Climate Physics and Chemistry

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Outline

- **Current climate**
- **Climate change in the Industrial Era**
- **Radiative forcings and climate feedbacks**

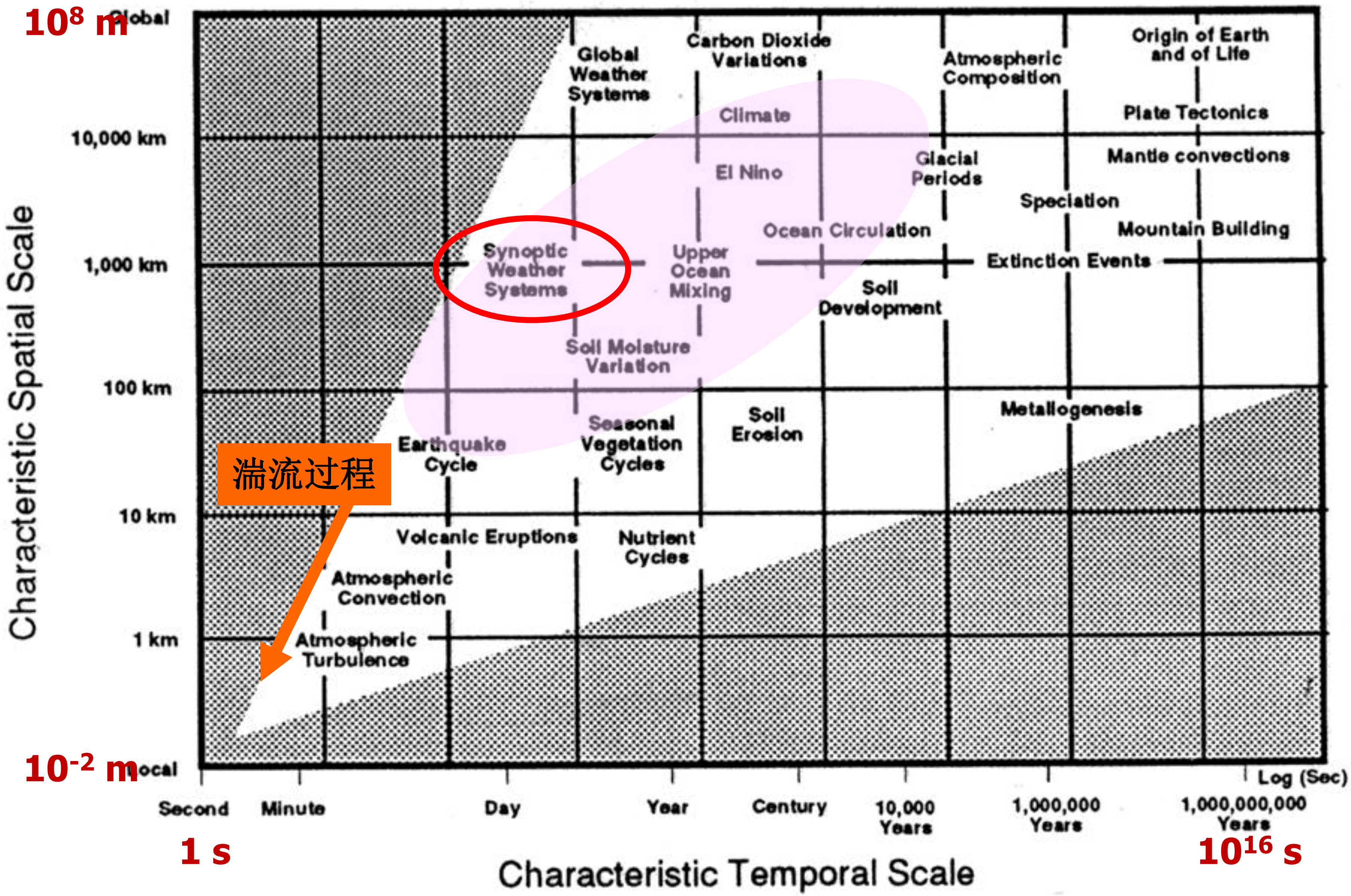
致谢：本课件中部分资料来自李成才老师（特别是关于辐射的部分）。

气候

- 气候系统：一个复杂的、各部分相互作用的系统，包括大气、陆地表面、冰雪、海洋和其它水体以及生物
- 传统/狭义上，气候通常被描述为从数月到数百万年的一段时间内（通常采用30年的时间段）的气温、降水、风等气象变量的平均值及变率

我们最关心的问题：气候系统的变化、原因（自然强迫、内部变率、人类活动）、对相关自然和人文环境的影响、以及未来气候变化和应对

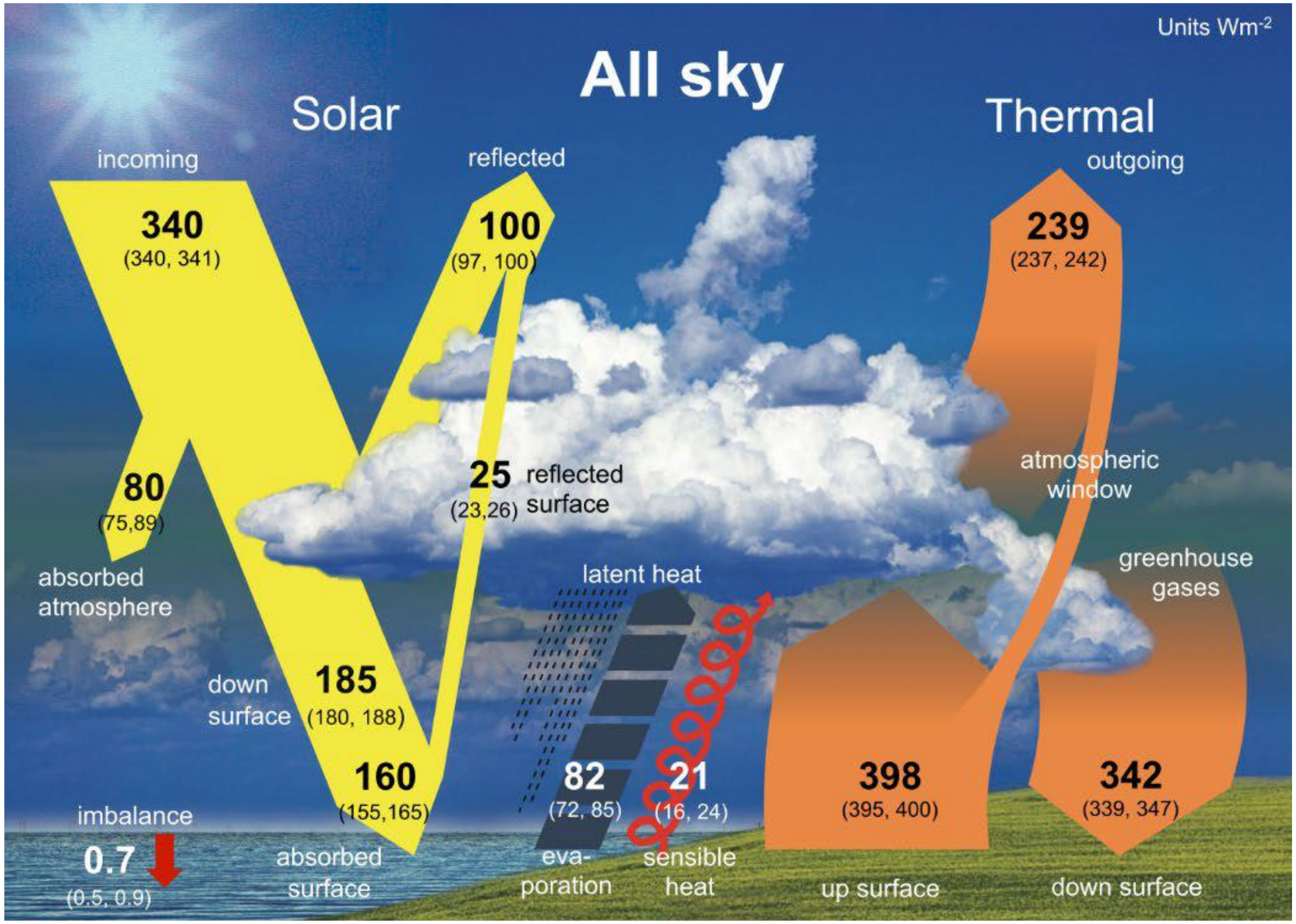
Spatiotemporal Scales in the Earth Climate System



Spatiotemporal Scales in the Atmosphere

	Scale	Name
20,000 km (weeks)		Planetary scale
2,000 km (1 week)		Synoptic scale
200 km (1 day)	Meso-α	Mesoscale
20 km (hours)	Meso-β	Mesoscale
2 km (mins)	Meso-γ	Mesoscale (convection)
200 m (mins)	Micro-α	Boundary-layer turbulence
20 m (secs)	Micro-β	Surface-layer turbulence
2 m (secs)	Micro-γ	Inertial subrange turbulence
2 mm (secs)	Micro-δ	Fine-scale turbulence
Air molecules (< 1 sec)	Molecular	Viscous dissipation subrange

Earth Energy Budget



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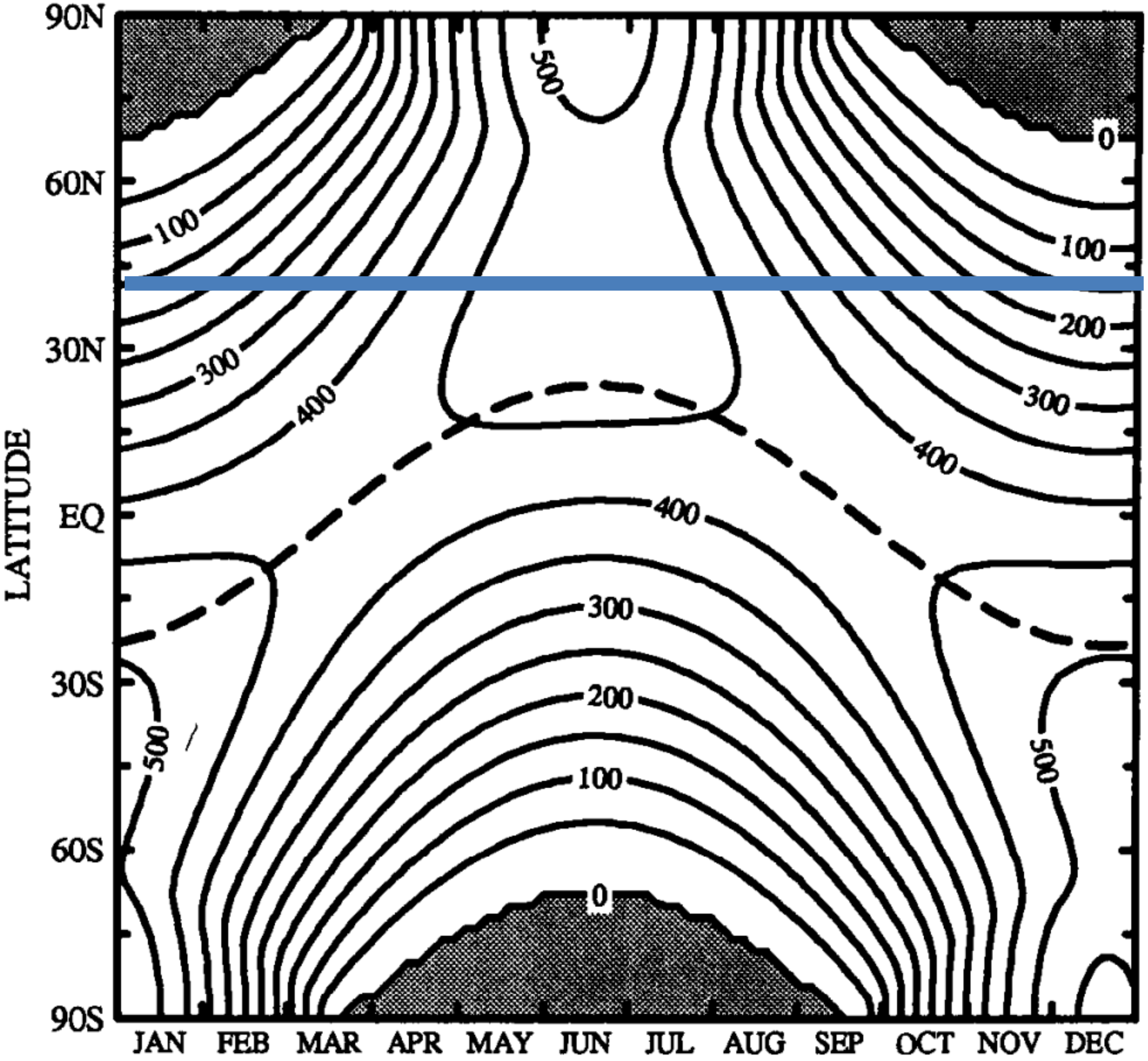
- Energy balance: Atmosphere 80+(398-40)+21+82-342-(239-40), Surface 160+342-398-21-82, Earth TOA 340-100-239
- Planetary albedo: ~29% (surface 7%, atmosphere 22%)

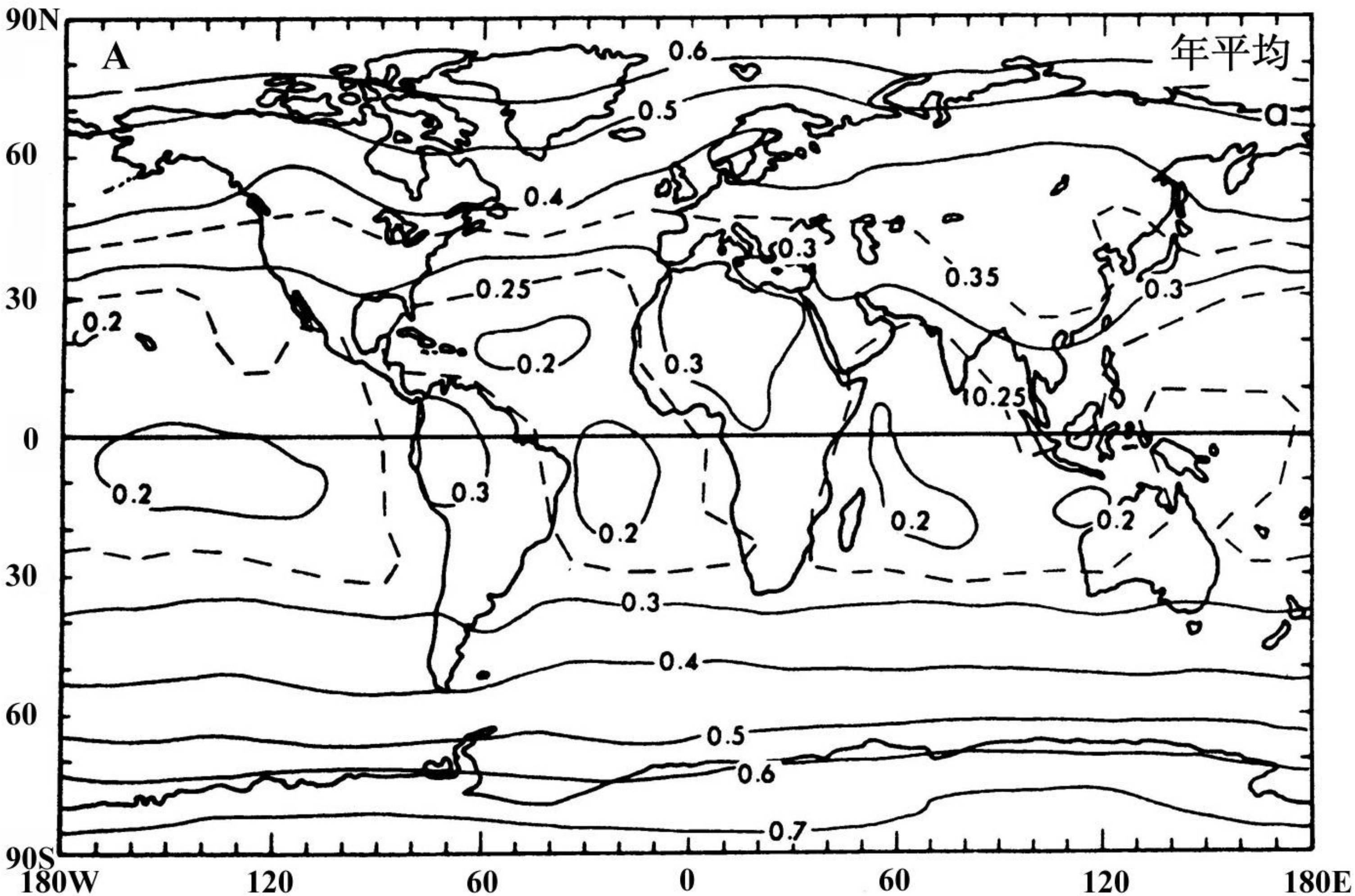
Top-Of-Atmosphere Incident Solar Radiation: F_{SW}



