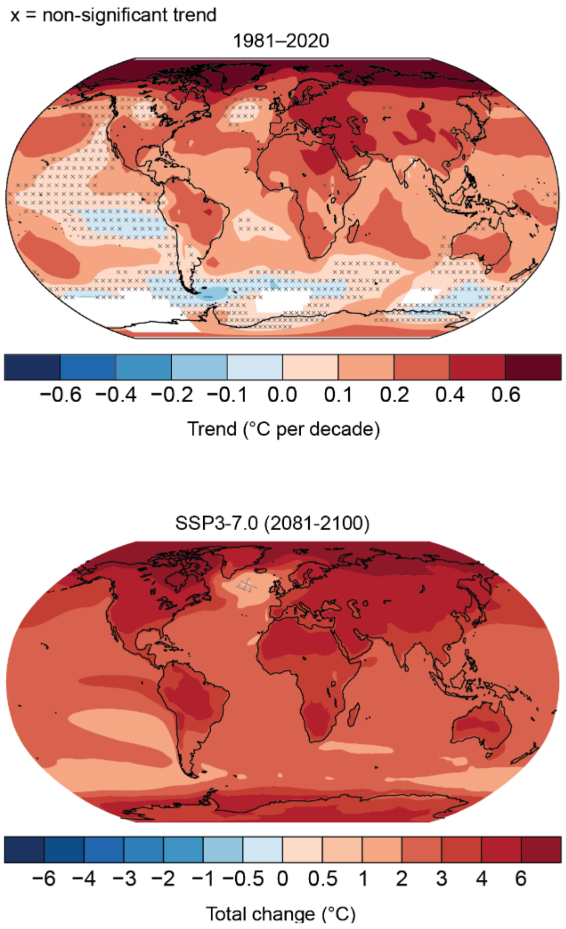


Special Report on 1.5$^{o}$C Warming

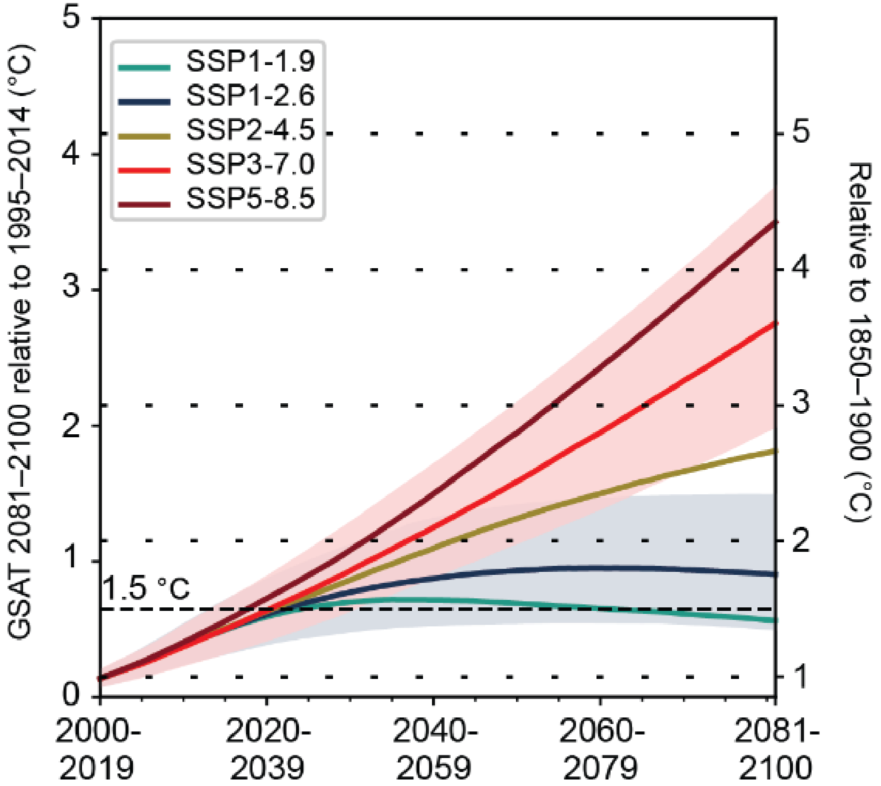
# Radiative Forcing: 2000 – 2300



# Projected Temperature Change



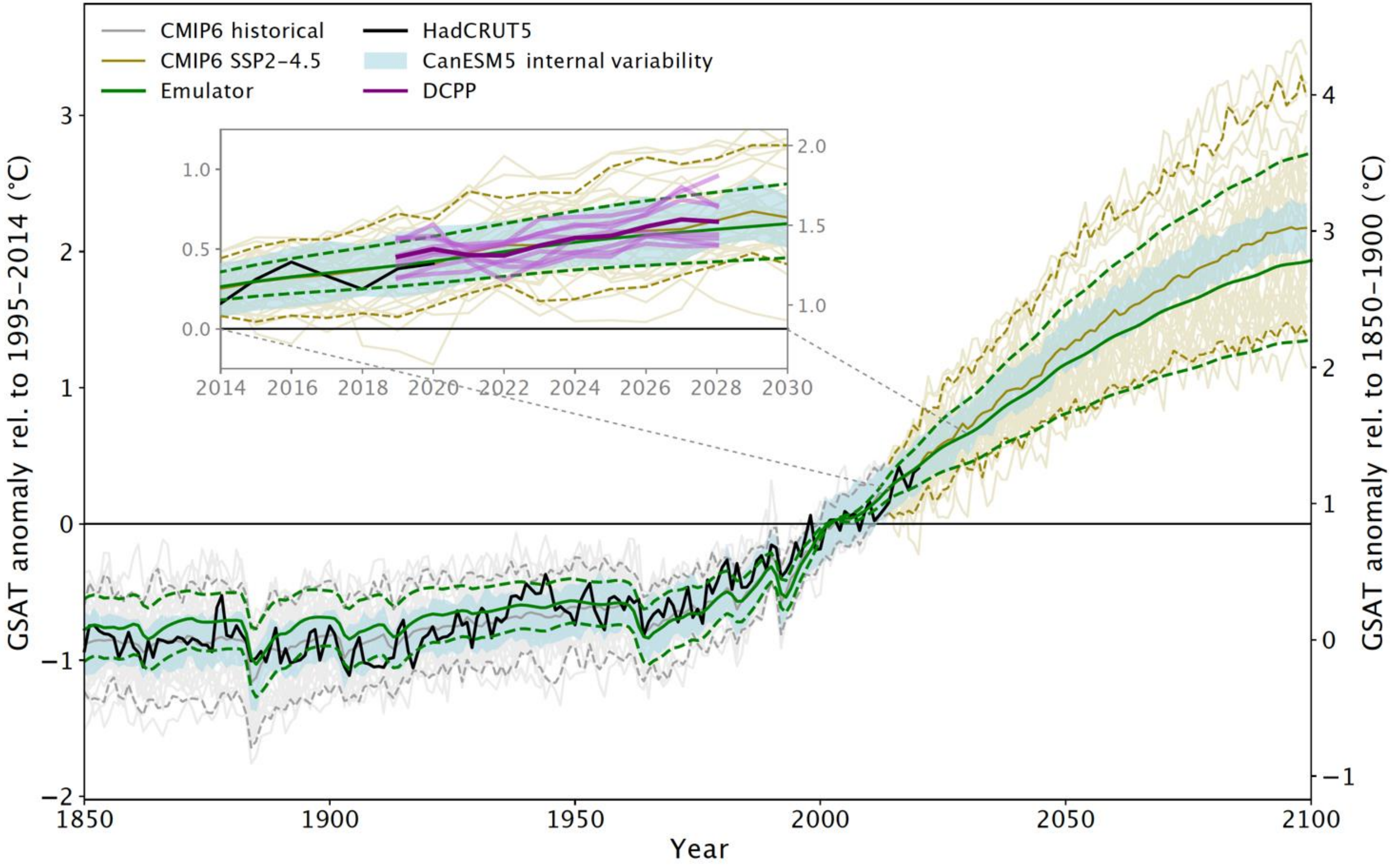
(b) Observed and projected warming are stronger over land than oceans, and strongest in the Arctic