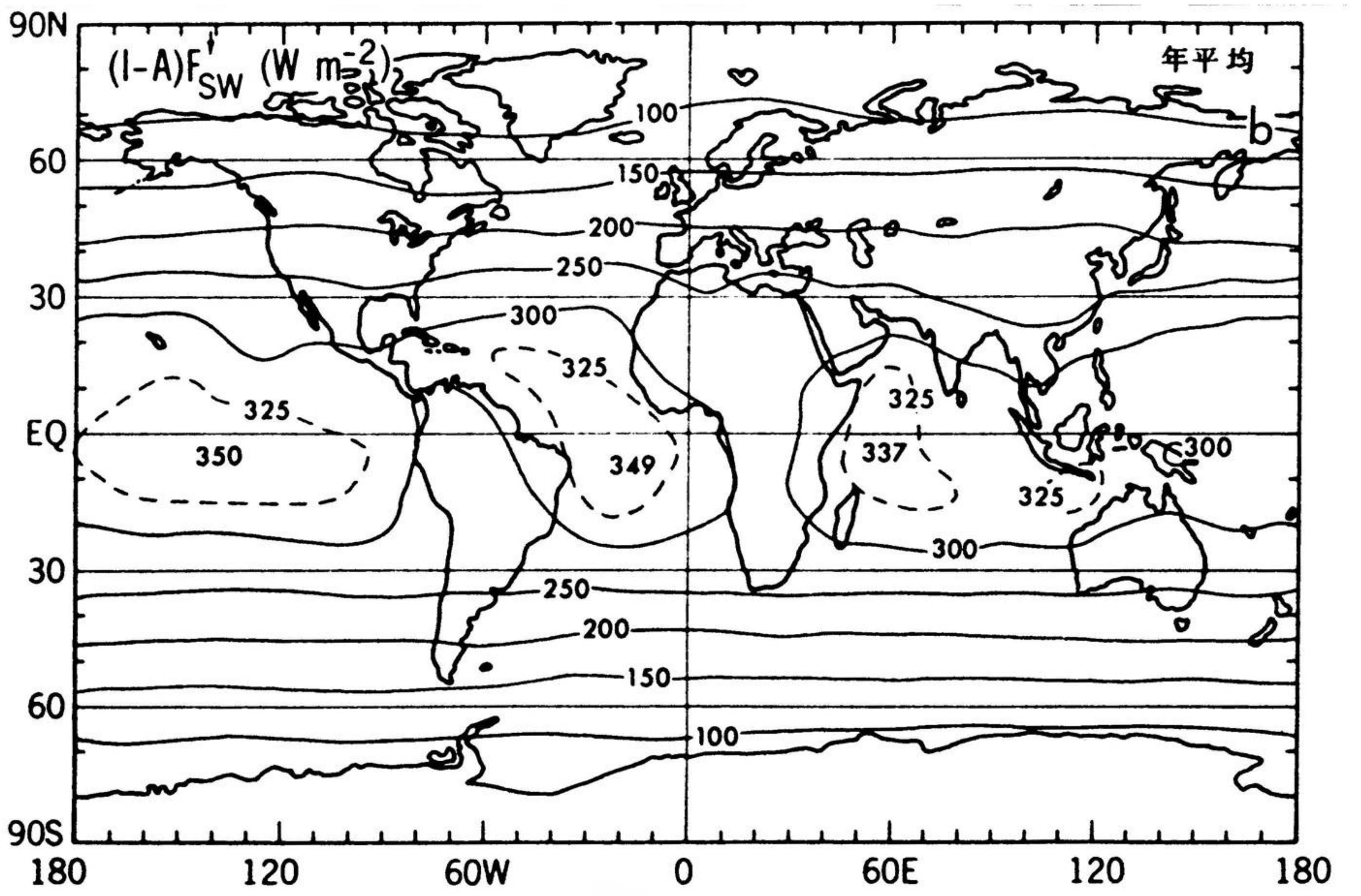
Beijing:
150-500 w/m²

15S-15N:
350-450 w/m²

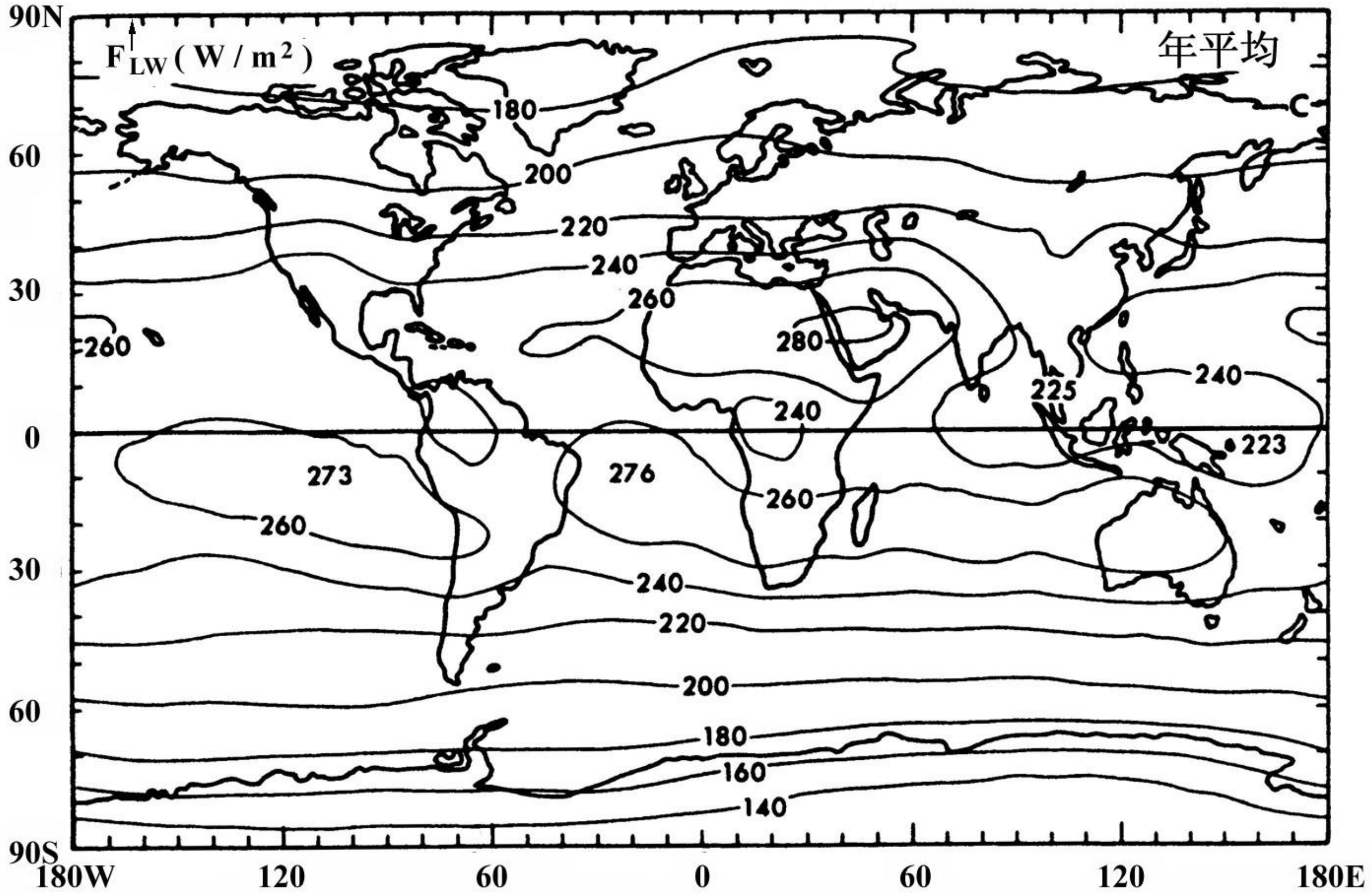
Planetary Albedo (at TOA): *R*



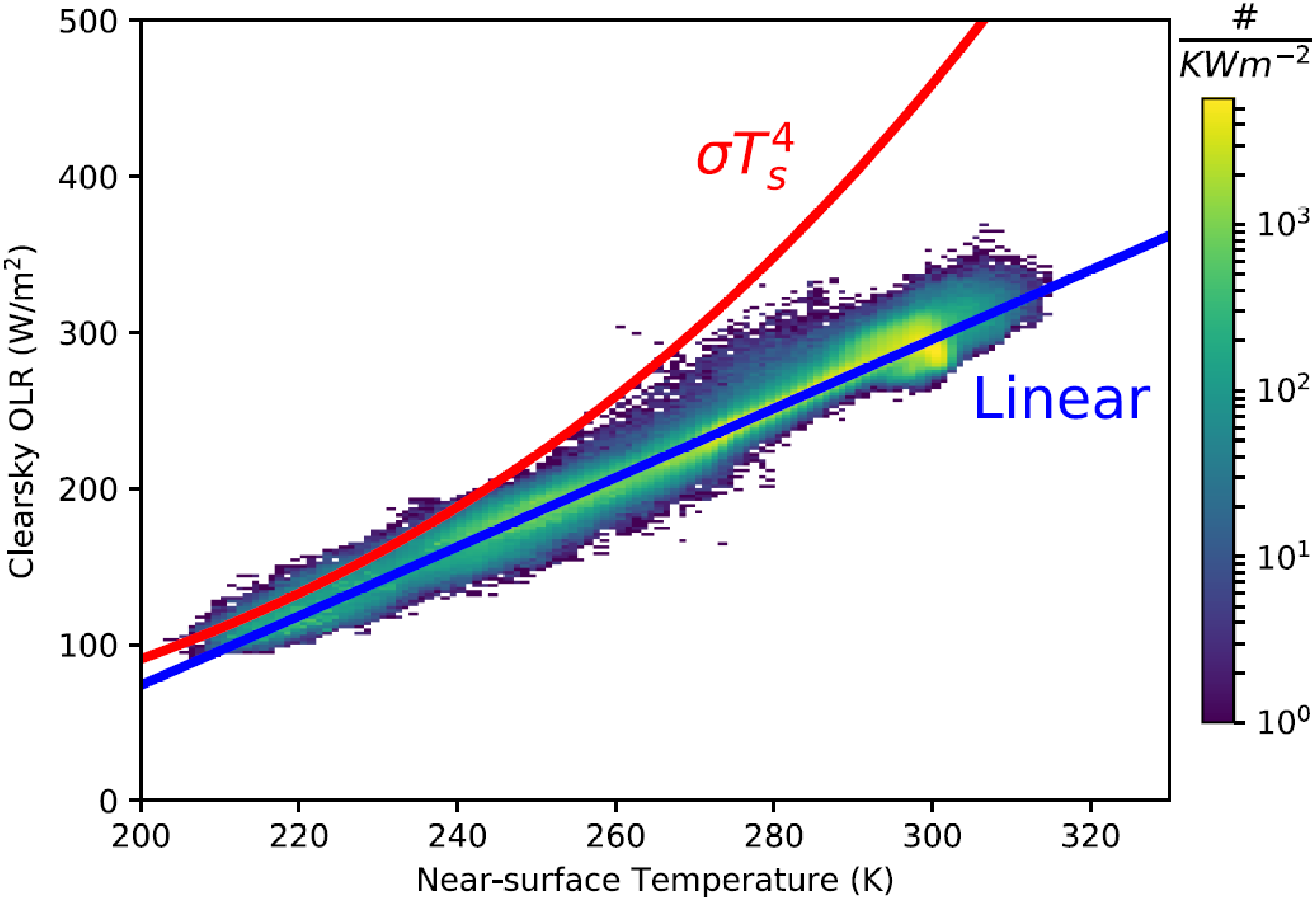
TOA Net Downward Solar Radiation: $(1 - R)\ F_{SW}$