(e) Warming to 2100 depends on the scenario

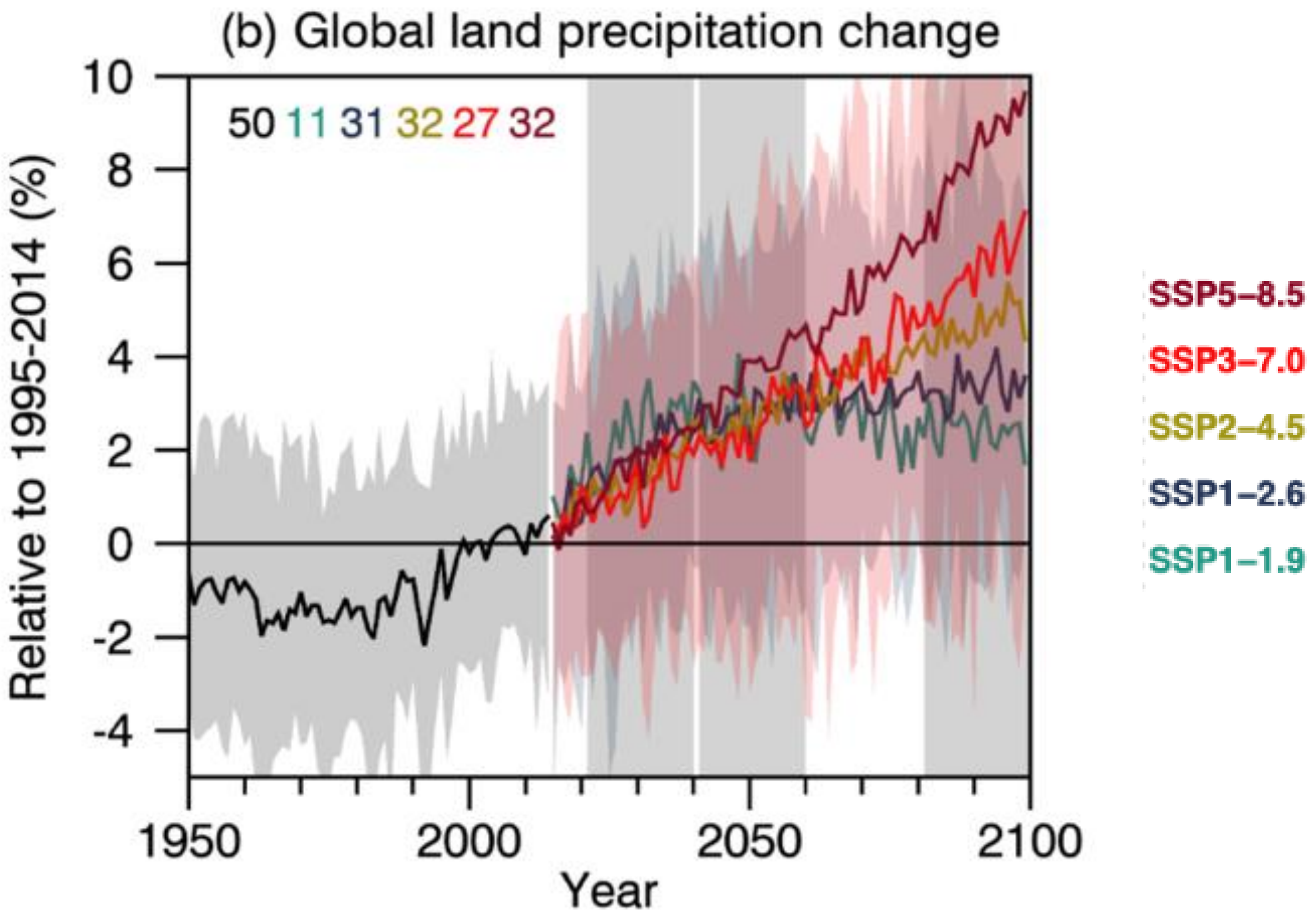
IPCC, 2021

# Uncertainty in Temperature Projections



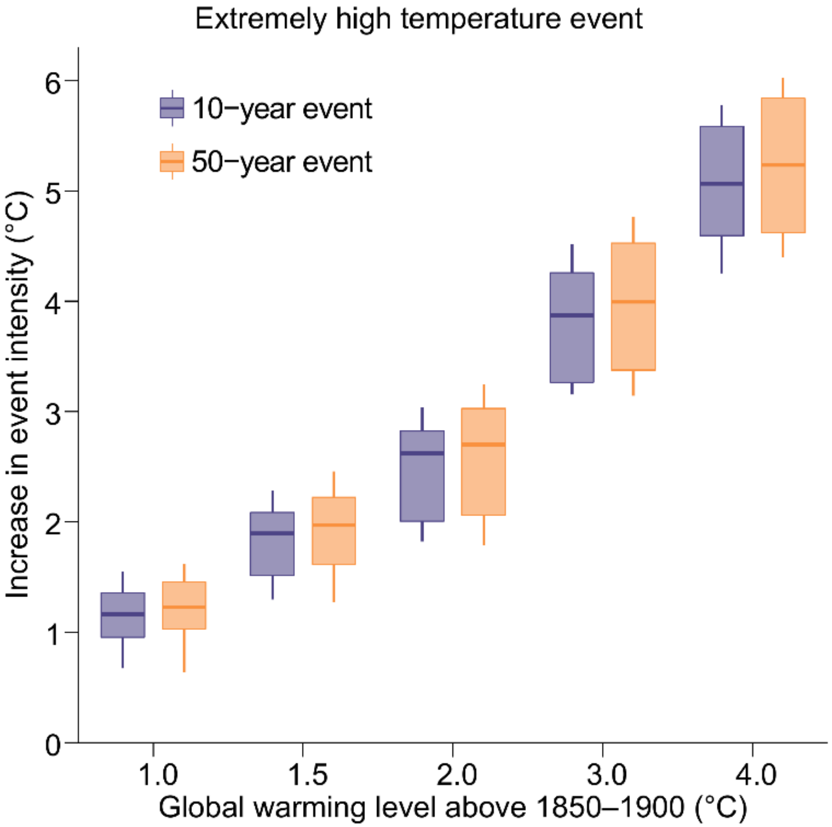
IPCC, 2021

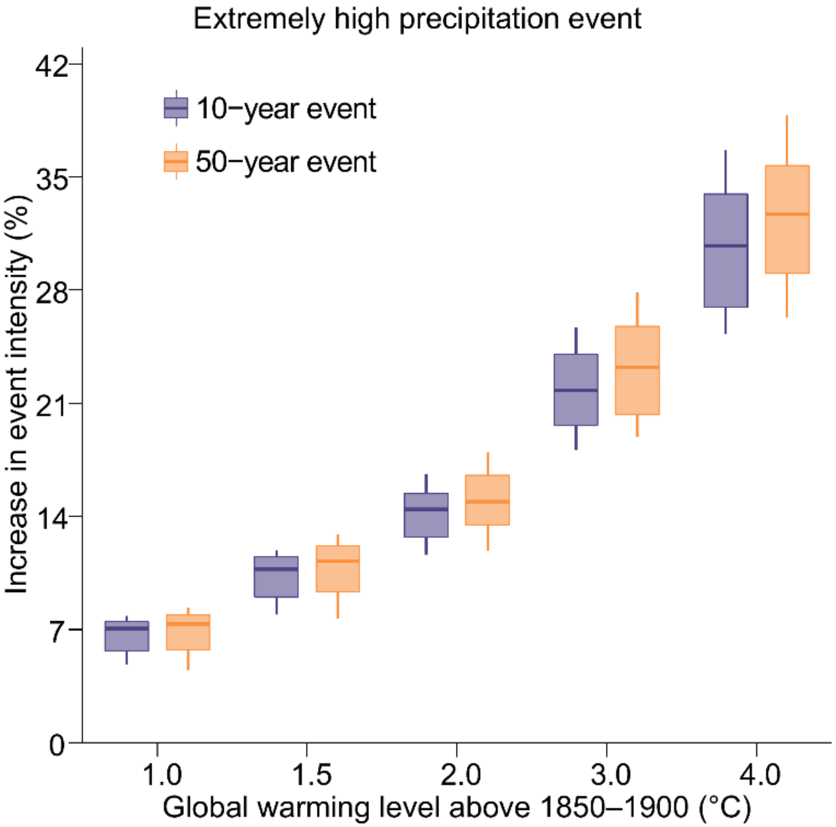
# Projected Precipitation Change



IPCC, 2021

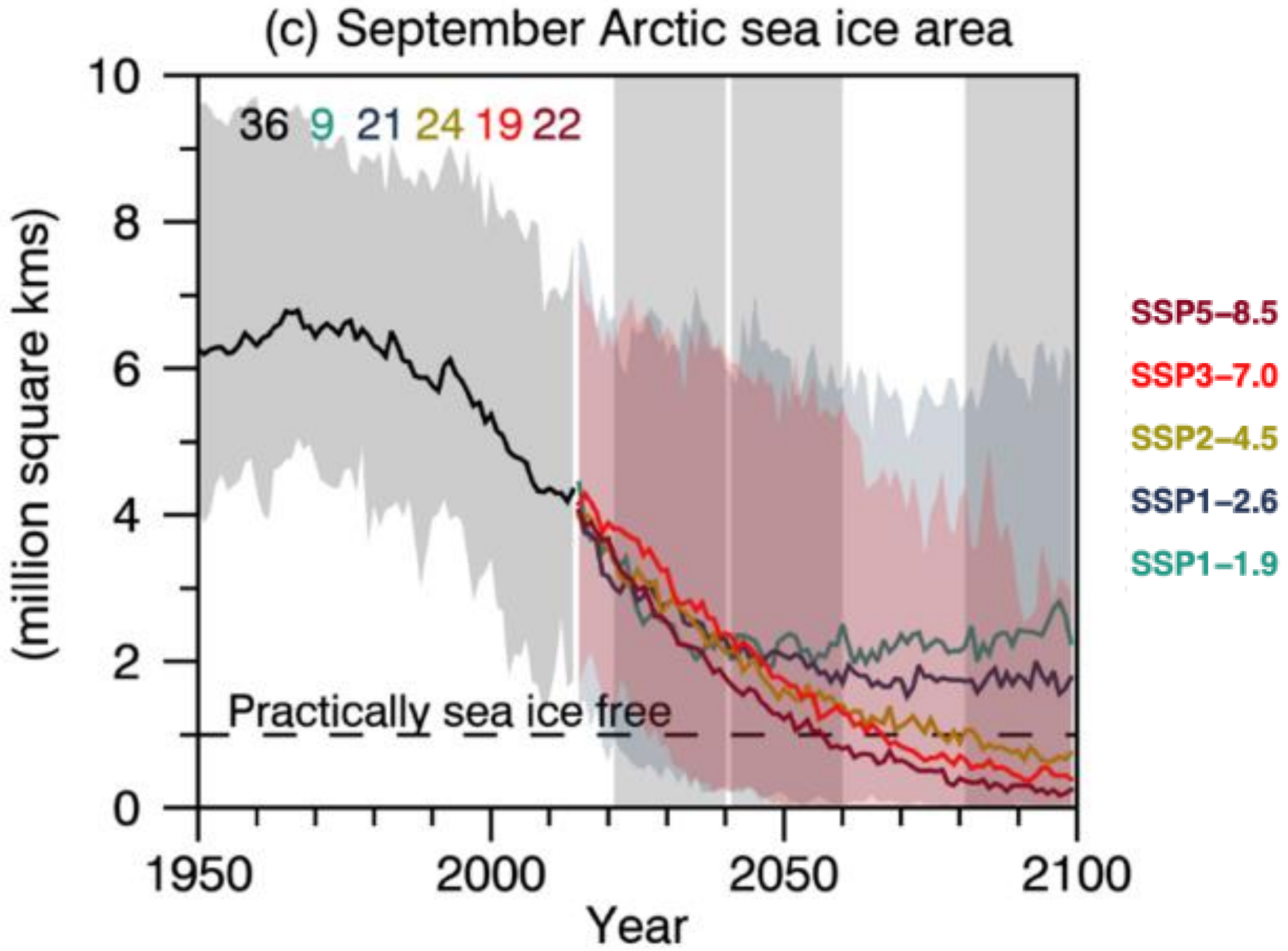
# Projected Change in Extreme Events





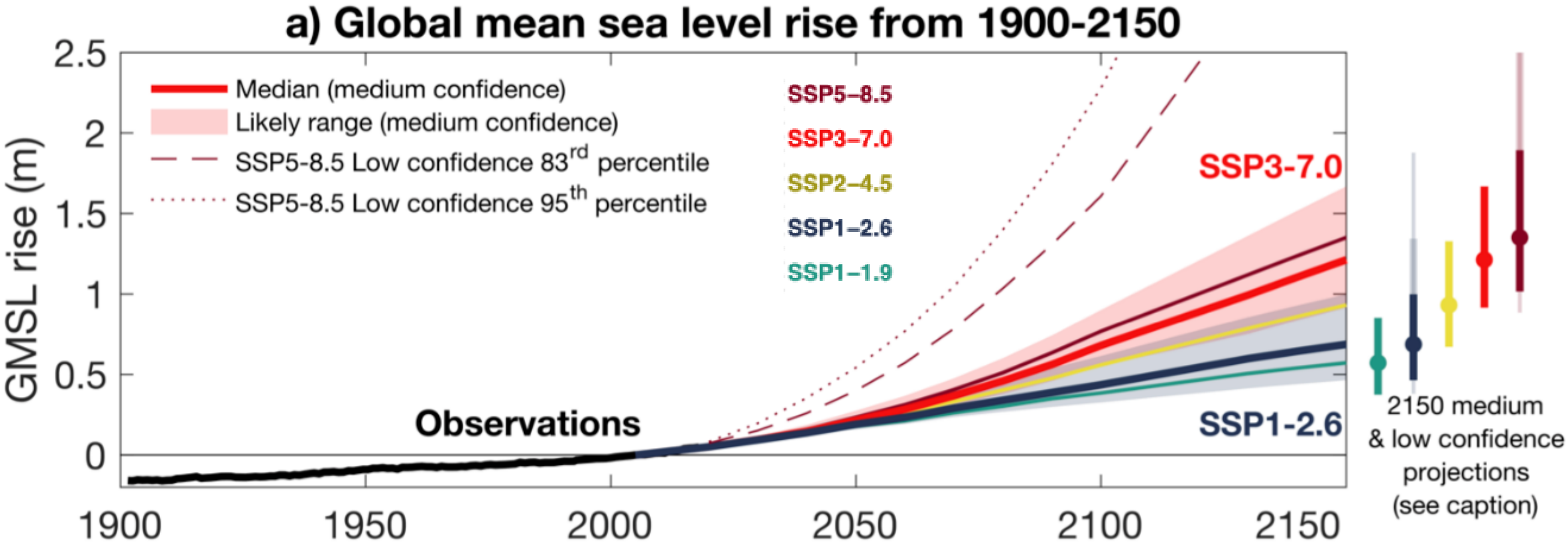
IPCC, 2021

# Projected Change in Sea Ice Extent



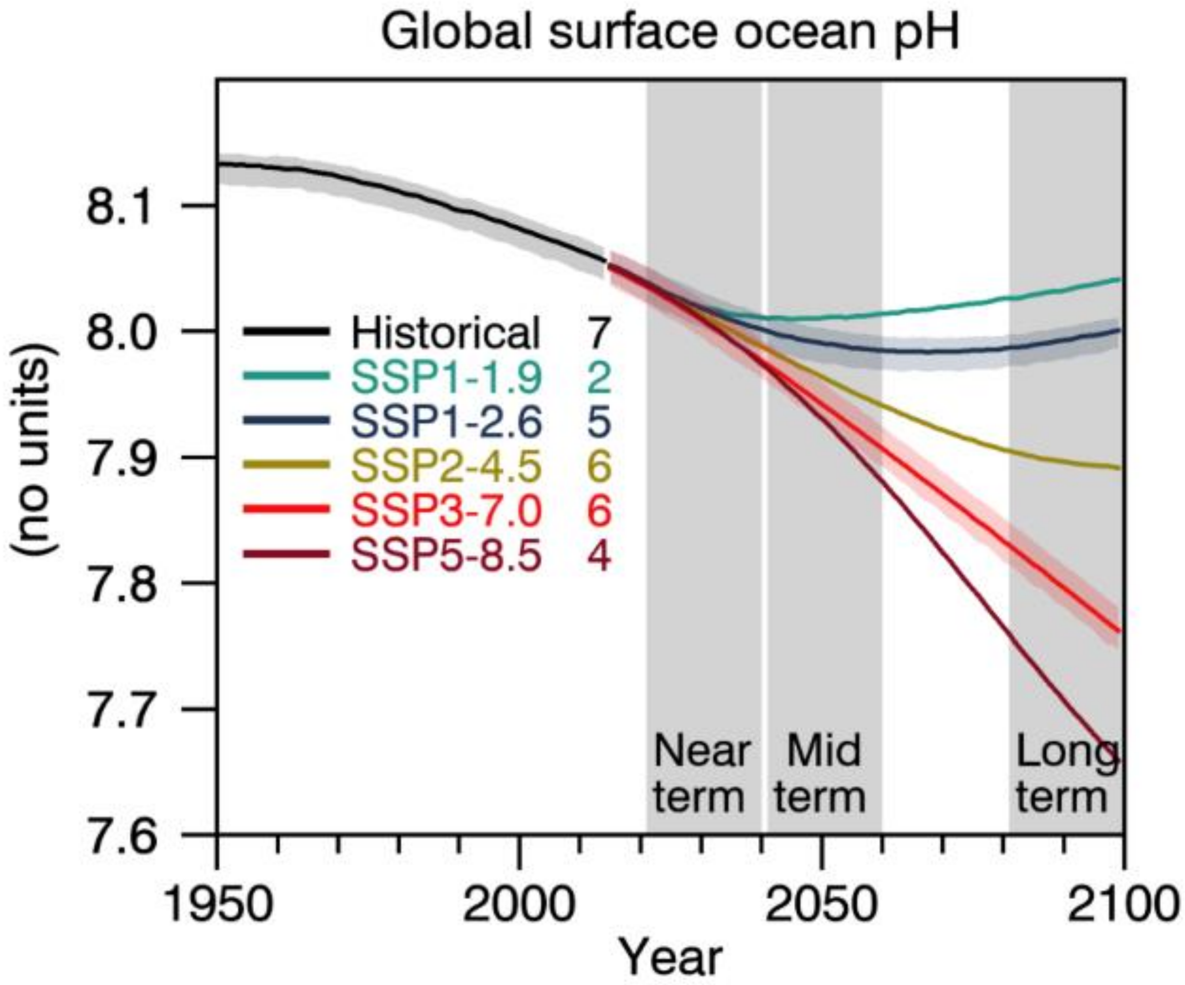
IPCC, 2021

# Projected Change in Sea Level



IPCC, 2021

# Projected Change in Ocean Acidification



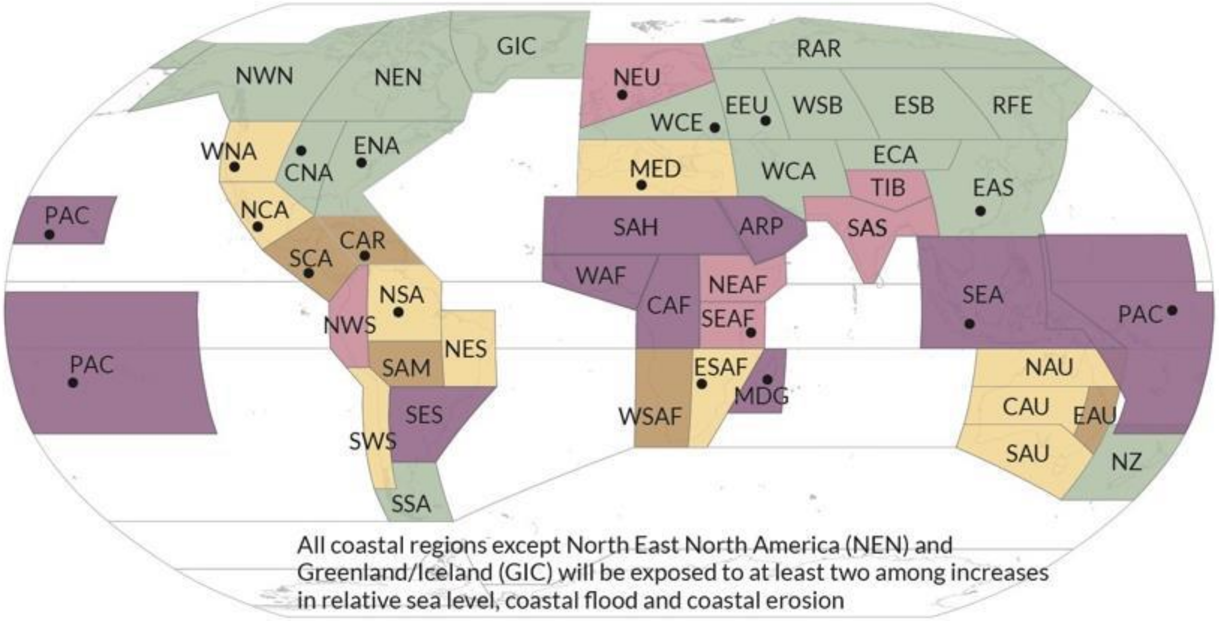
IPCC, 2021

# 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

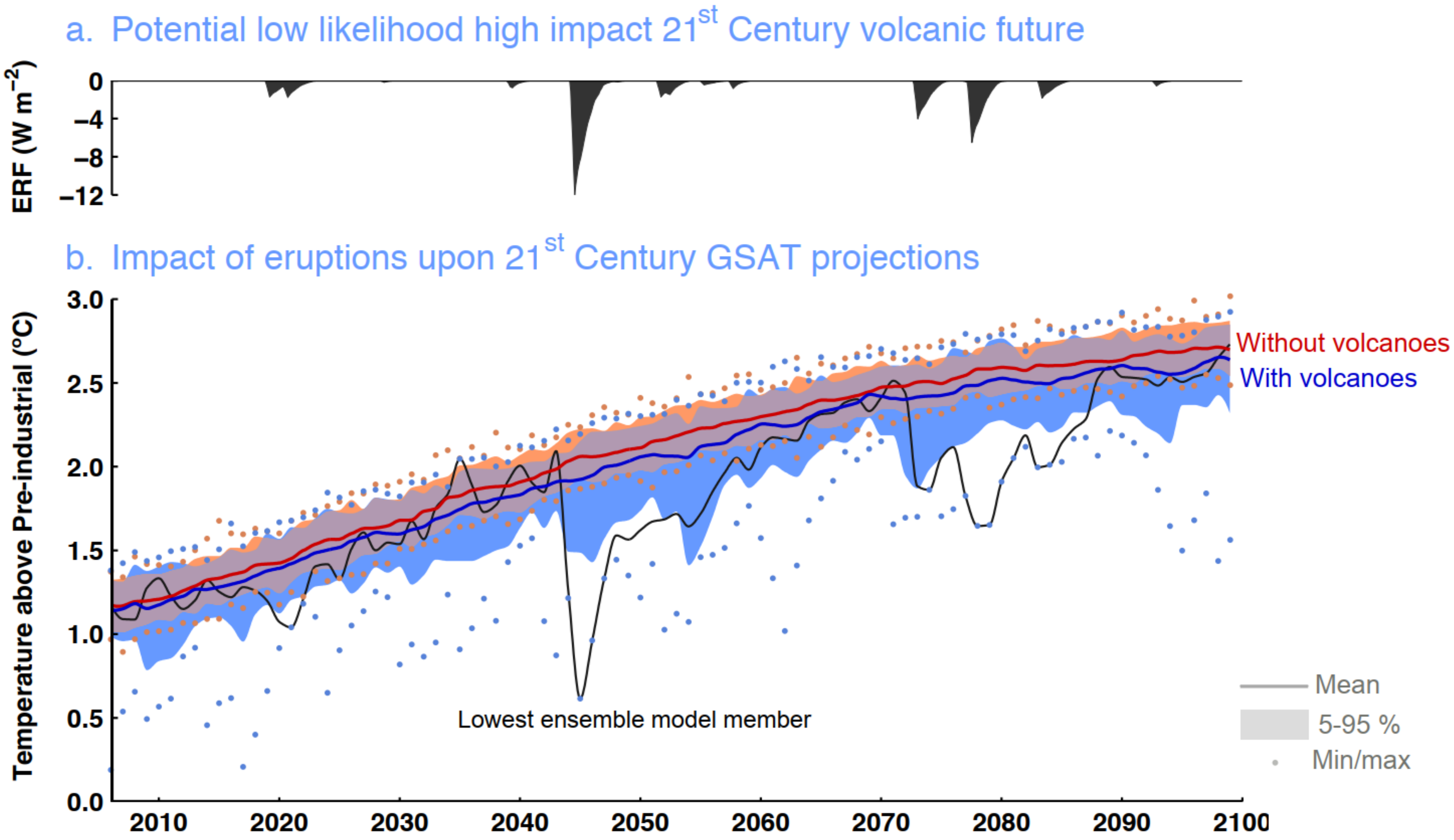


All coastal regions except North East North America (NEN) and Greenland/Iceland (GIC) will be exposed to at least two among increases in relative sea level, coastal flood and coastal erosion