TOA Upward Longwave Radiation: F_{LW}

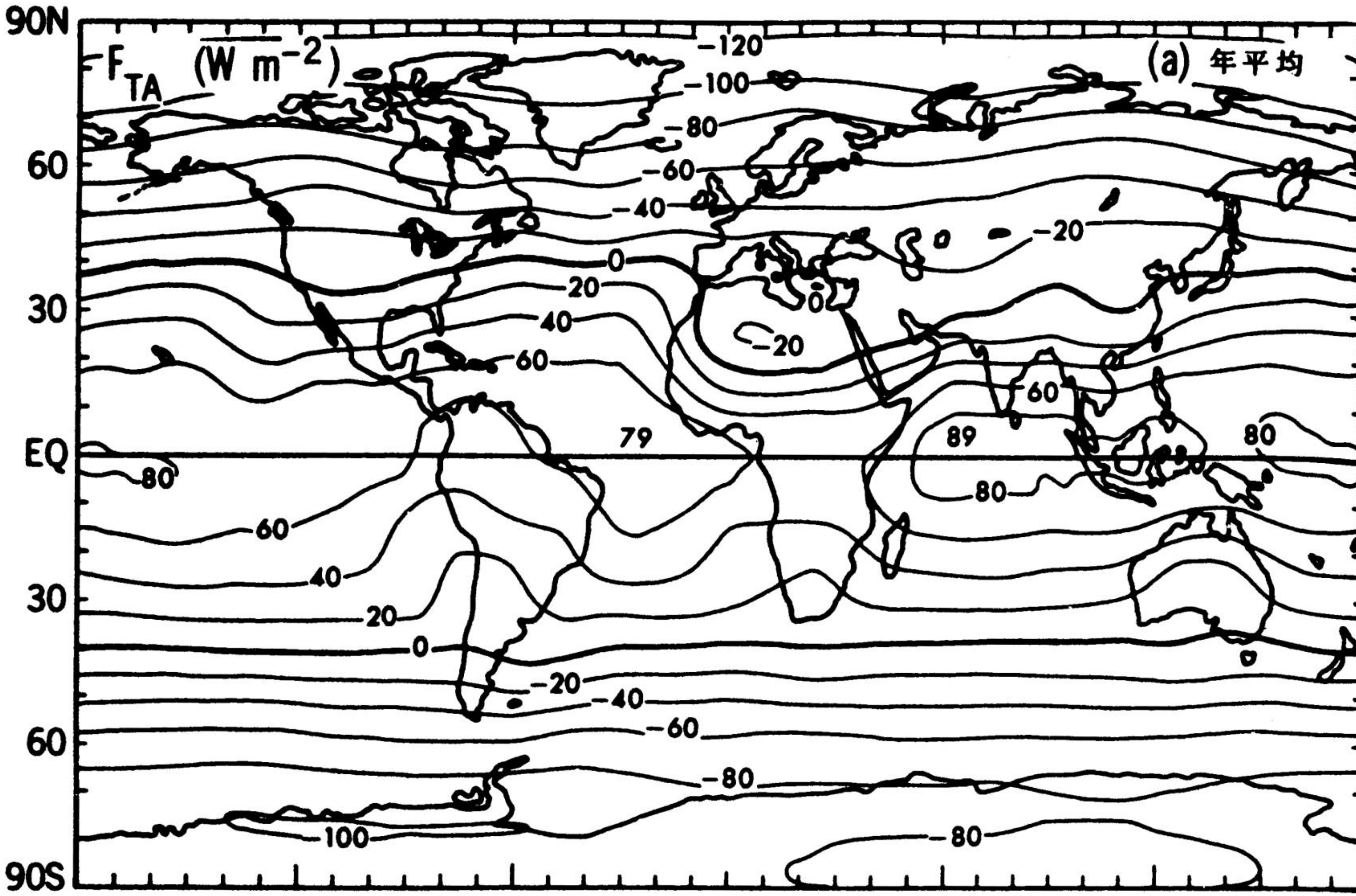


F_{LW} As a Linear Function of Surface Temperature

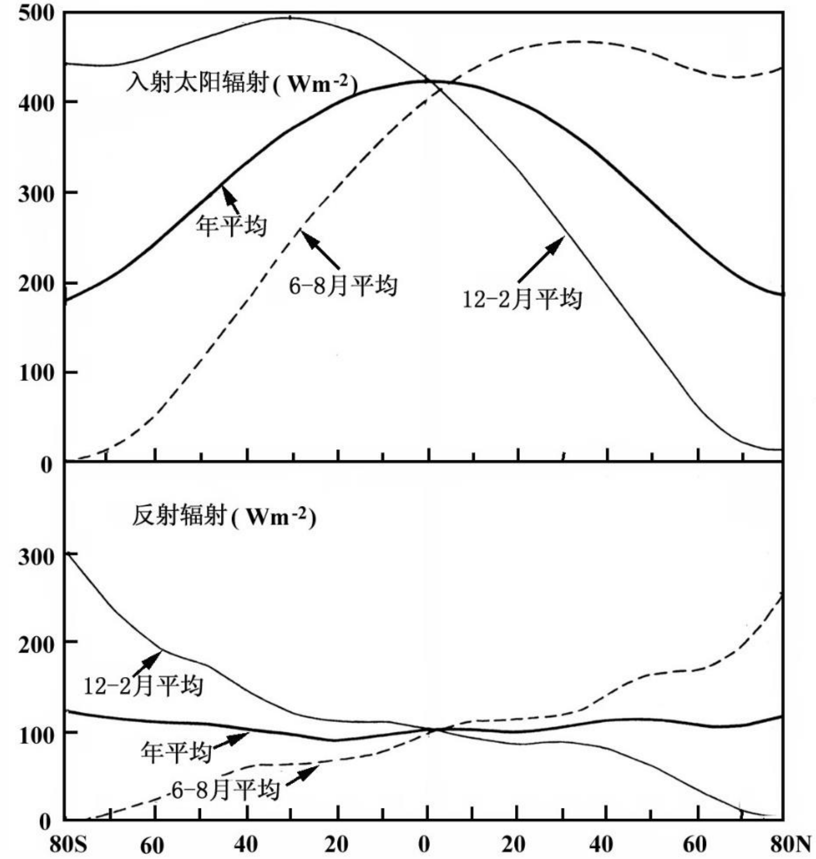


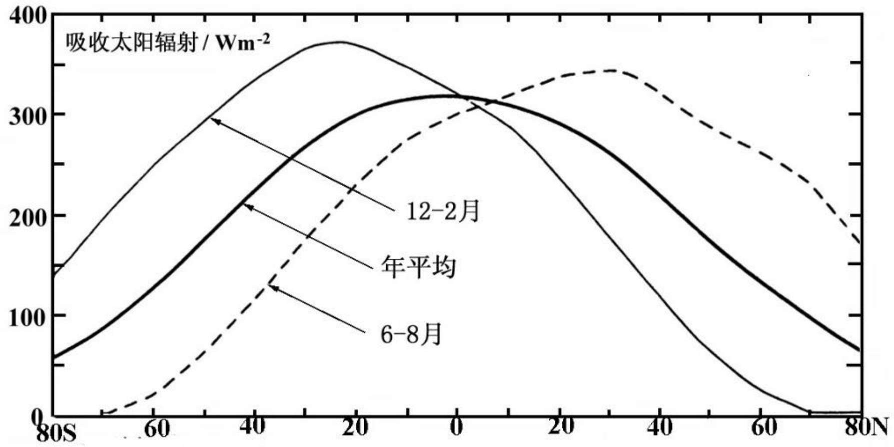
Koll et al., 2018, PNAS

TOA Net Radiation: F_{TA}

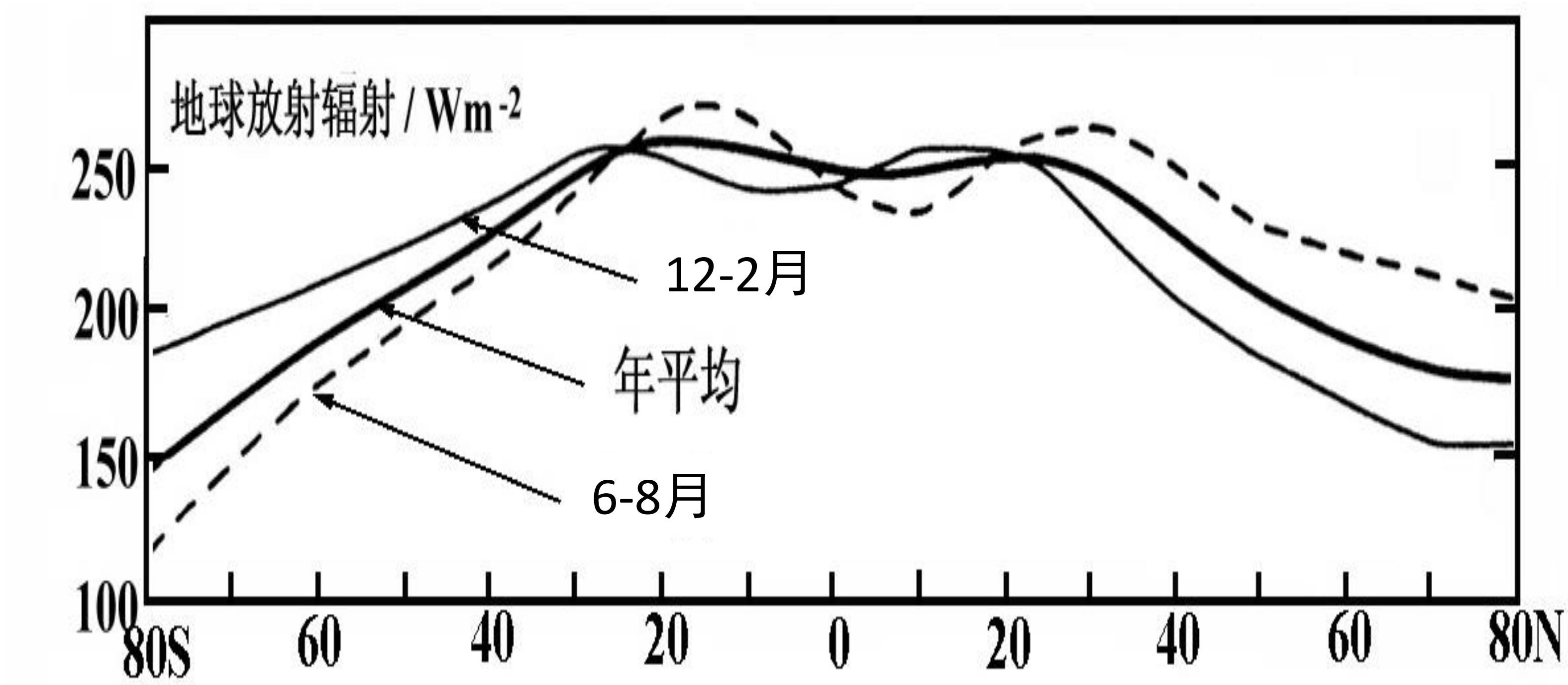


TOA Solar Radiation: Meridional Distribution



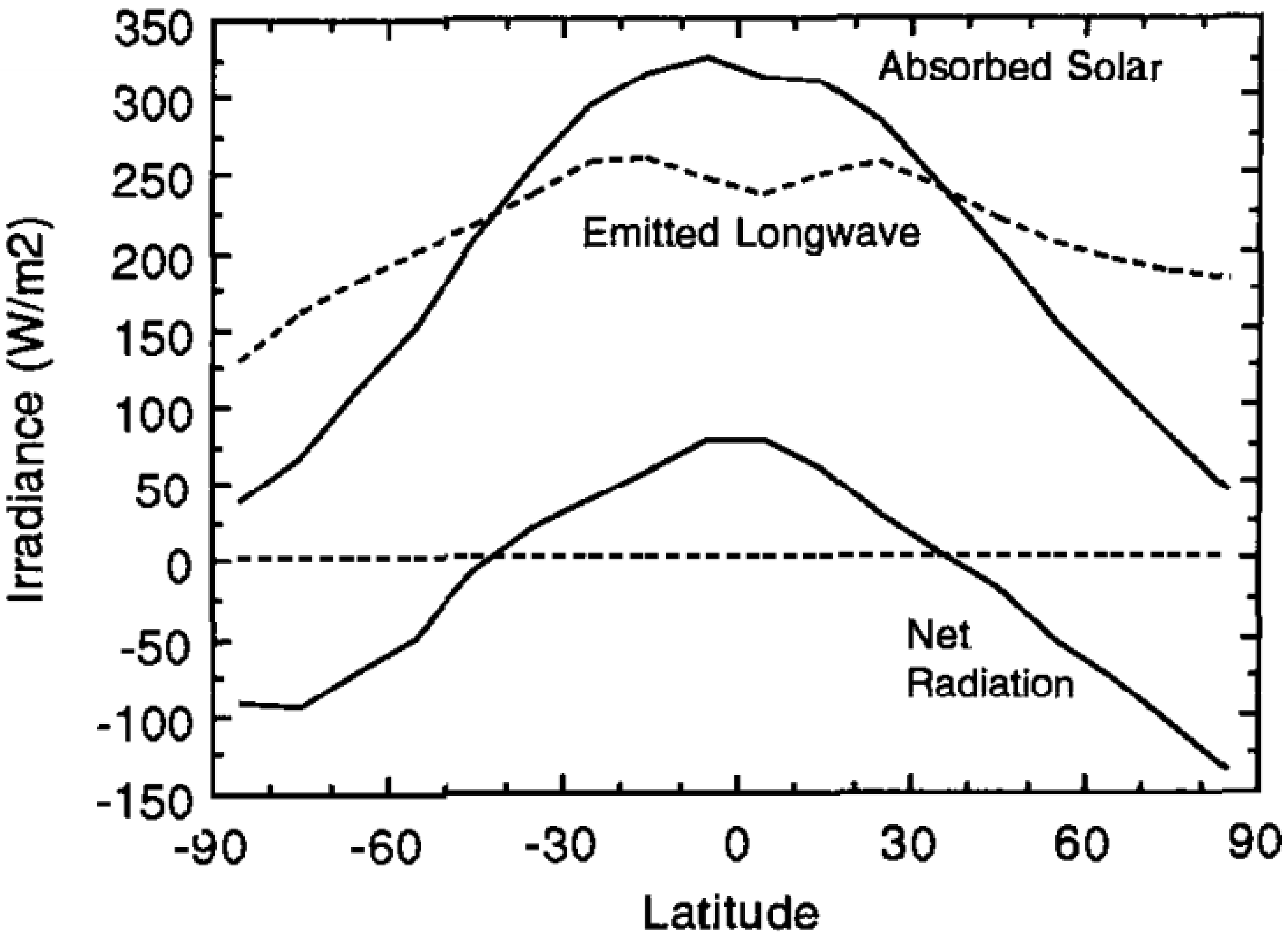


TOA Upward Longwave Radiation: Meridional Distribution

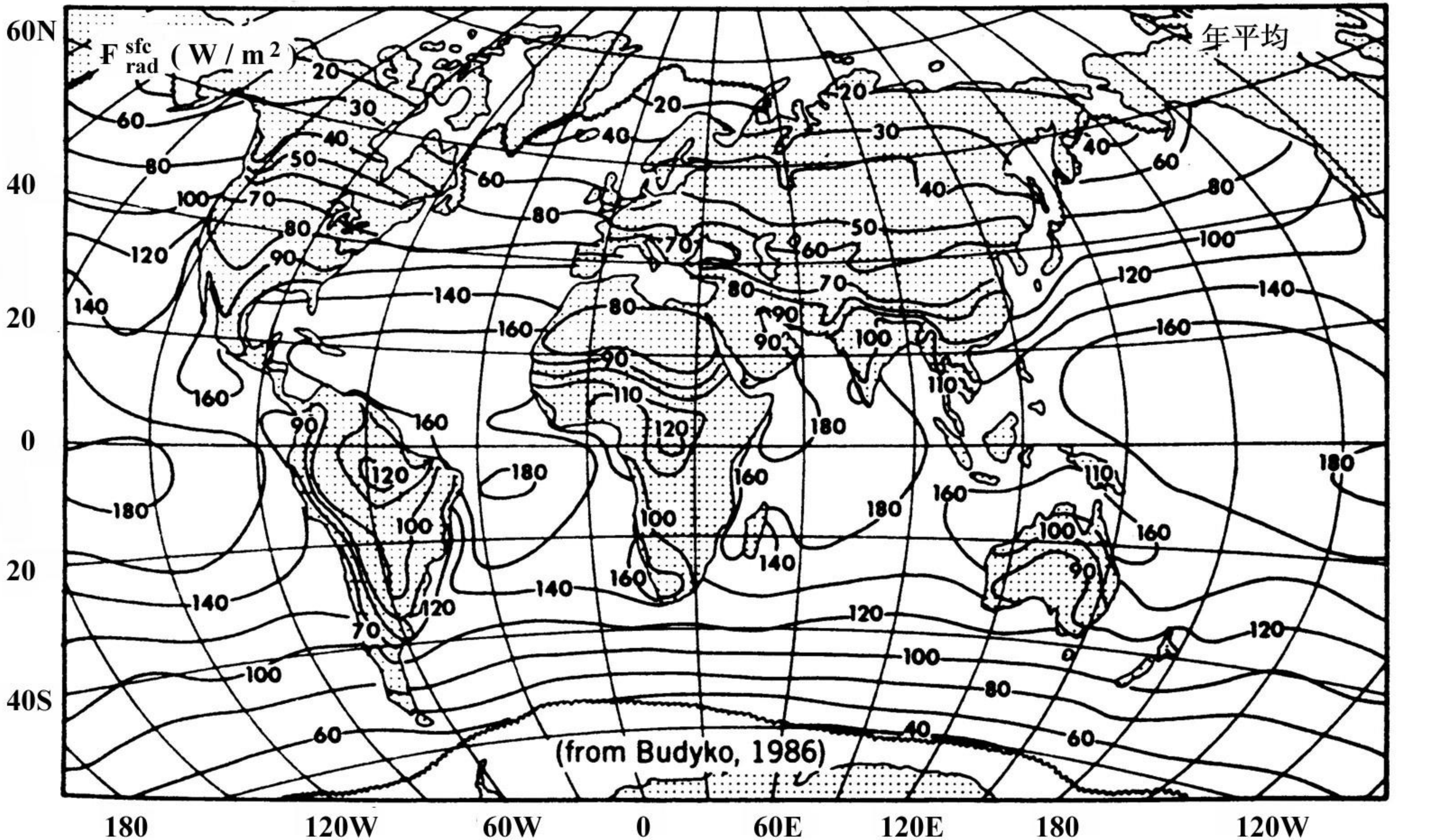


- High values of about 250 wm^{-2} in 30S-30N
- Higher values in northern than southern polar regions
- Weaker gradient than solar radiation