- 🟤 1) Hotter and drier
- 🟡 2) Hotter and drier and in some regions wetter extremes
- 🟢 3) Hotter and wetter extremes and in some regions more precipitation or fire weather
- 🔴 4) Hotter and wetter and in some regions more flooding
- 🟣 5) Hotter and in some regions wetter extremes or more precipitation
- • 6) Increase in Tropical cyclones intensity or Severe winds

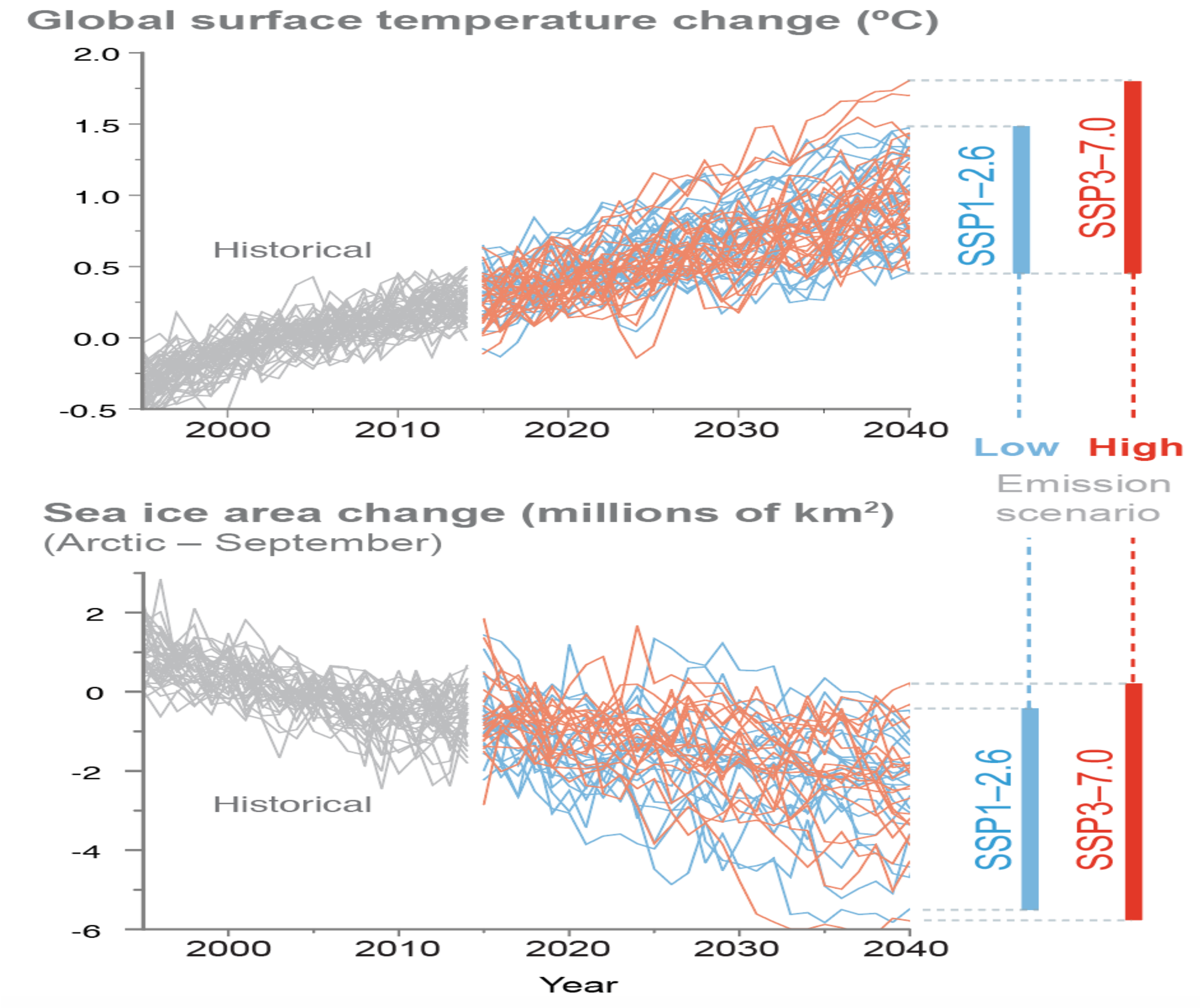
IPCC, 2021

# Projected Warming with Natural Influences



IPCC, 2021

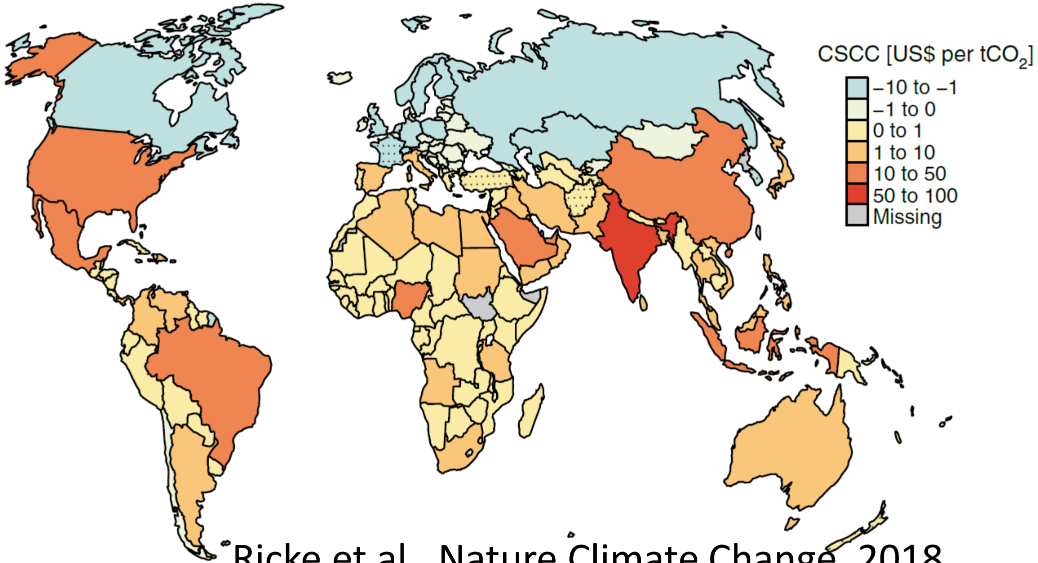
# Near-Term Climate Change Under Natural Variability



IPCC, 2021

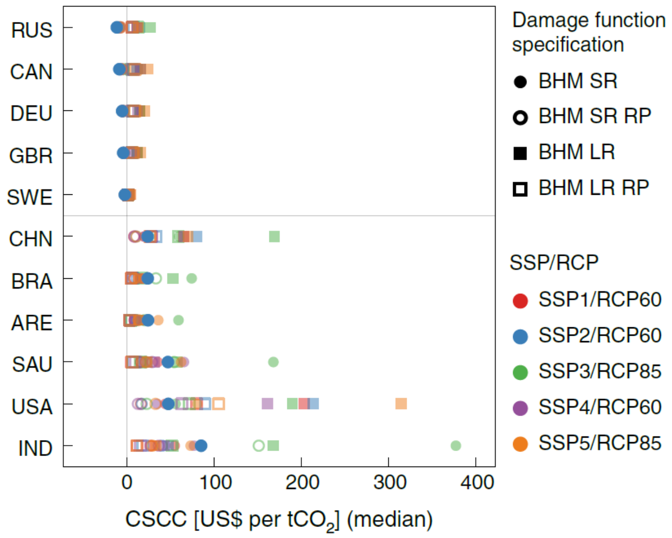
# 气候变化的影响：Social Cost of Carbon

情景：SSP2/RCP6.0 + BHM-SR + Discount



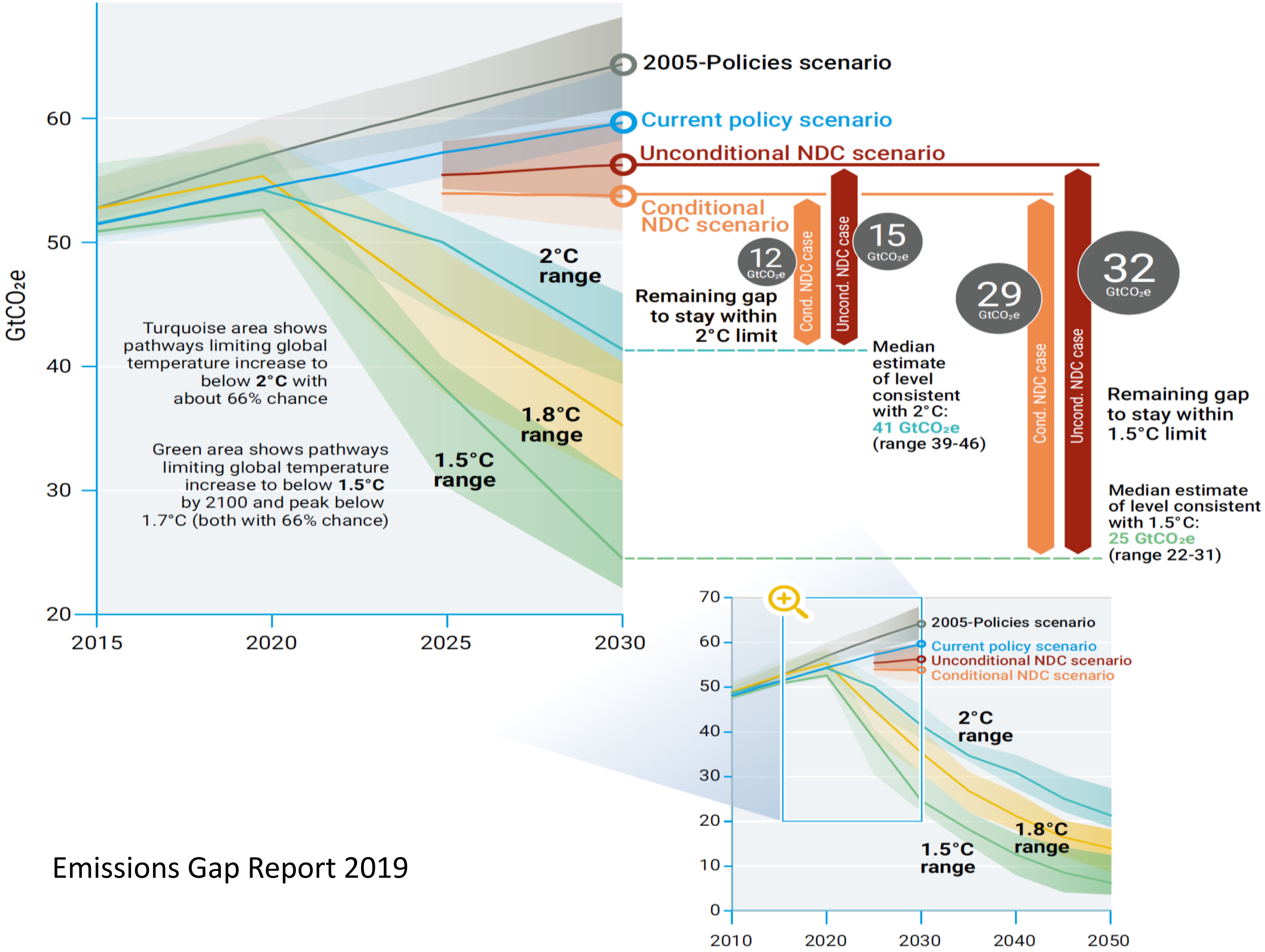
Ricke et al., Nature Climate Change, 2018