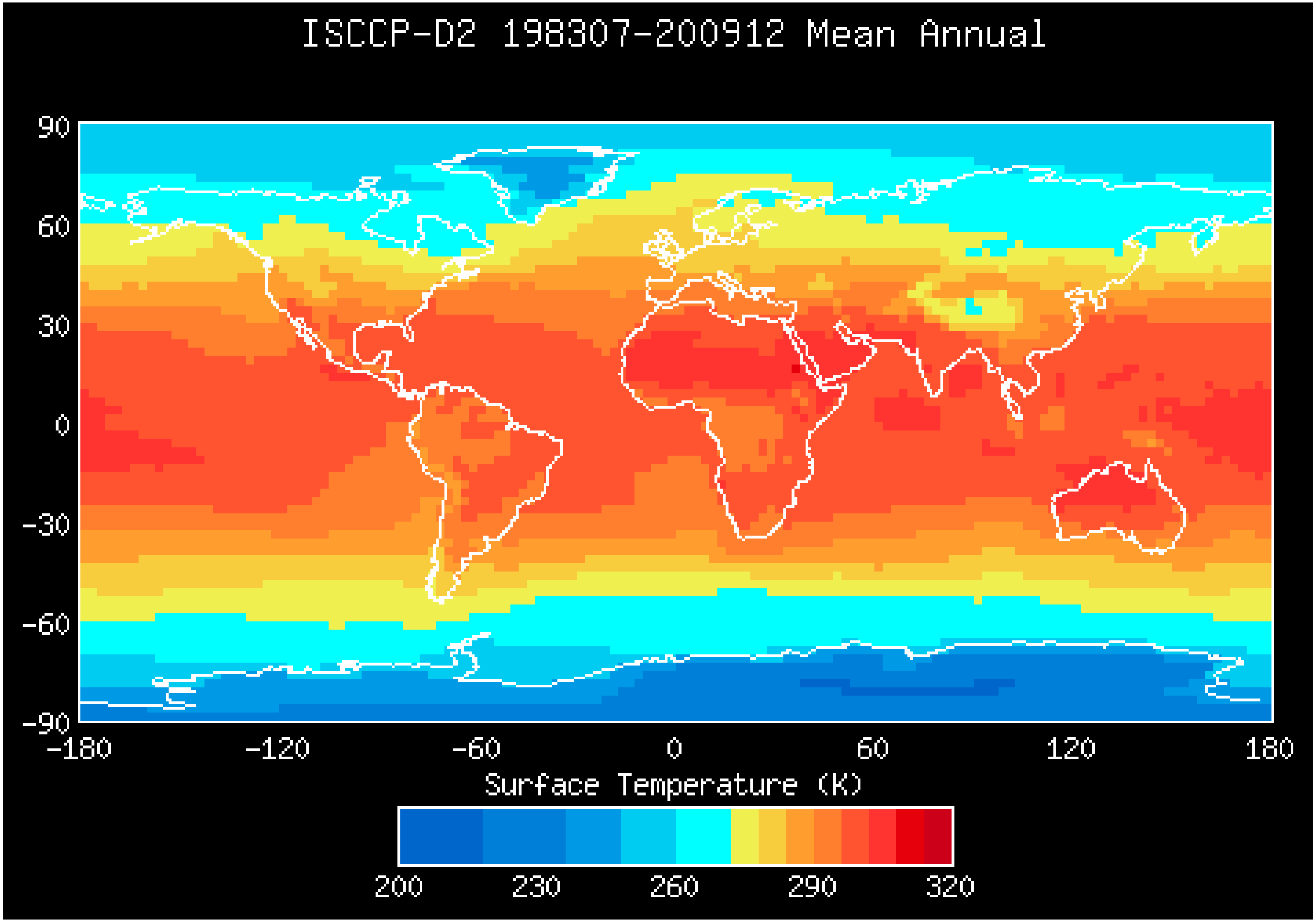
TOA Net Flux (Solar + Longwave): Meridional Distribution



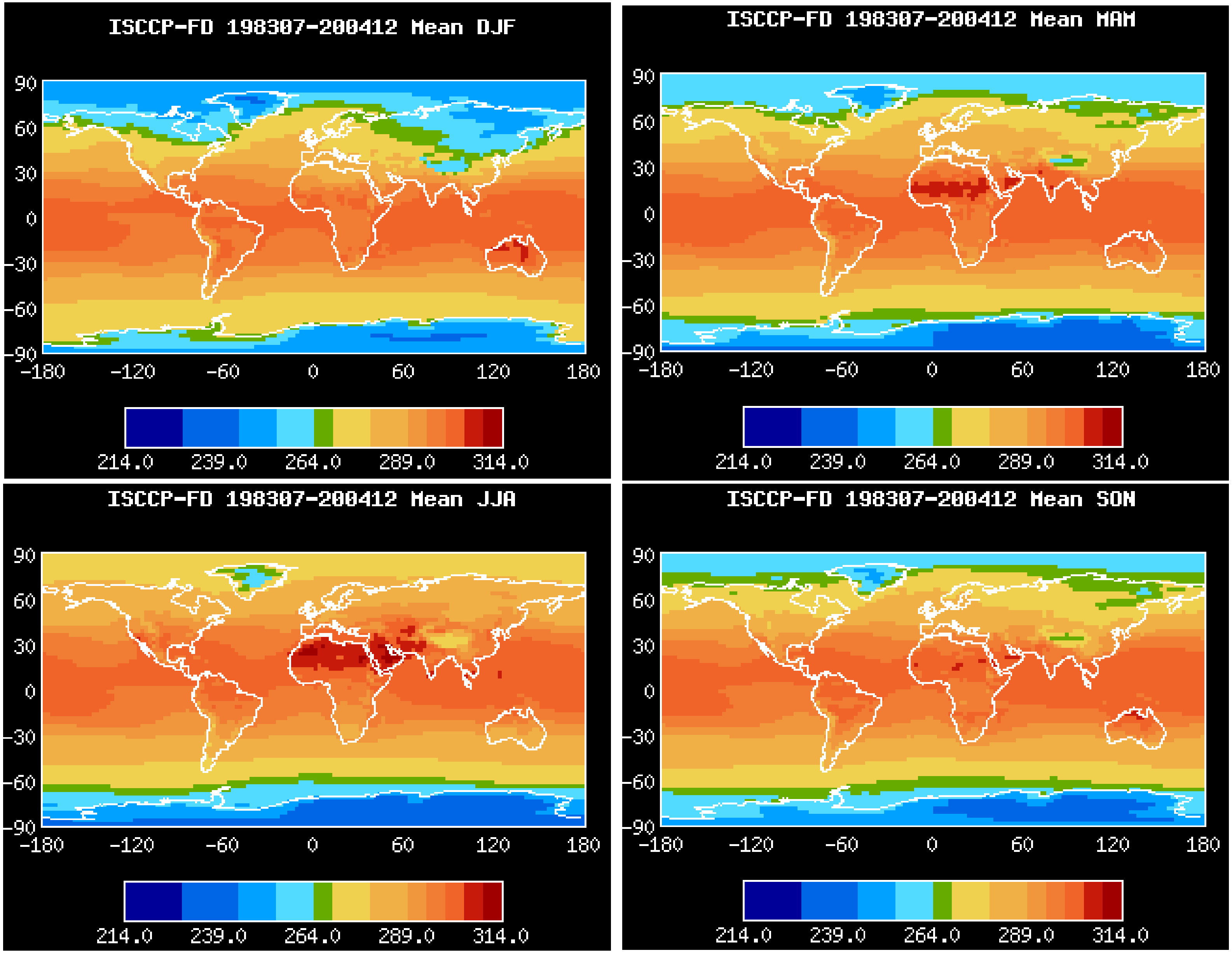
Surface Net (Solar + Longwave) Flux



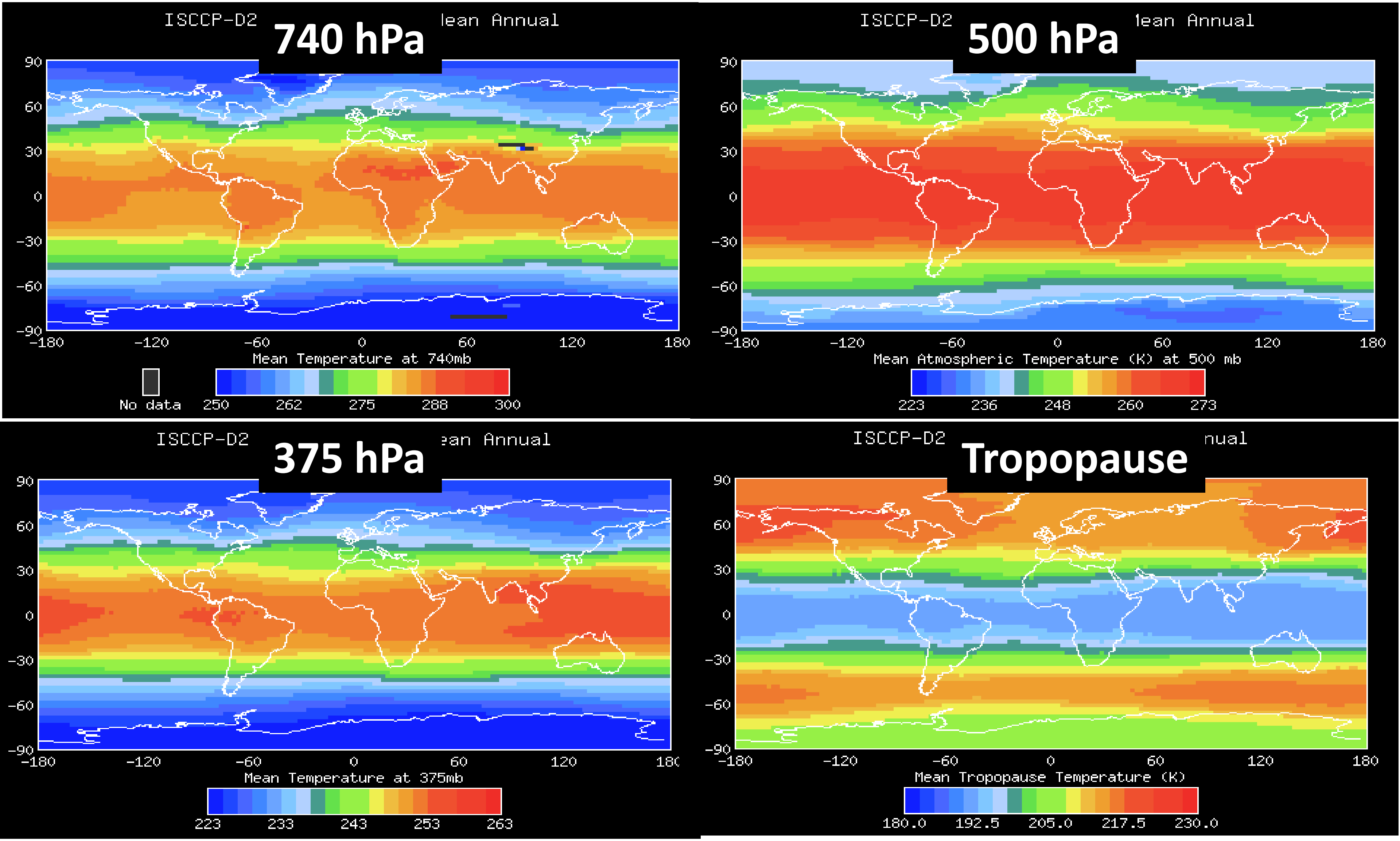
Global Surface Temperature: 1983-2009



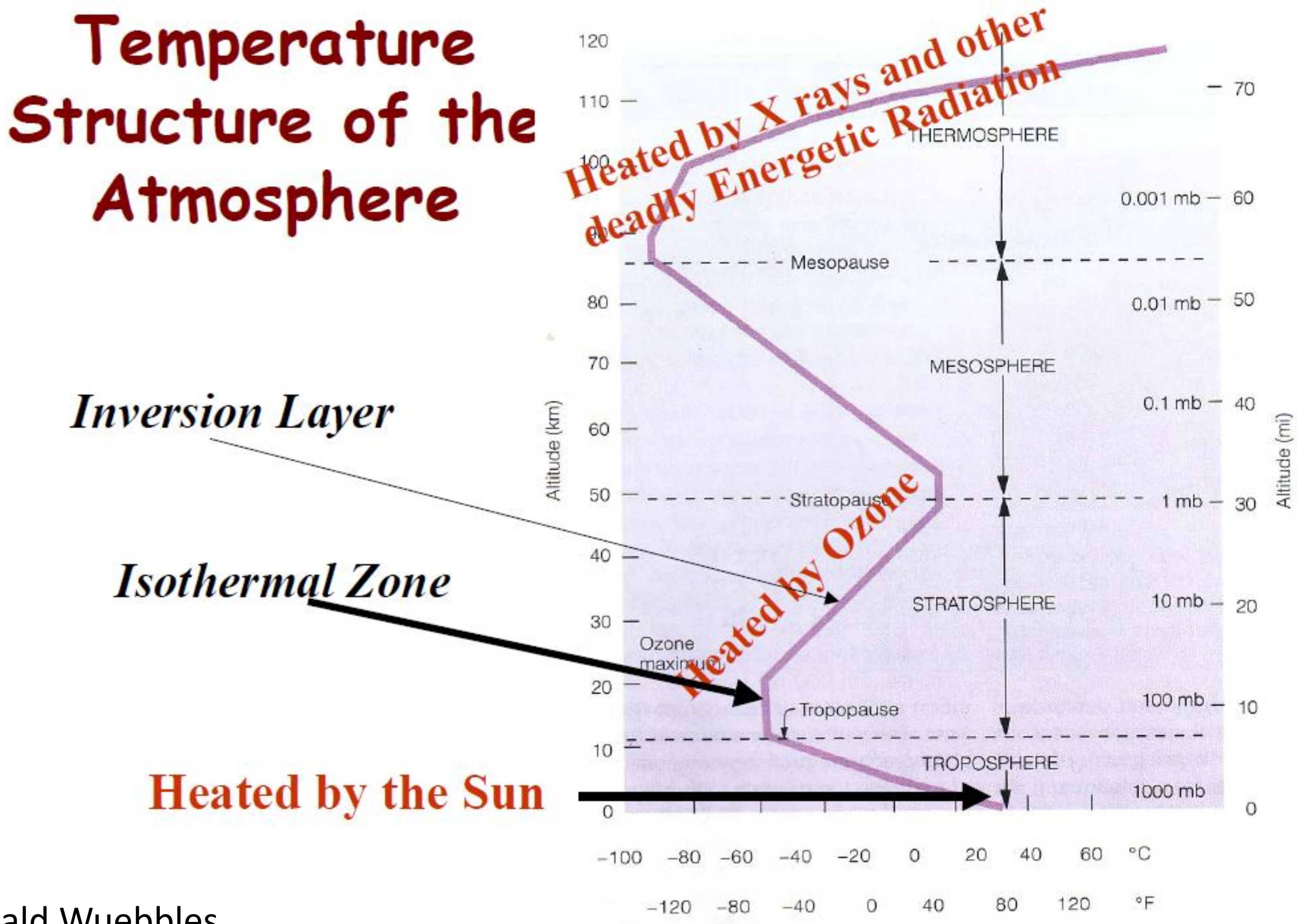
Global Seasonal Surface Temperature: 1983-2004