多个情景下的差异



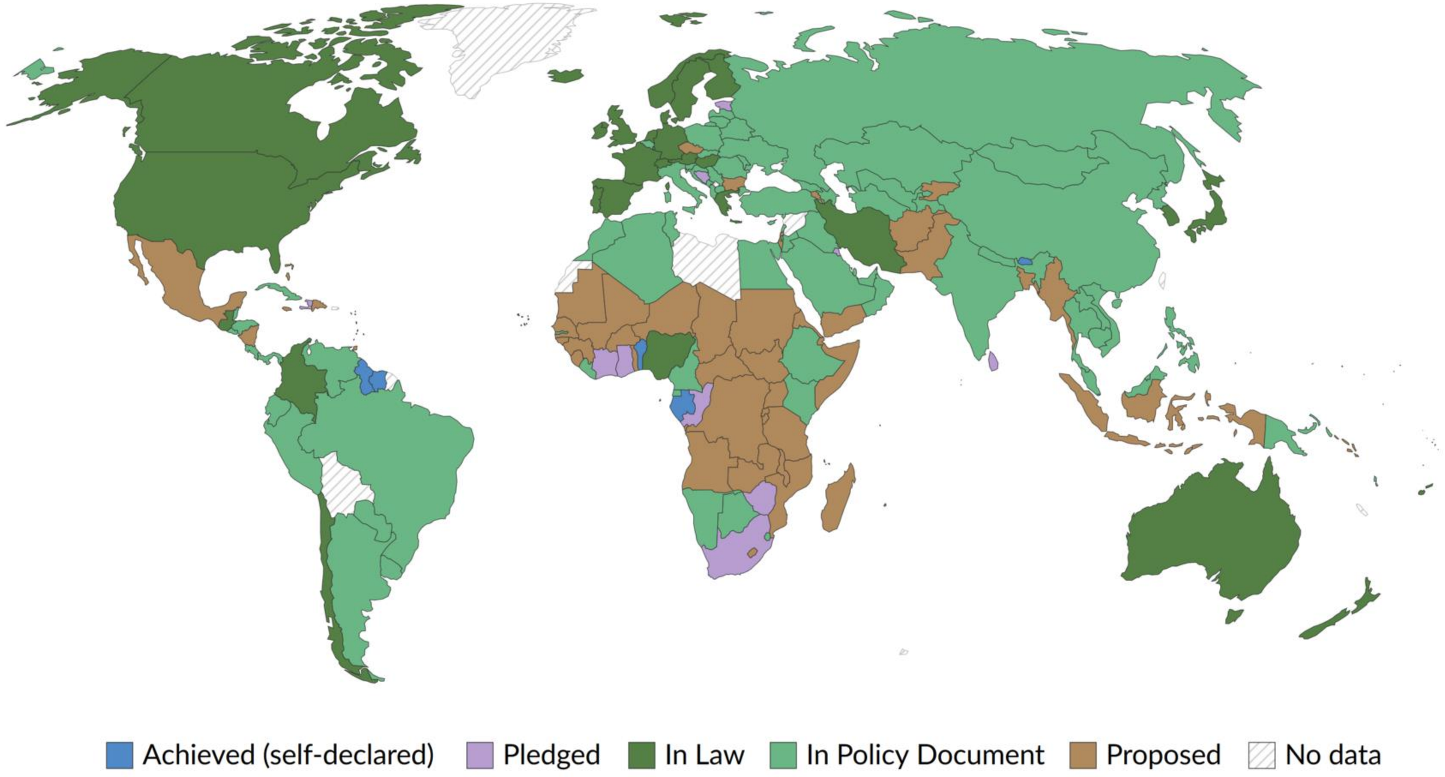
- SCC计算不确定性很大：受未来情景、气候模拟、经济计算影响
- 相比之下，碳价为：中国（2024年）~ 15 US$/tCO$_2$；欧盟 > 60 US$/tCO$_2$

# Towards 1.5$^0$C Warming: Is It Possible ?



Emissions Gap Report 2019

# Carbon Neutrality ?



Status of net-zero carbon emissions targets as of October, 2023

Our World in Data

The inclusion criteria for net-zero commitments may vary from country to country. For example, the inclusion of international aviation emissions; or the acceptance of carbon offsets. To see the year for which countries have pledged to achieve net-zero, hover over the country in the interactive version of this chart.

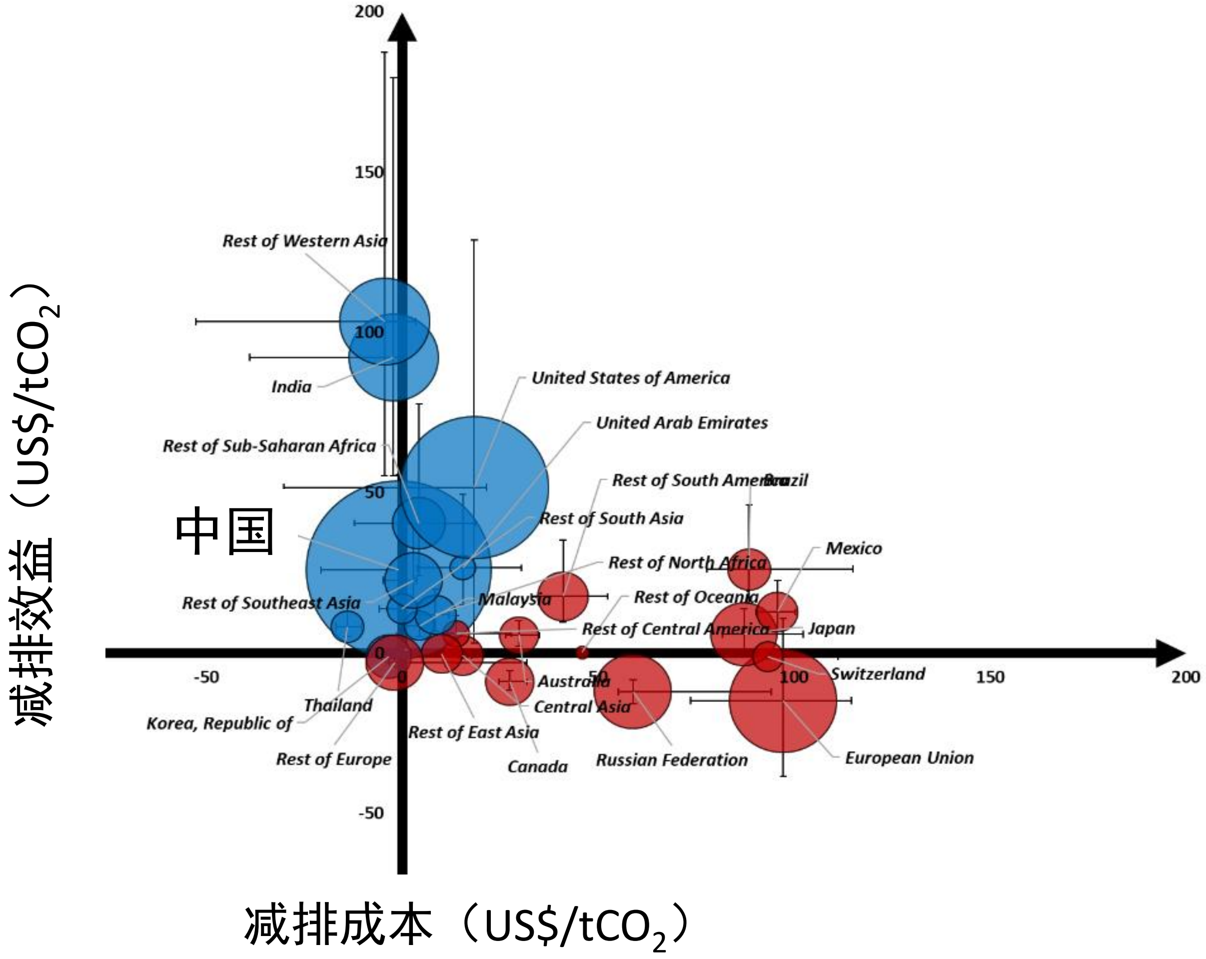
**Data source:** Energy and Climate Intelligence Unit, Data-Driven EnviroLab, NewClimate Institute, Oxford Net Zero - Net Zero Tracker (2023)

OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

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

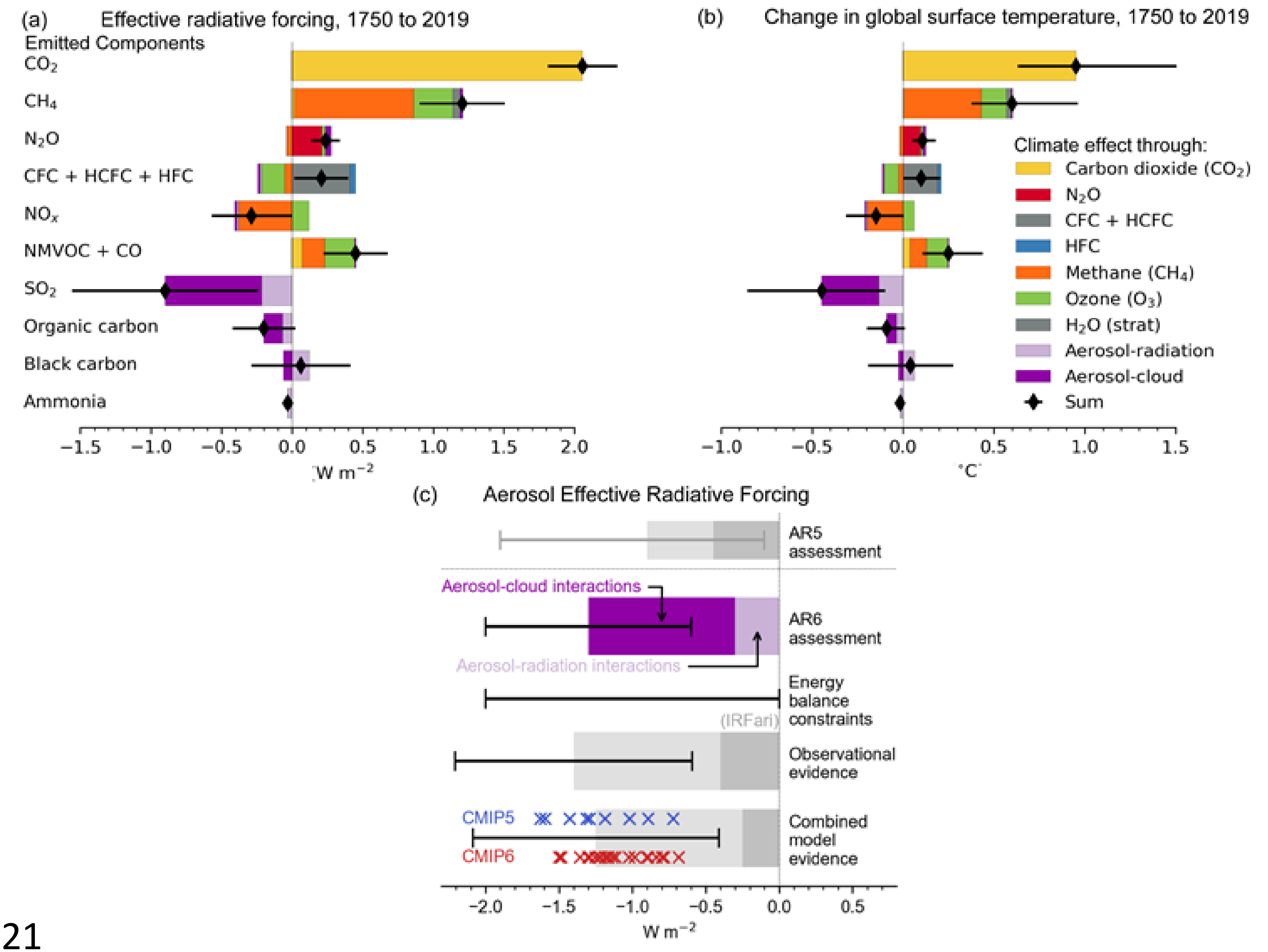


Liu et al., Nature Communications, 2022

# Quiz

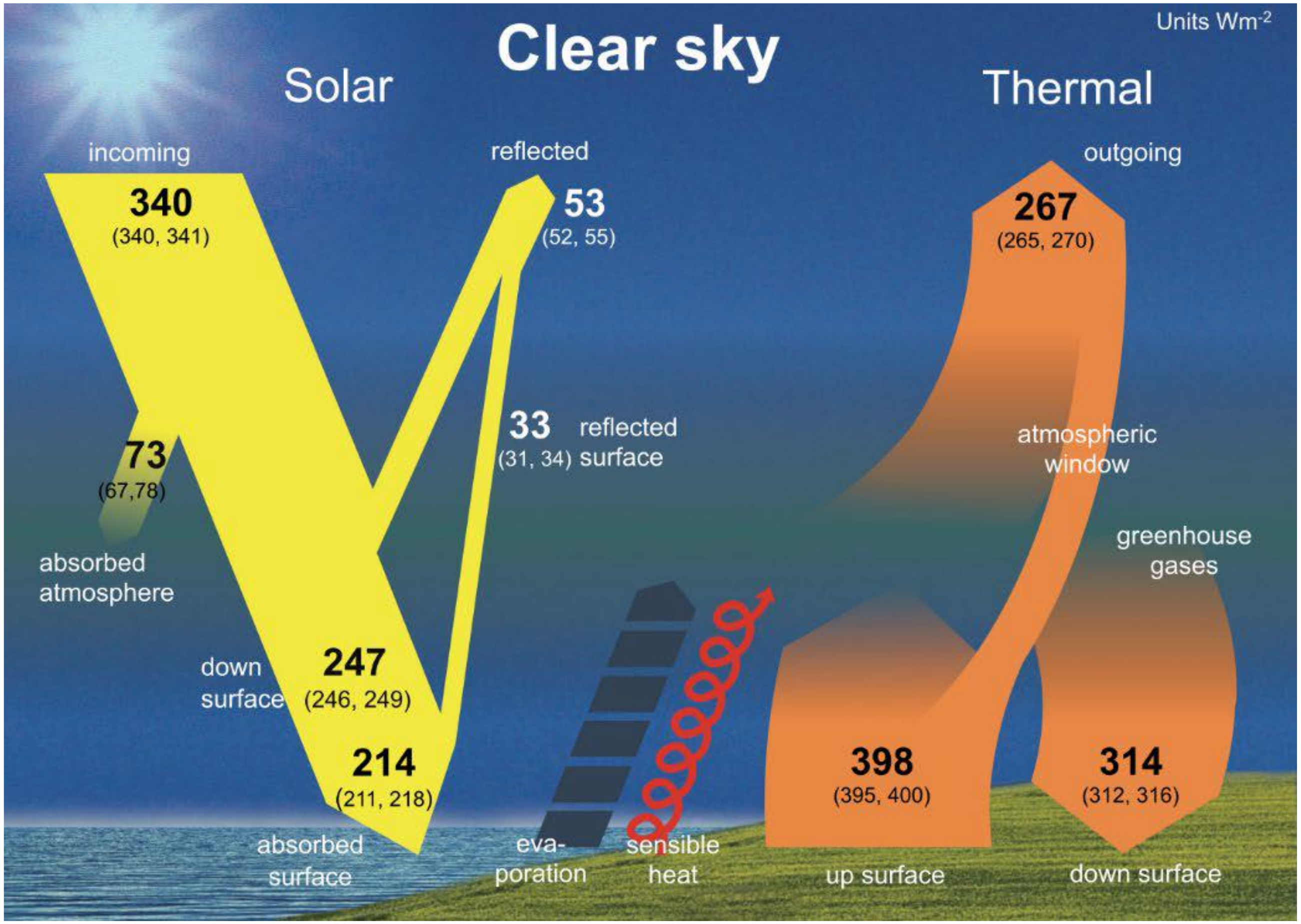
1. **Explain the direct, semi-direct and indirect radiative forcing of aerosols**
2. **Explain the different effects of $CH_4$ emission changes and $CH_4$ concentration changes in climate forcing**
3. **Explain the role of NOx emissions in climate forcing**
4. **Surface warming in the Arctic is most 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.)?**