Tropospheric Air Temperature: 1983-2009

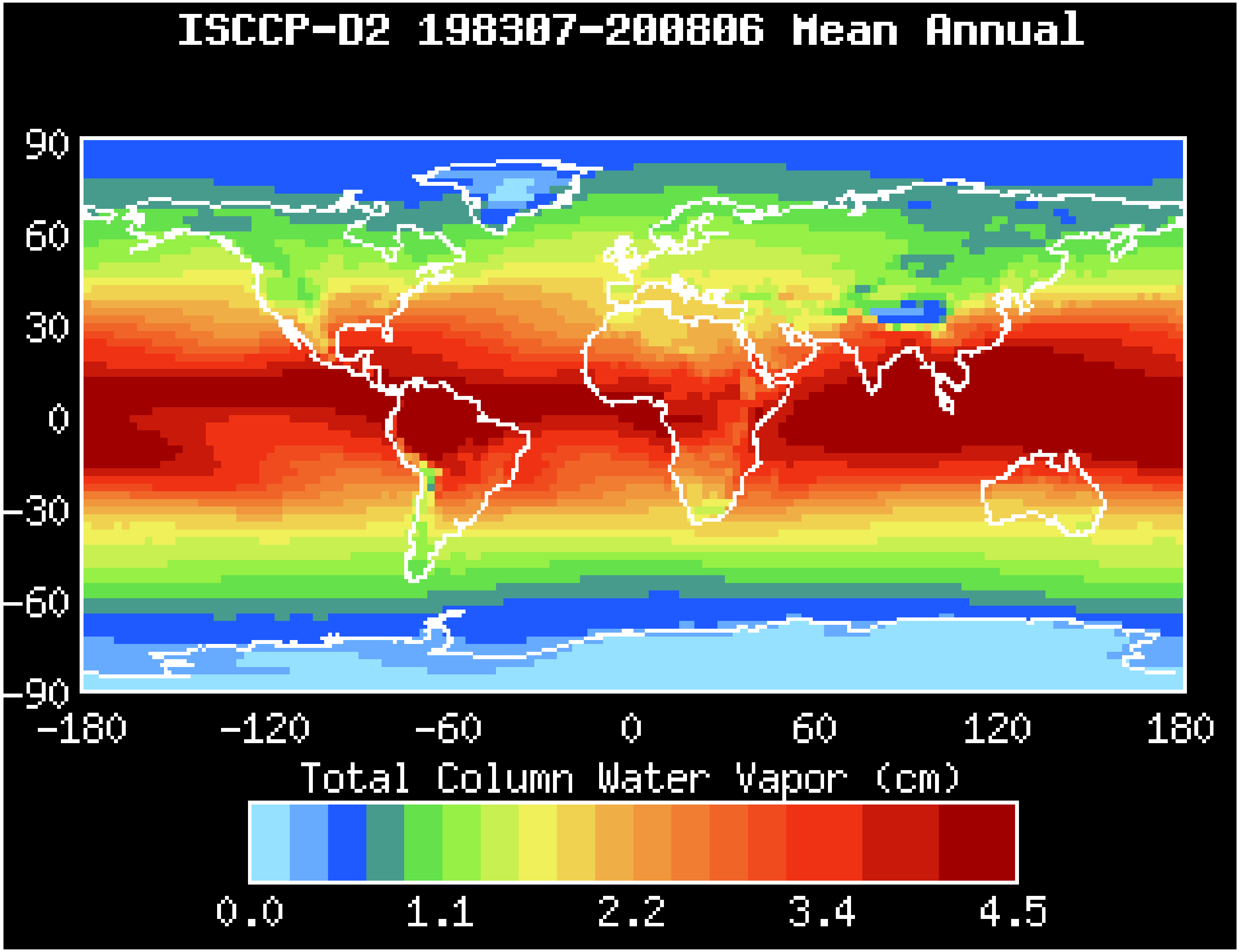


Vertical Distribution of Air Temperature and Its Drivers

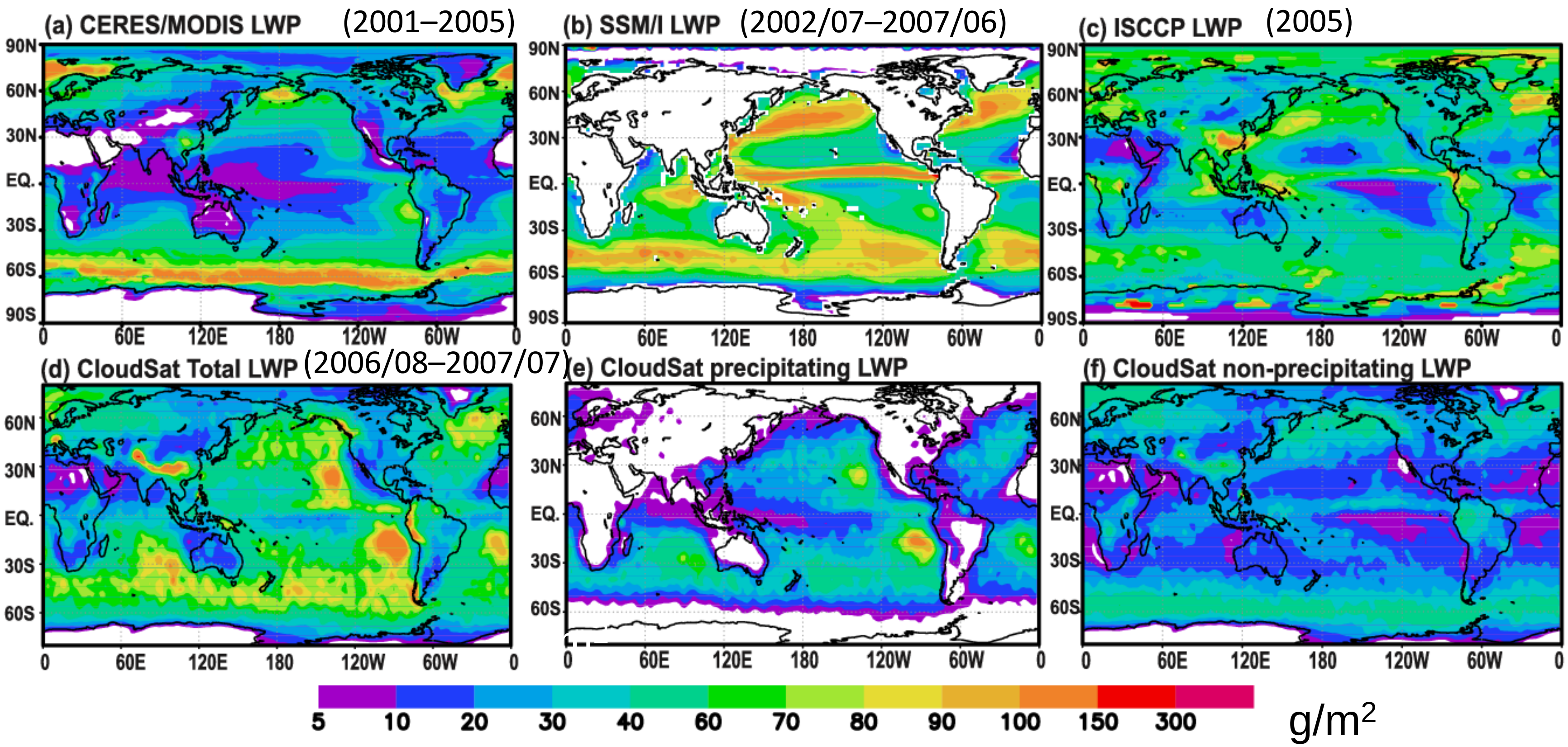


Donald Wuebbles

Global Water Vapor Content: 1983-2008

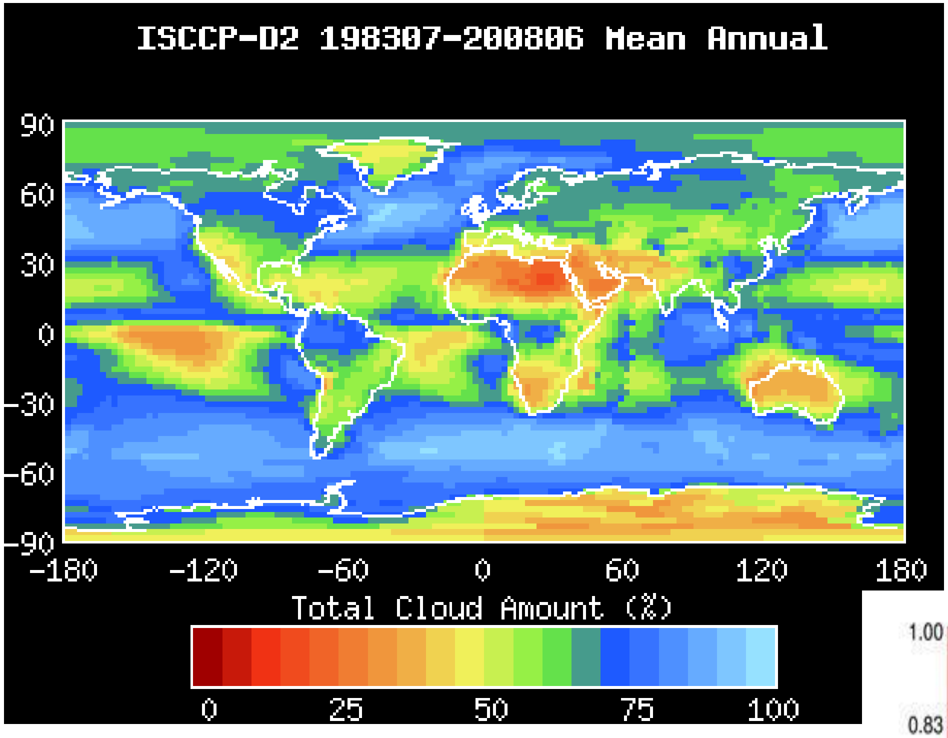


Global Cloud Water Content: 1983-2008

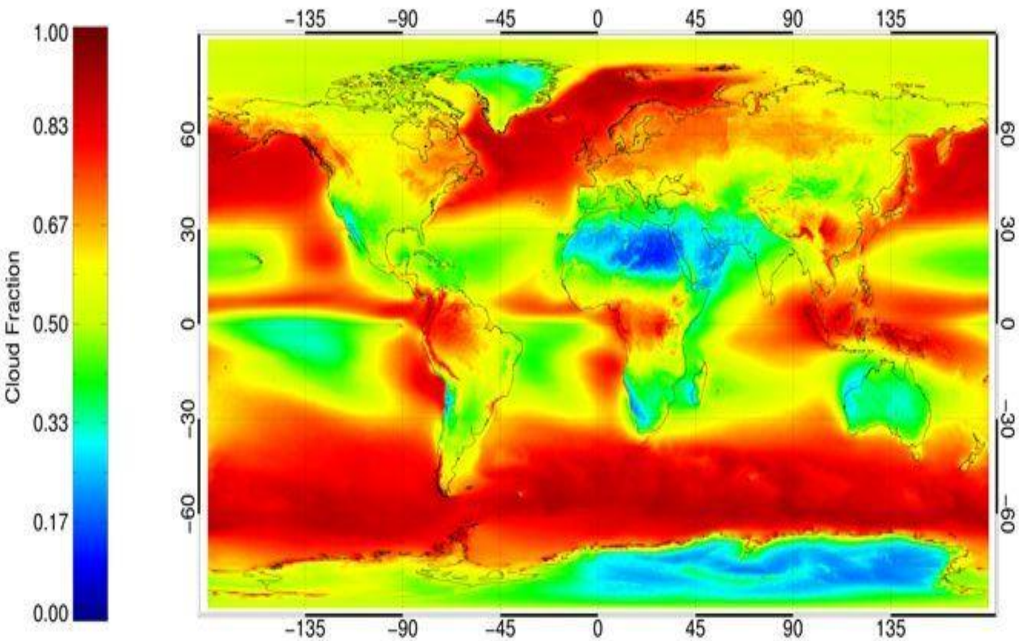


1 mm = 1000 g/m^2

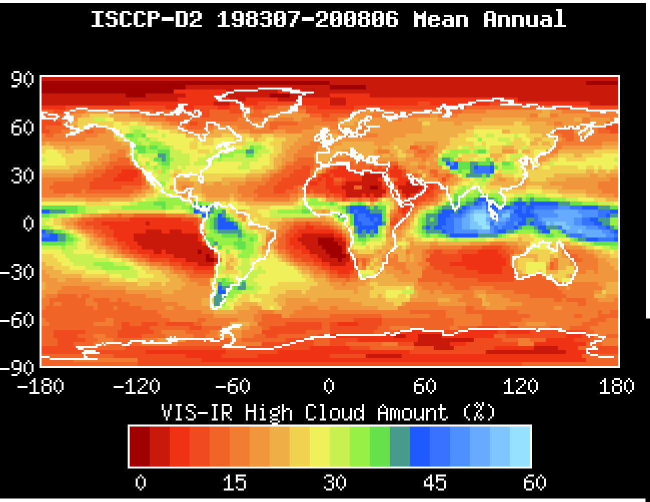
Global Cloud Cover

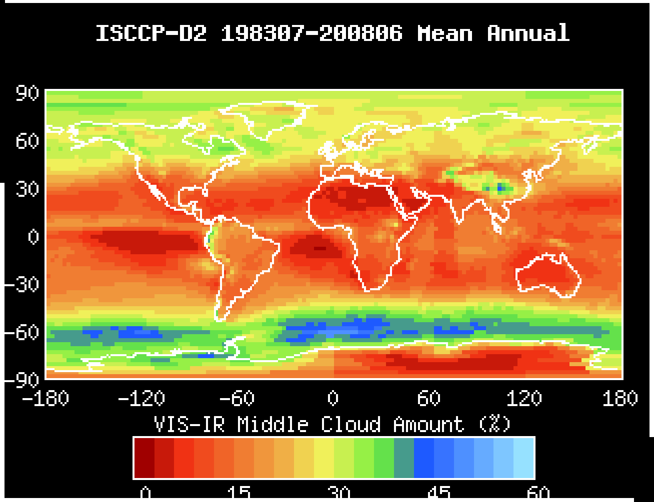


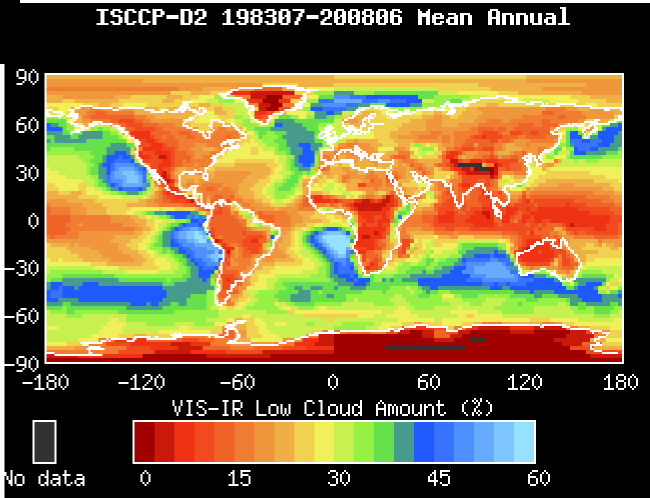
CLARA-A2 (1982-2015)