# Effective Radiative Forcing



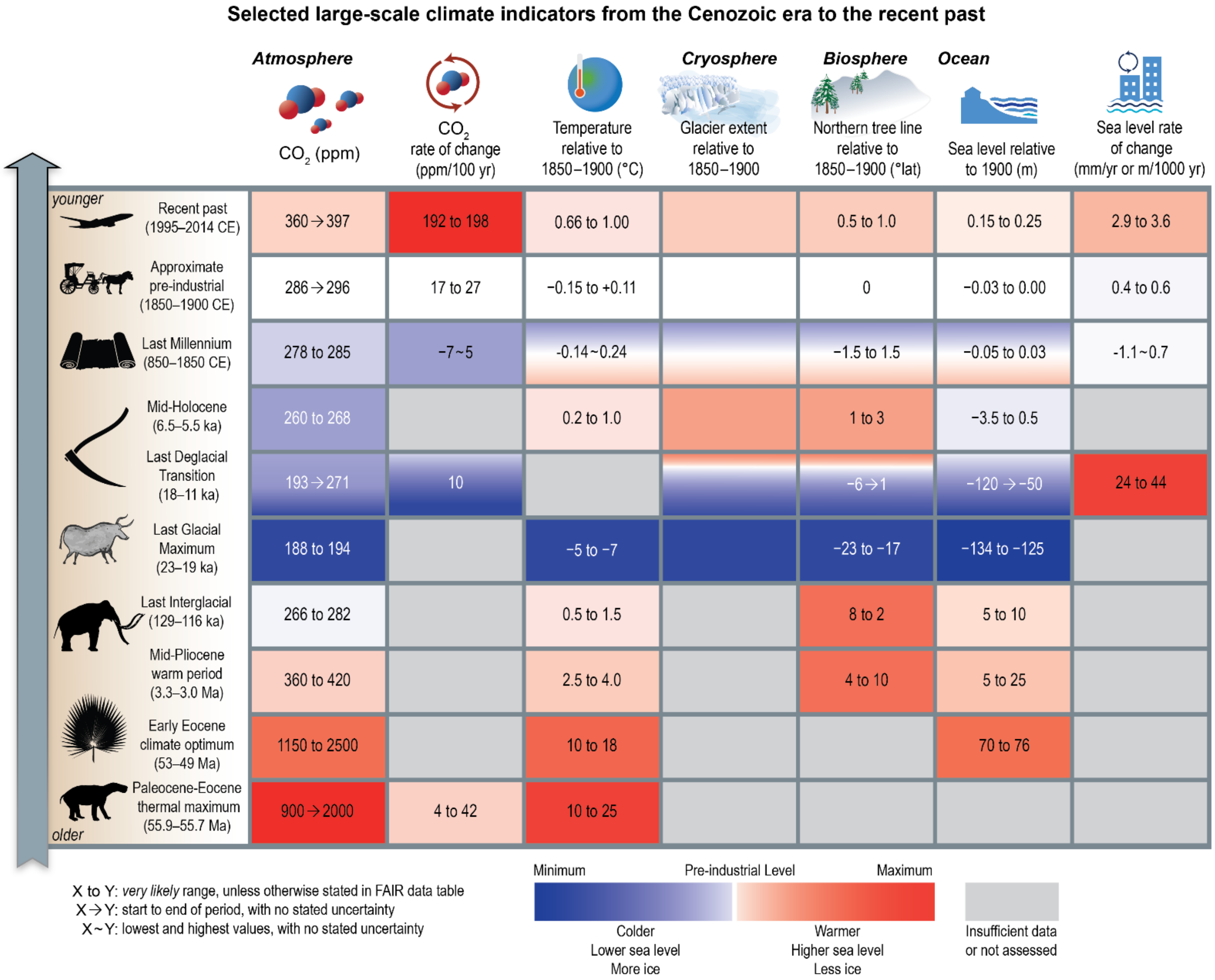
IPCC, 2021

# Clear Sky Radiative Budget of Earth



IPCC, 2021

# Changes in Climate Indicators



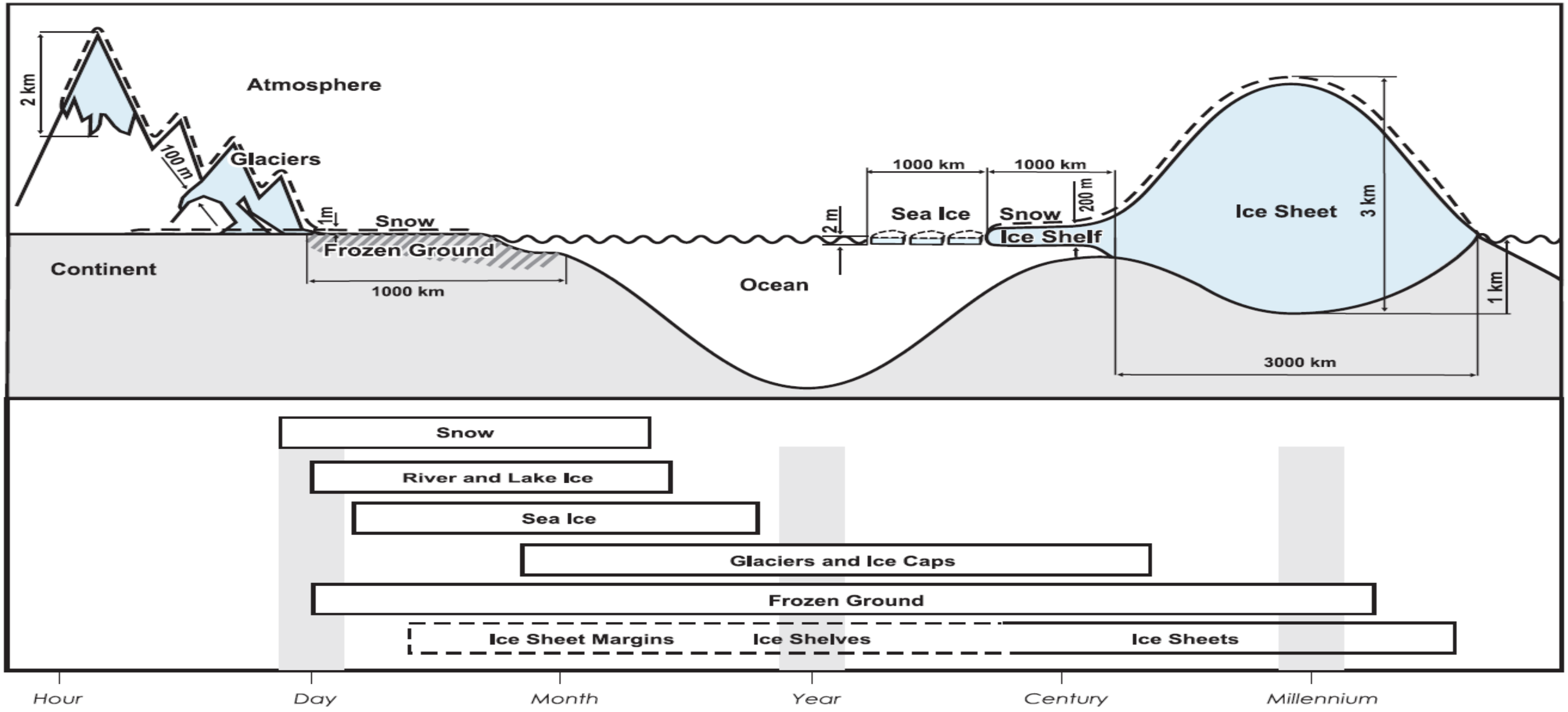
**Selected large-scale climate indicators from the Cenozoic era to the recent past**

|  | $CO_2$ (ppm) | $CO_2$ rate of change (ppm/100 yr) | Temperature relative to 1850–1900 (°C) | Glacier extent relative to 1850–1900 | Northern tree line relative to 1850–1900 (°lat) | Sea level relative to 1900 (m) | Sea level rate of change (mm/yr or m/1000 yr) |
|---|---|---|---|---|---|---|---|
| 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) | 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

IPCC, 2021

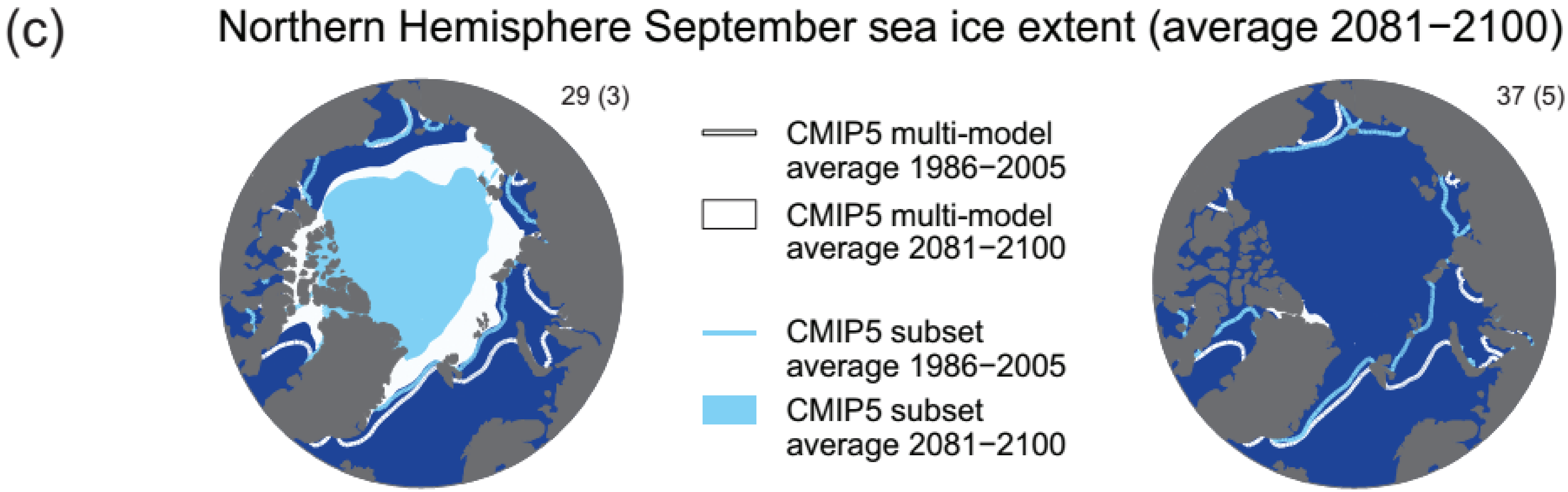
# Cryosphere and Its Components



| Cryospheric Component | Area ($10^6$ km$^2$) | Ice Volume ($10^6$ km$^3$) | 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

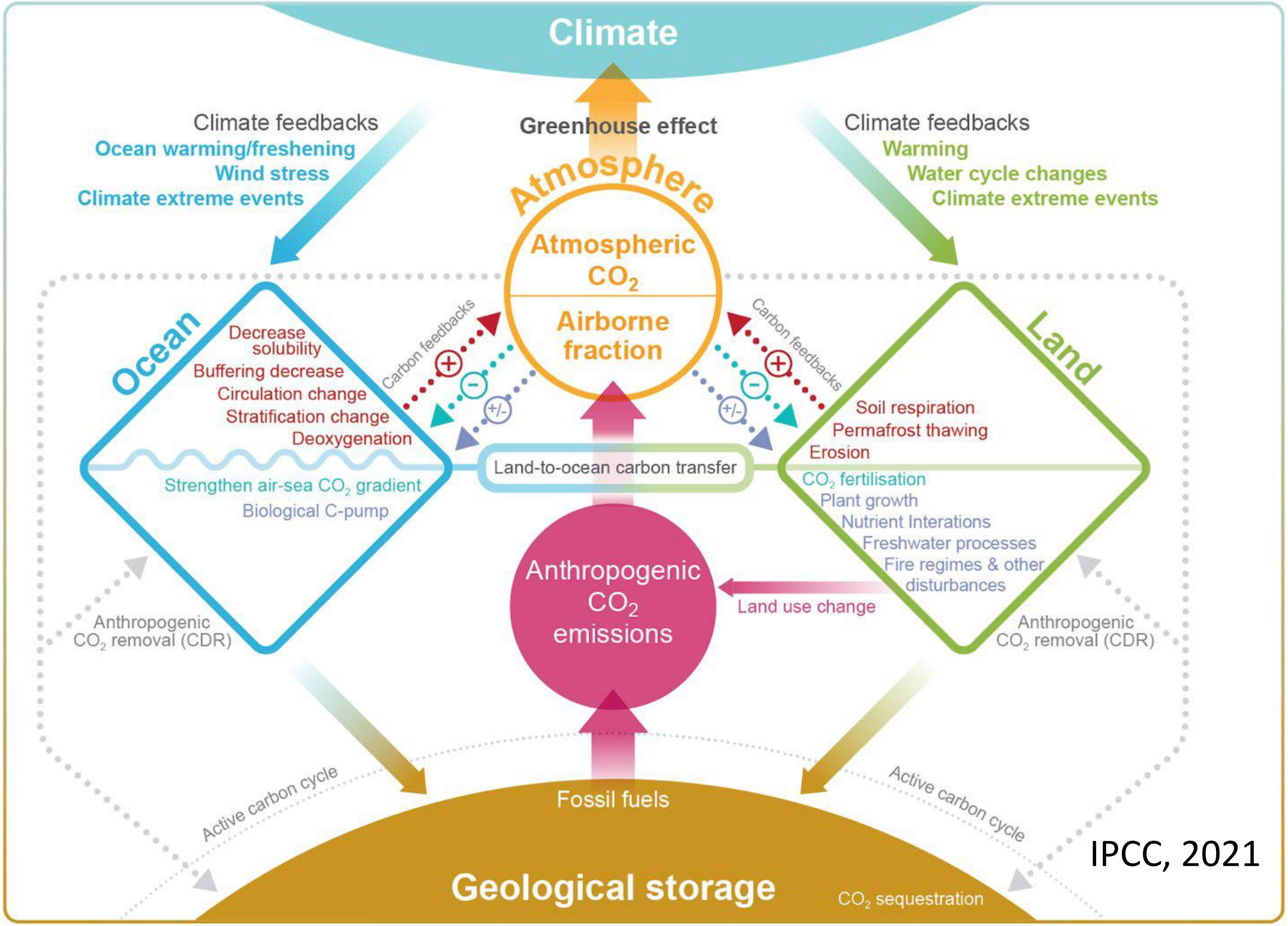
# Projected Change in Sea Ice Extent



(c) Northern Hemisphere September sea ice extent (average 2081−2100)