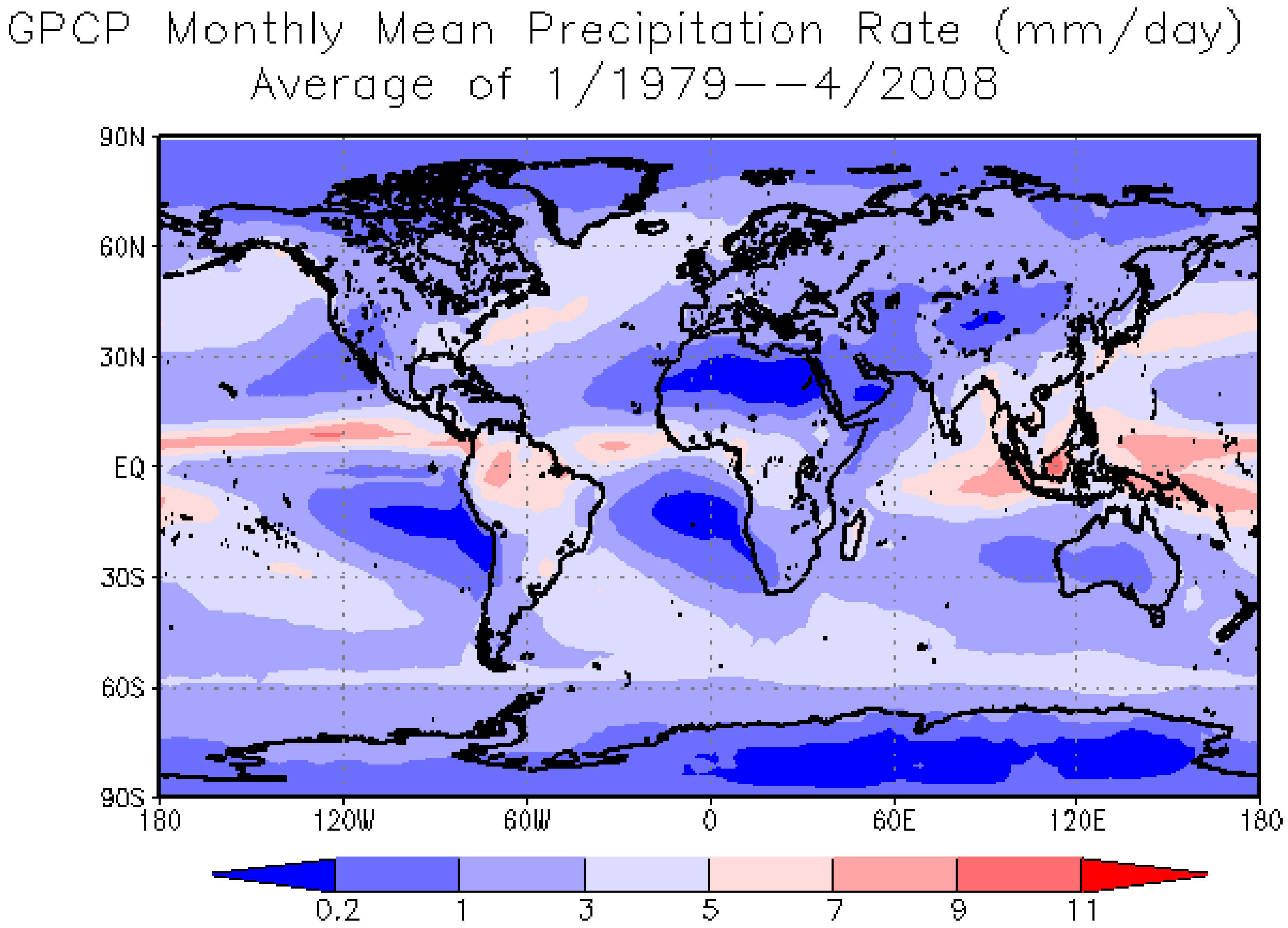
Global Cloud Cover: 1983-2008



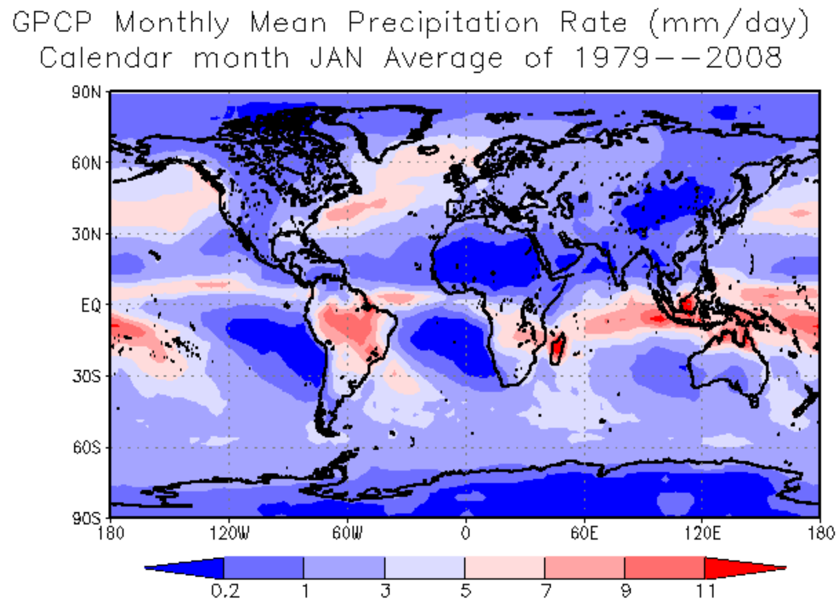


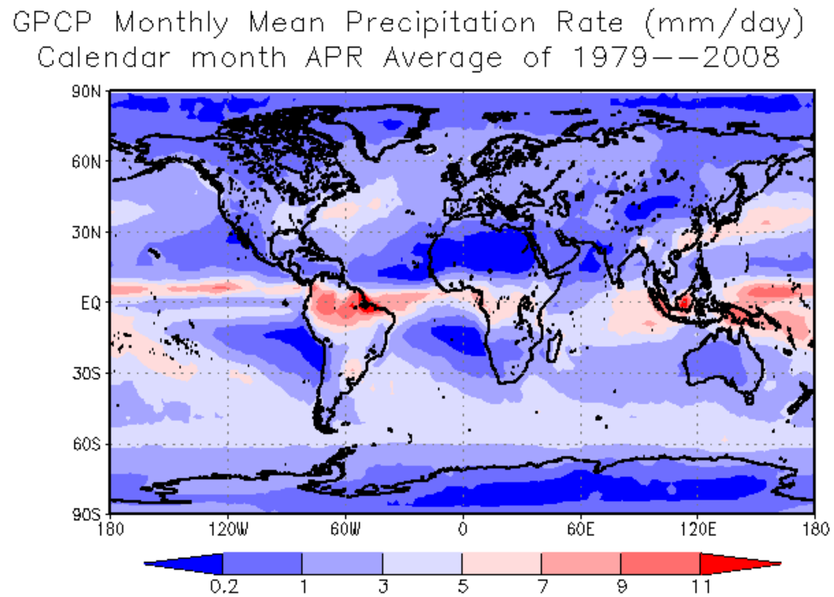


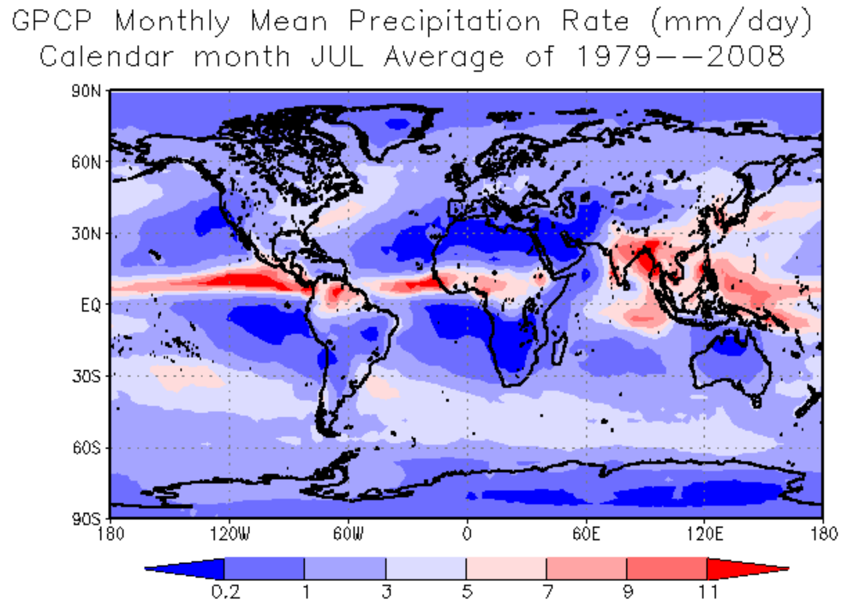
Global Precipitation: 1979-2008

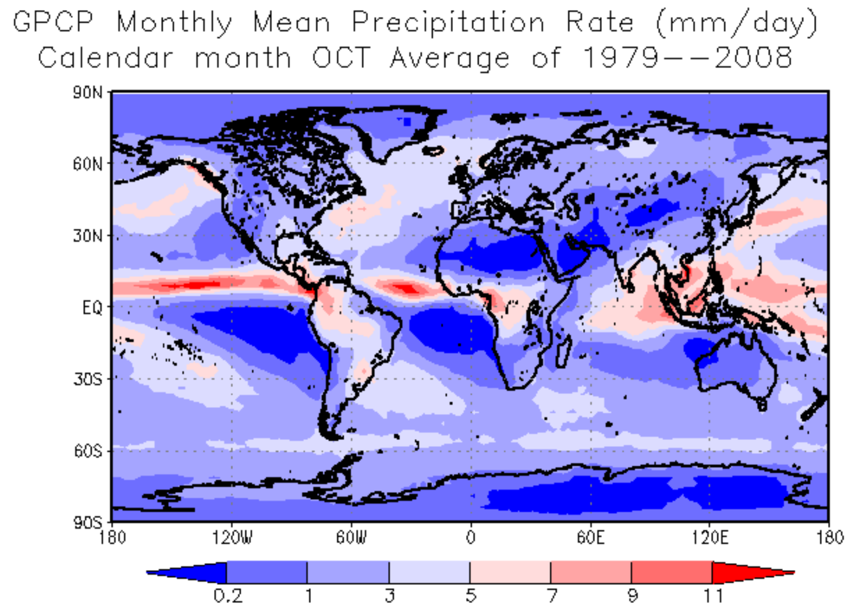


Global Seasonal Precipitation: 1979-2008





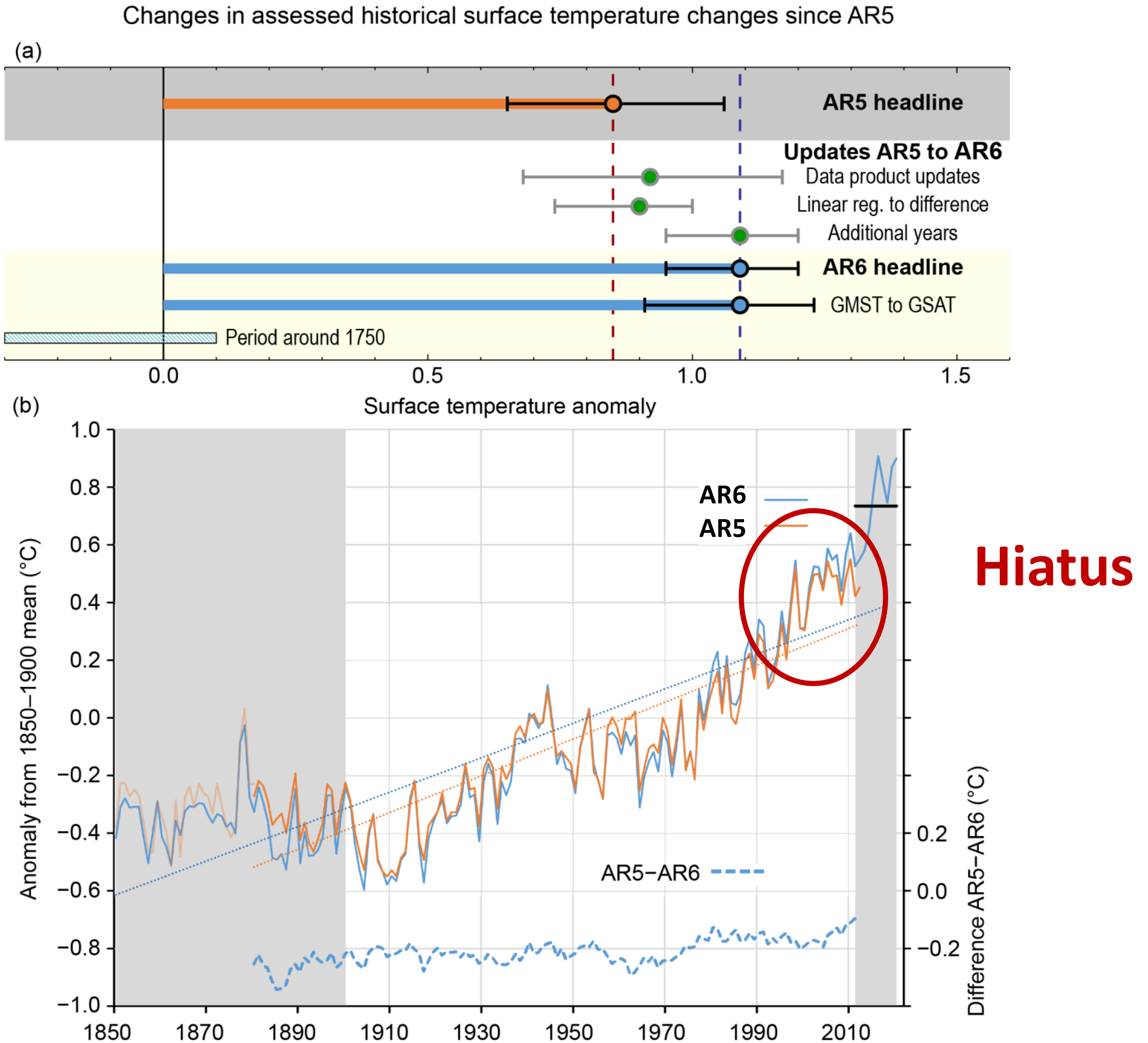




Global Warming

2022

Global Temperature Anomaly: 1850-2020



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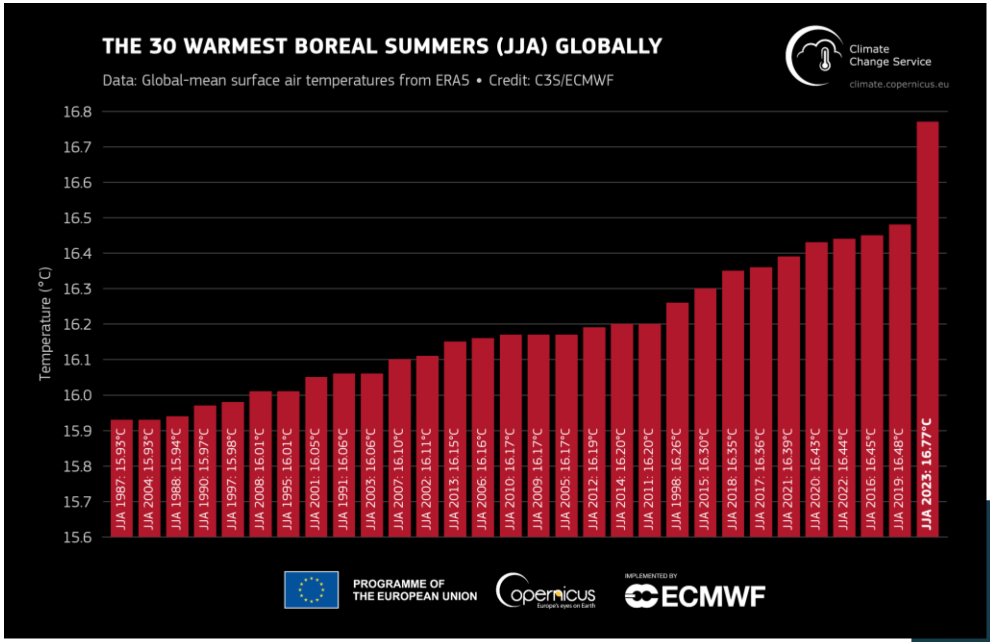
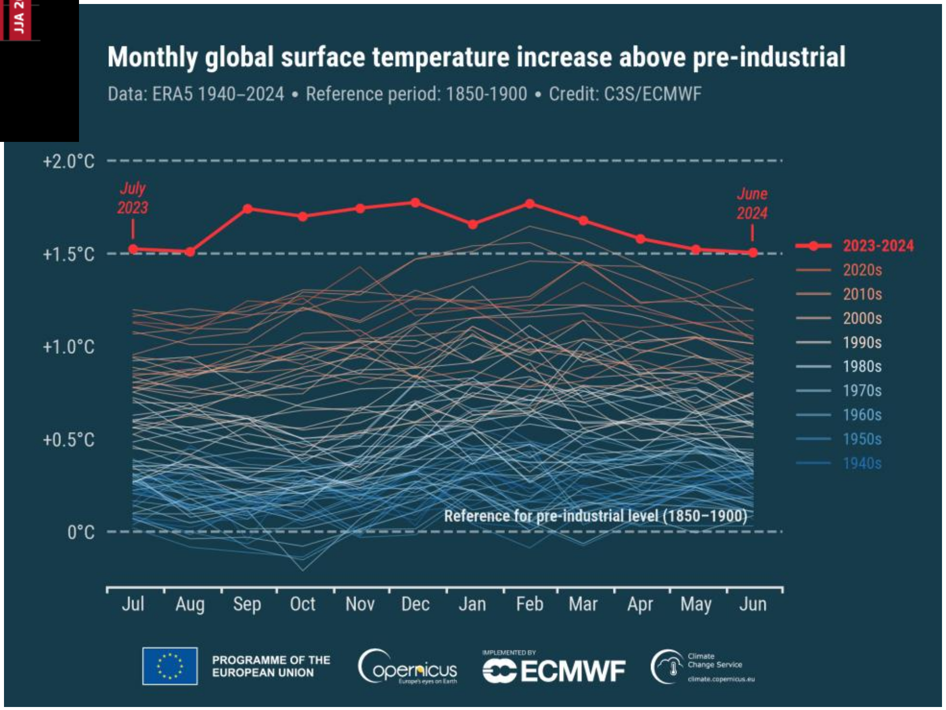
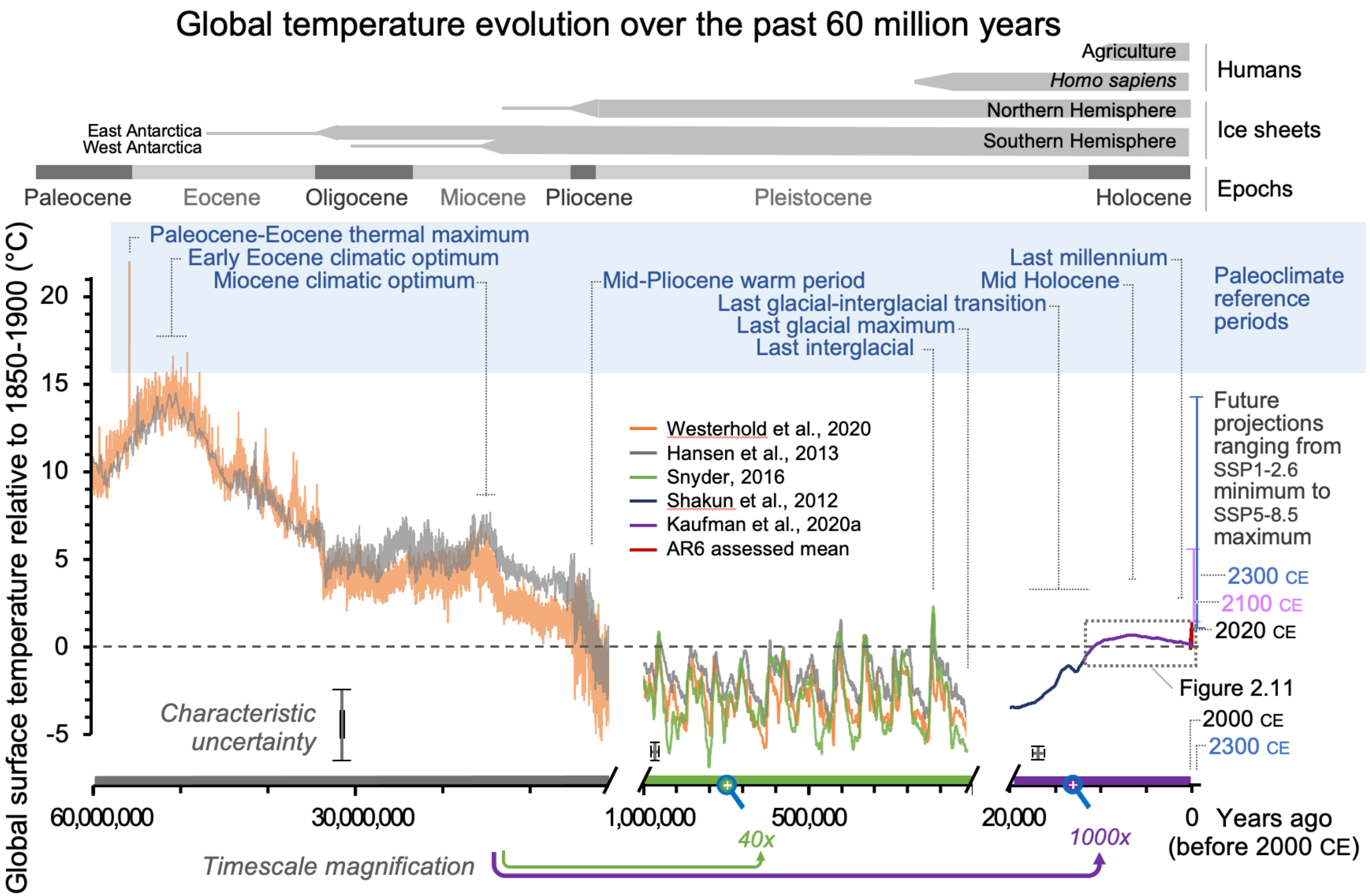
Global Temperature in 2023 and 2024





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.

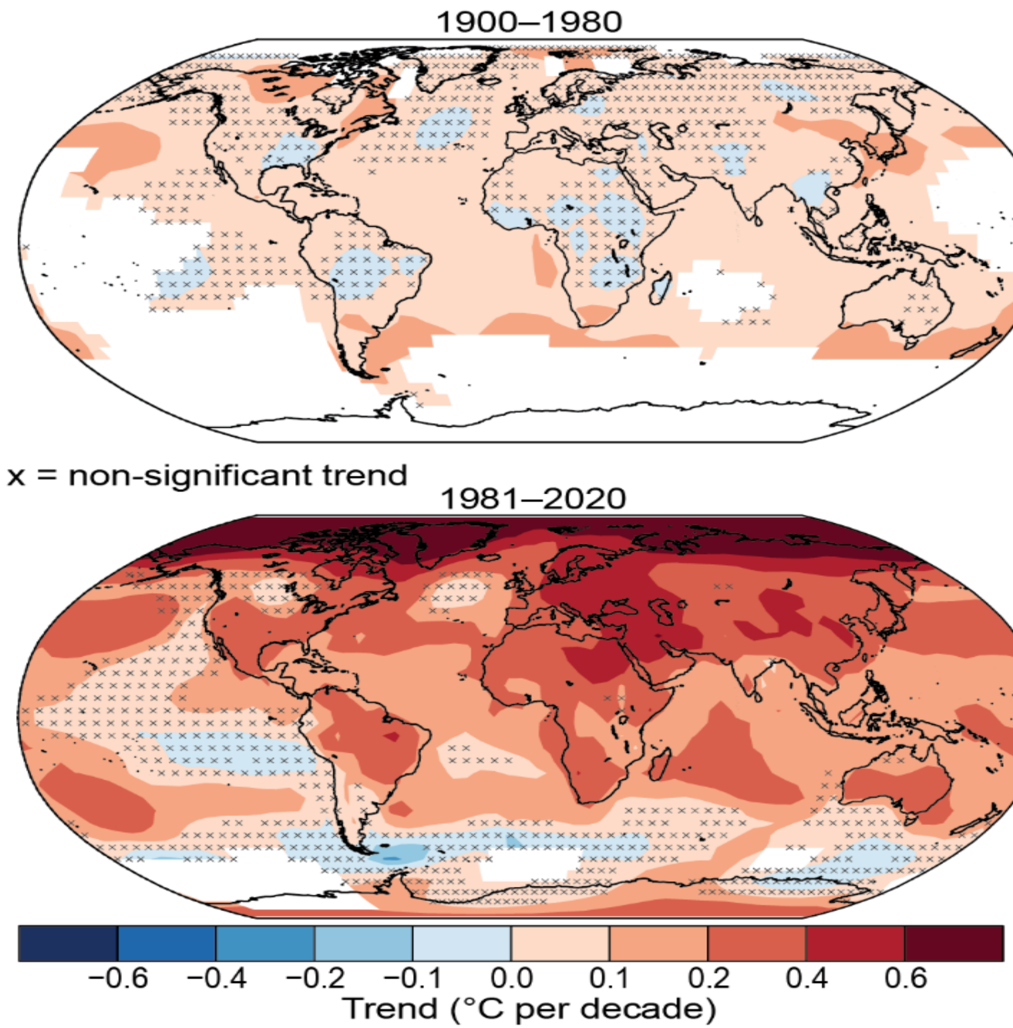
Global Temperature Evolution



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

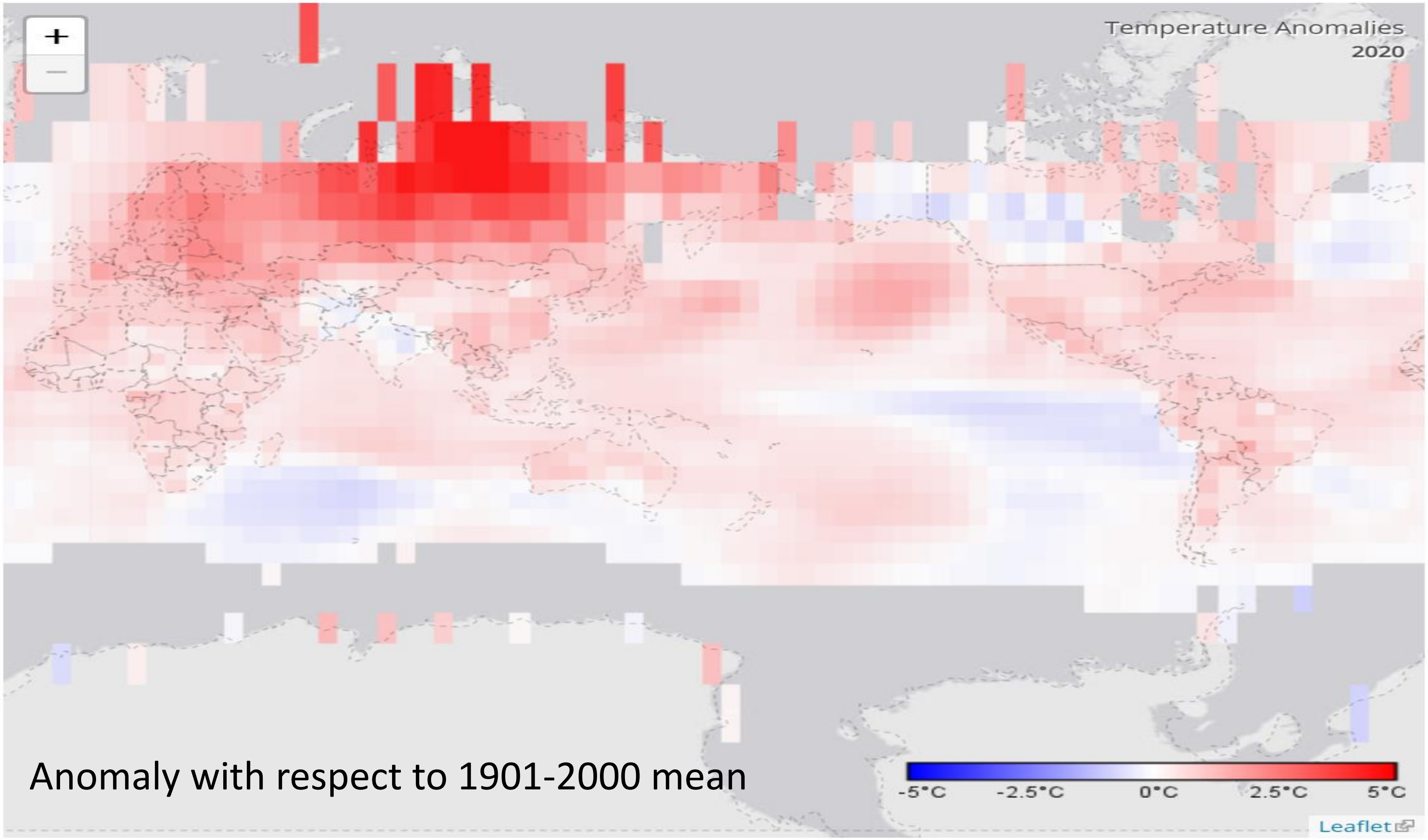
Global Temperature Anomaly: 1850-2020



IPCC, 2021

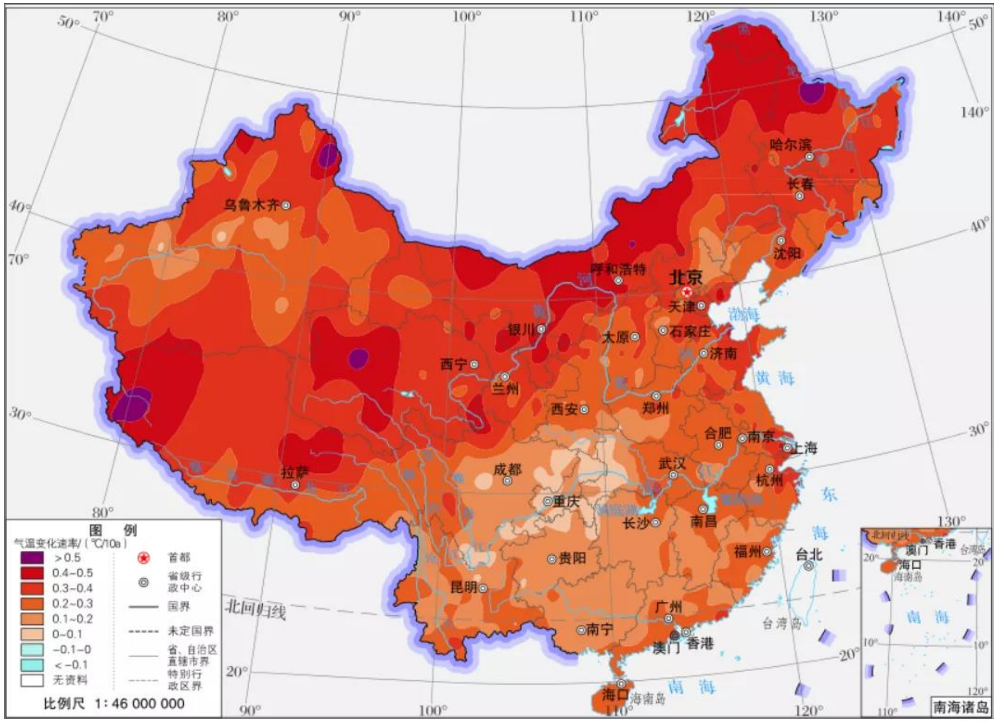
Jim Hansen: ΔT variability and biodiversity?