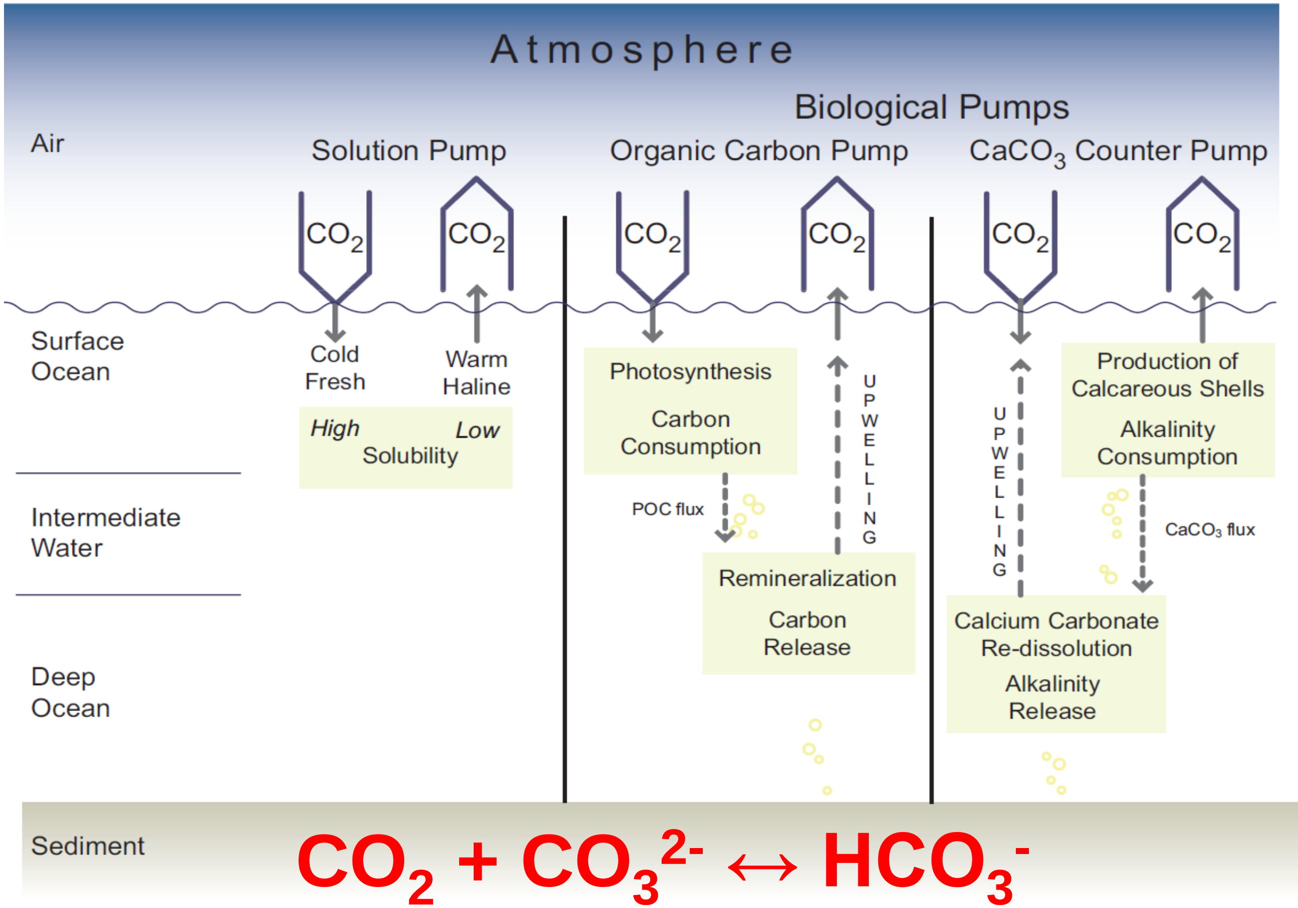
IPCC, 2013

# Feedbacks of Carbon Cycle



IPCC, 2021

# Feedbacks of Ocean Carbon Cycle

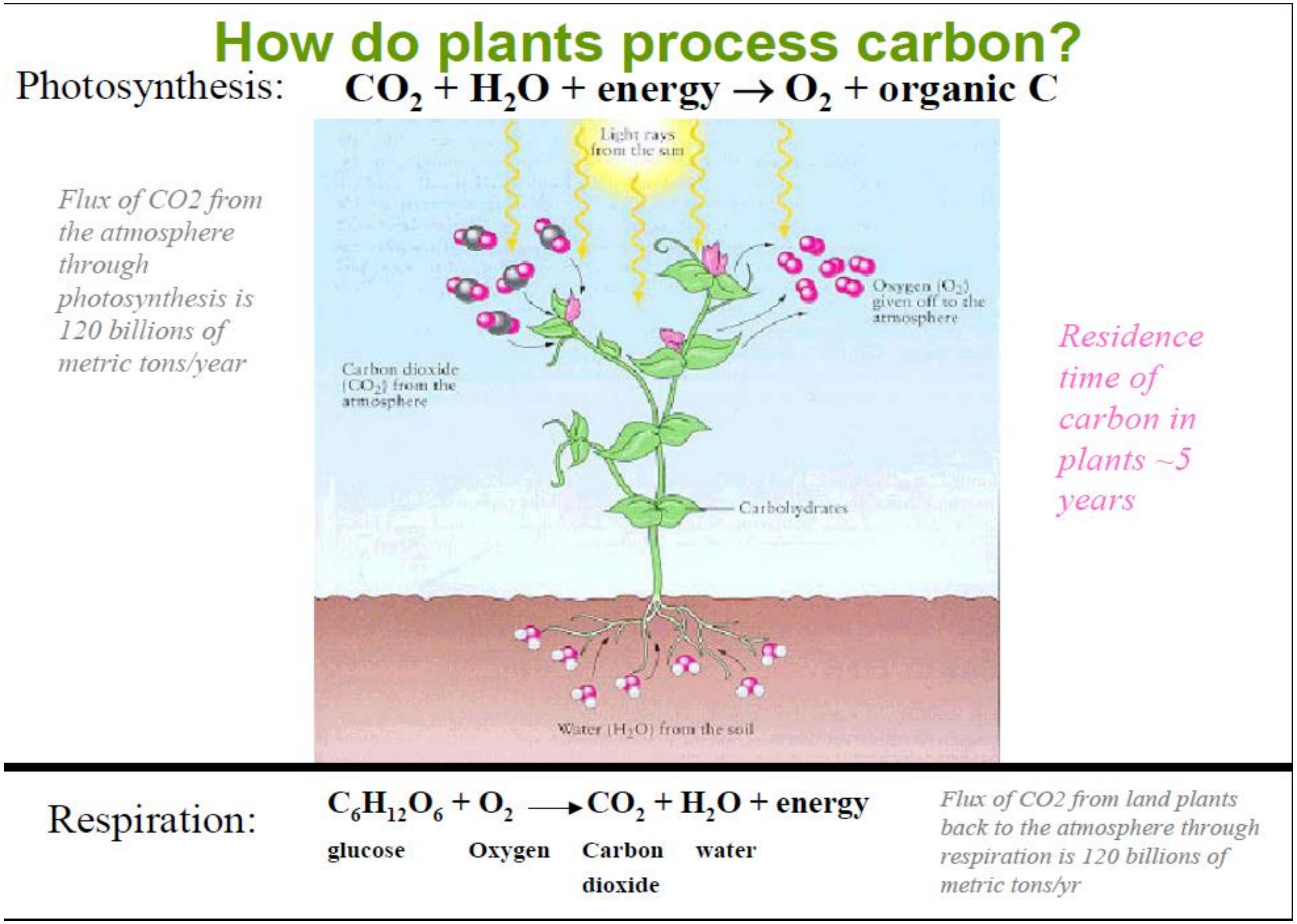


$$CO_2 + CO_3^{2-} \leftrightarrow HCO_3^-$$

- $CO_3^{2-}$
- 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*

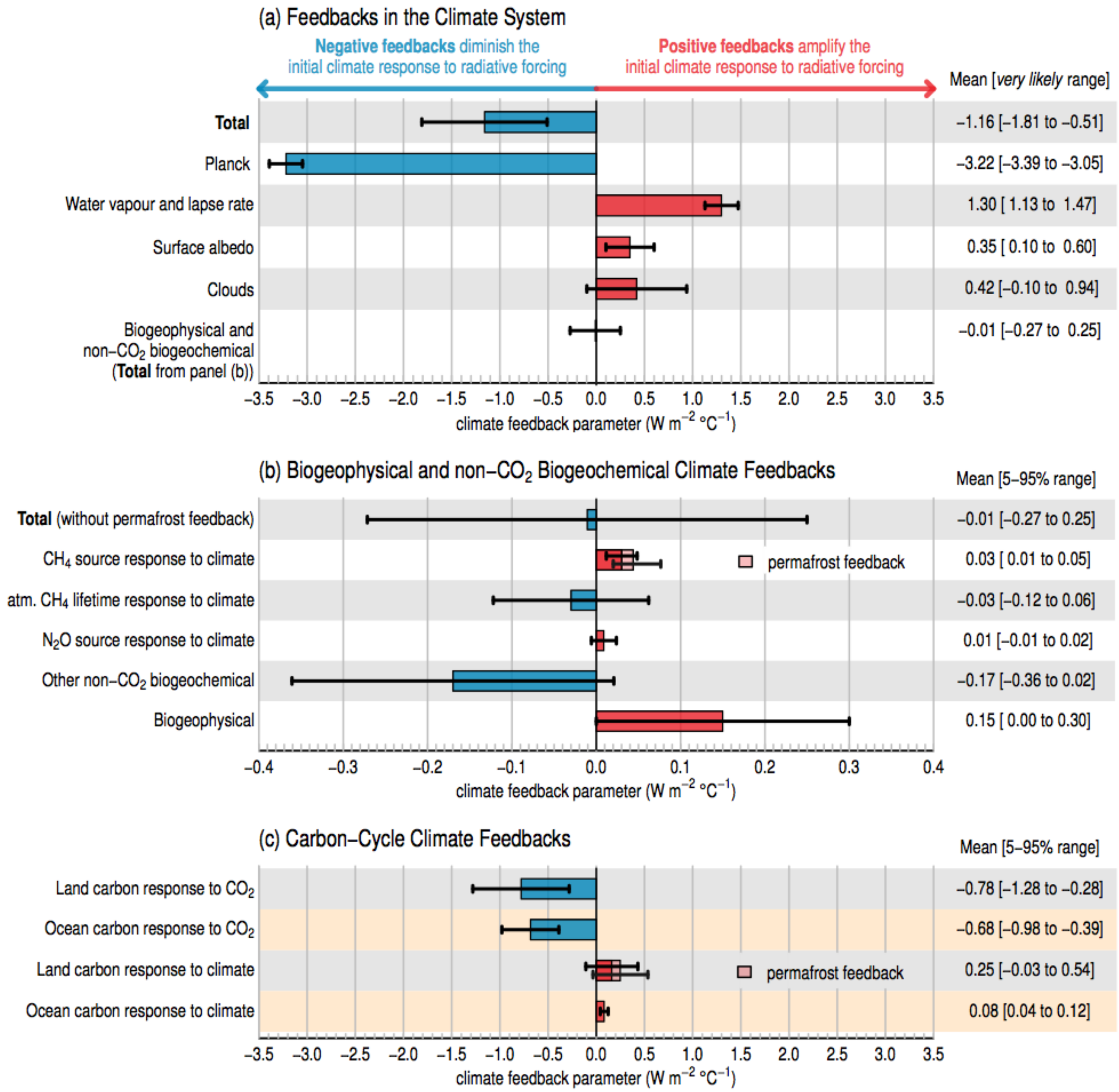
Respiration: $C_6H_{12}O_6 + O_2 \longrightarrow CO_2 + H_2O + \text{energy}$

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