Global Temperature Anomaly: 2020



https://www.ncdc.noaa.gov/cag/global/mapping/2020

China Temperature Anomaly: 1901-2020

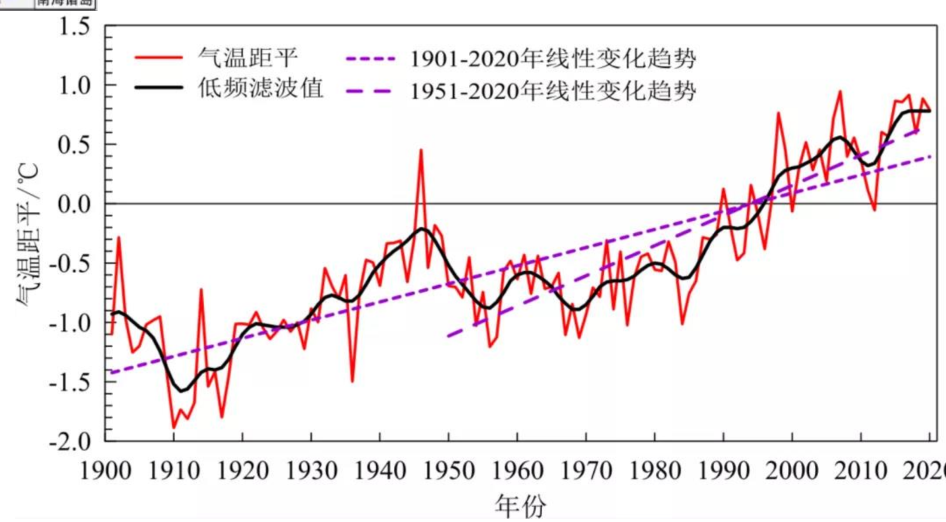


中国气候变化蓝皮书（2021）

- 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。

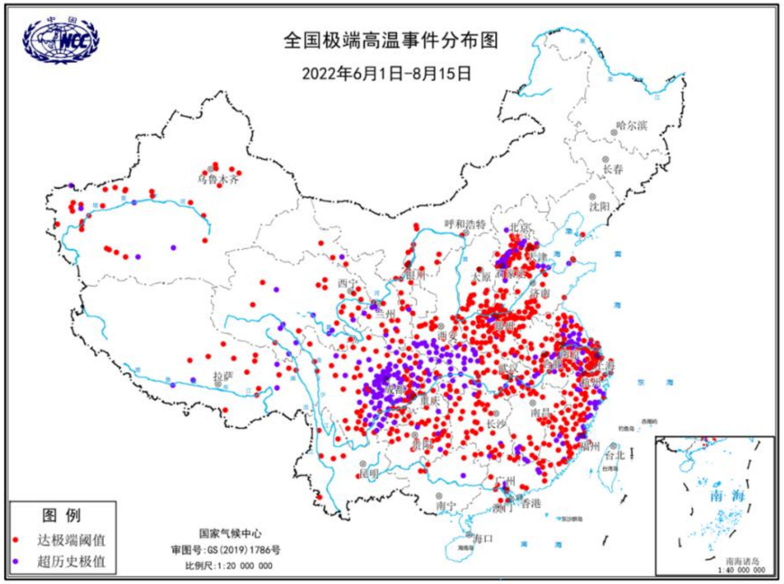
中国气候变化蓝皮书（2024）

- 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

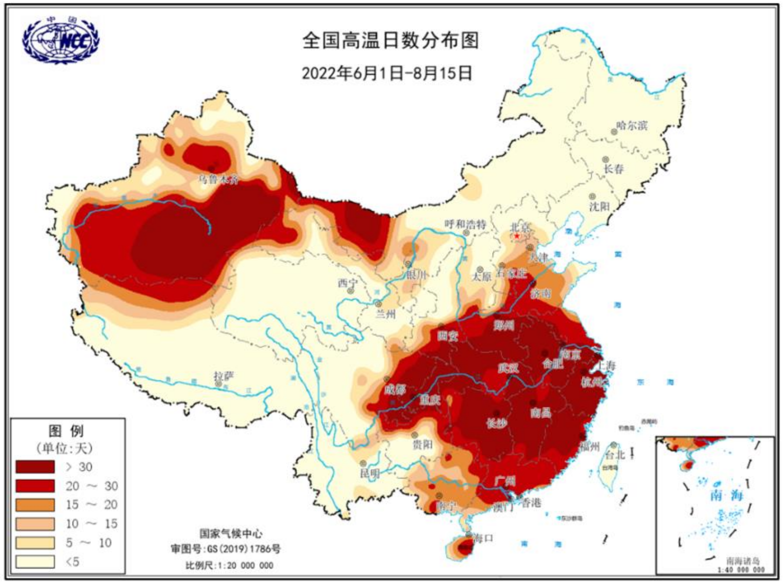


Heatwave in 2022 in China

极端高温事件（6月1日-8月15日）



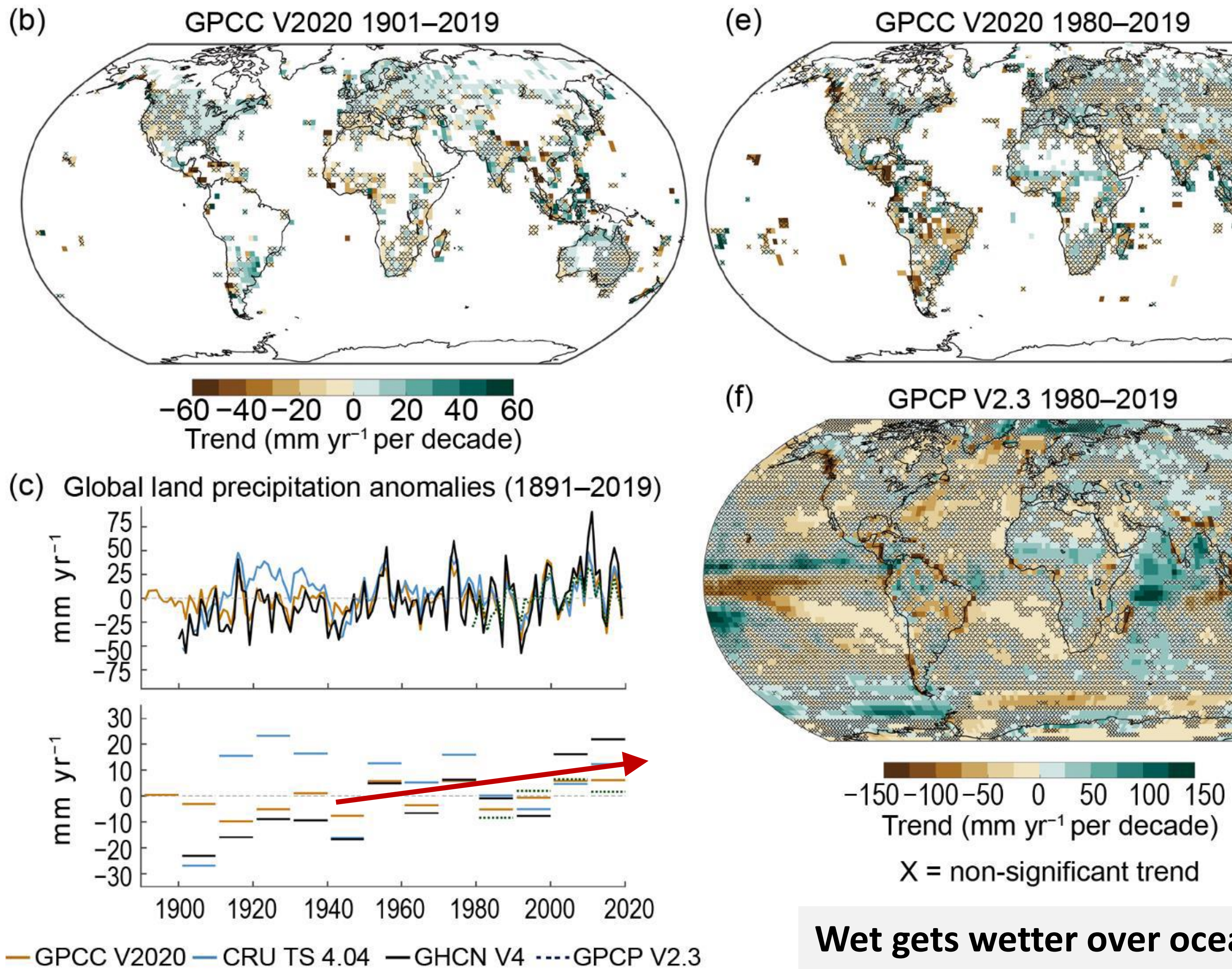
高温日数（6月1日-8月15日）



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 Precipitation Anomaly: 1901–2019



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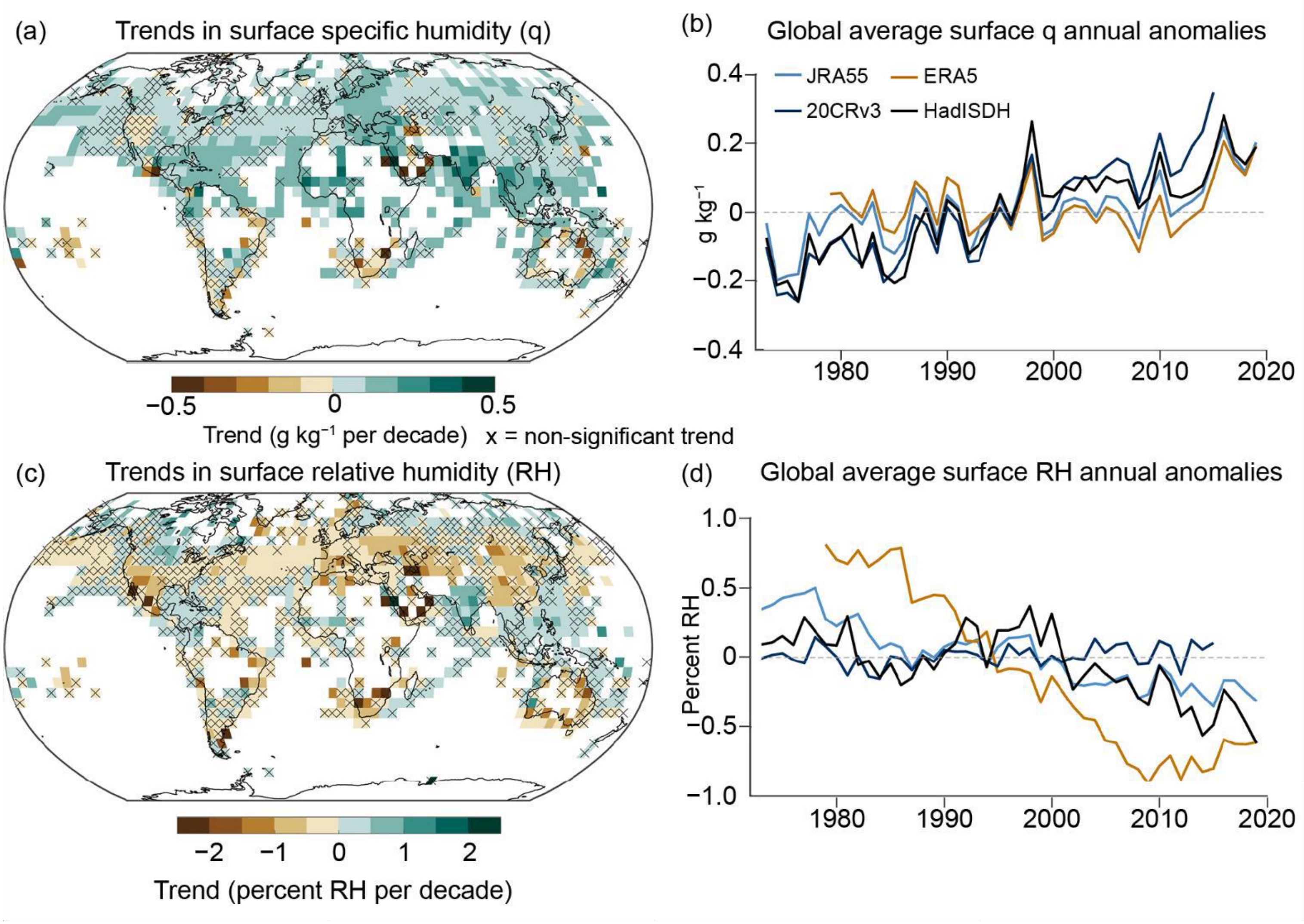
Wet gets wetter over oceans?

Humidity Change: 1973–2019



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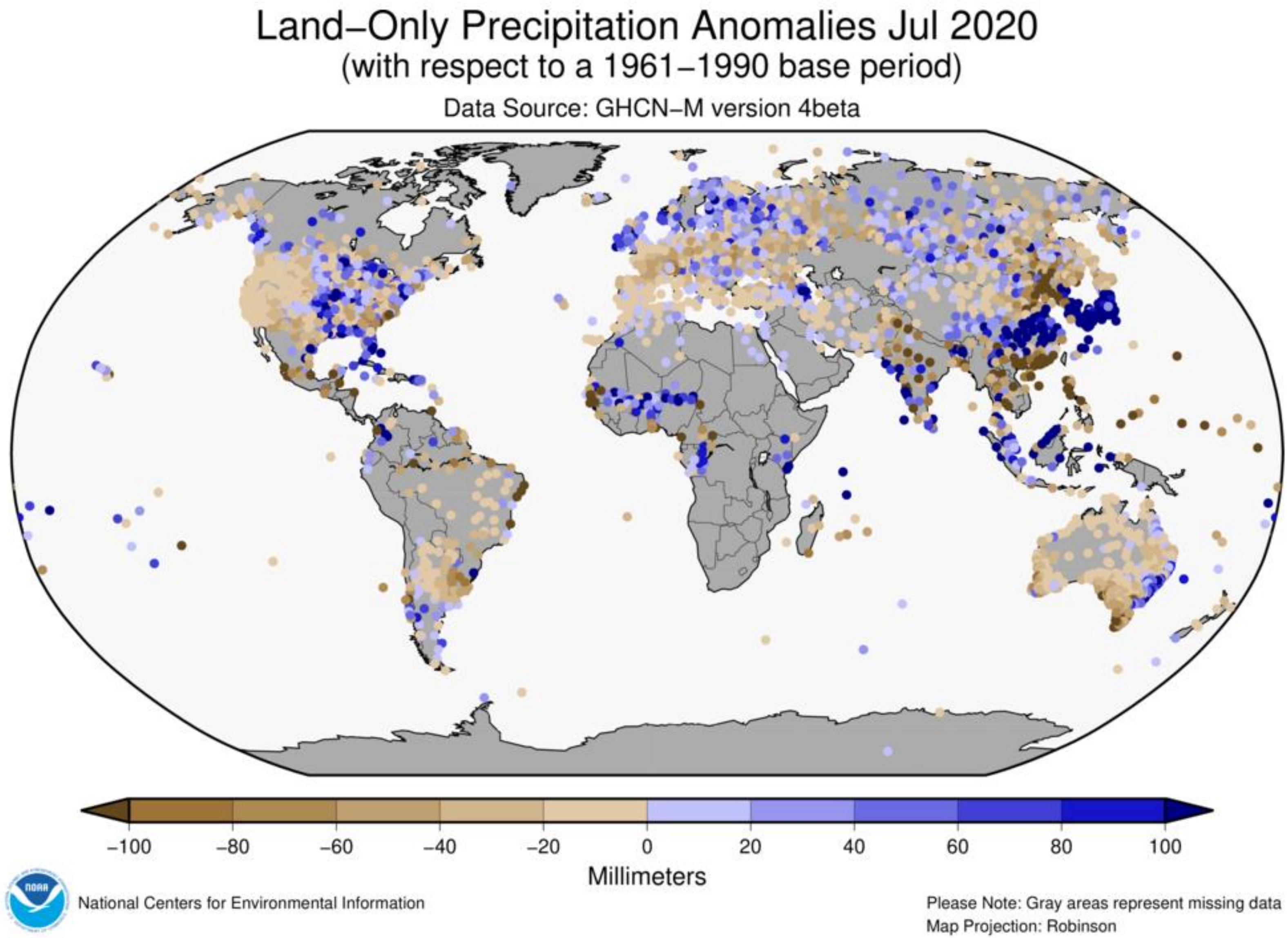
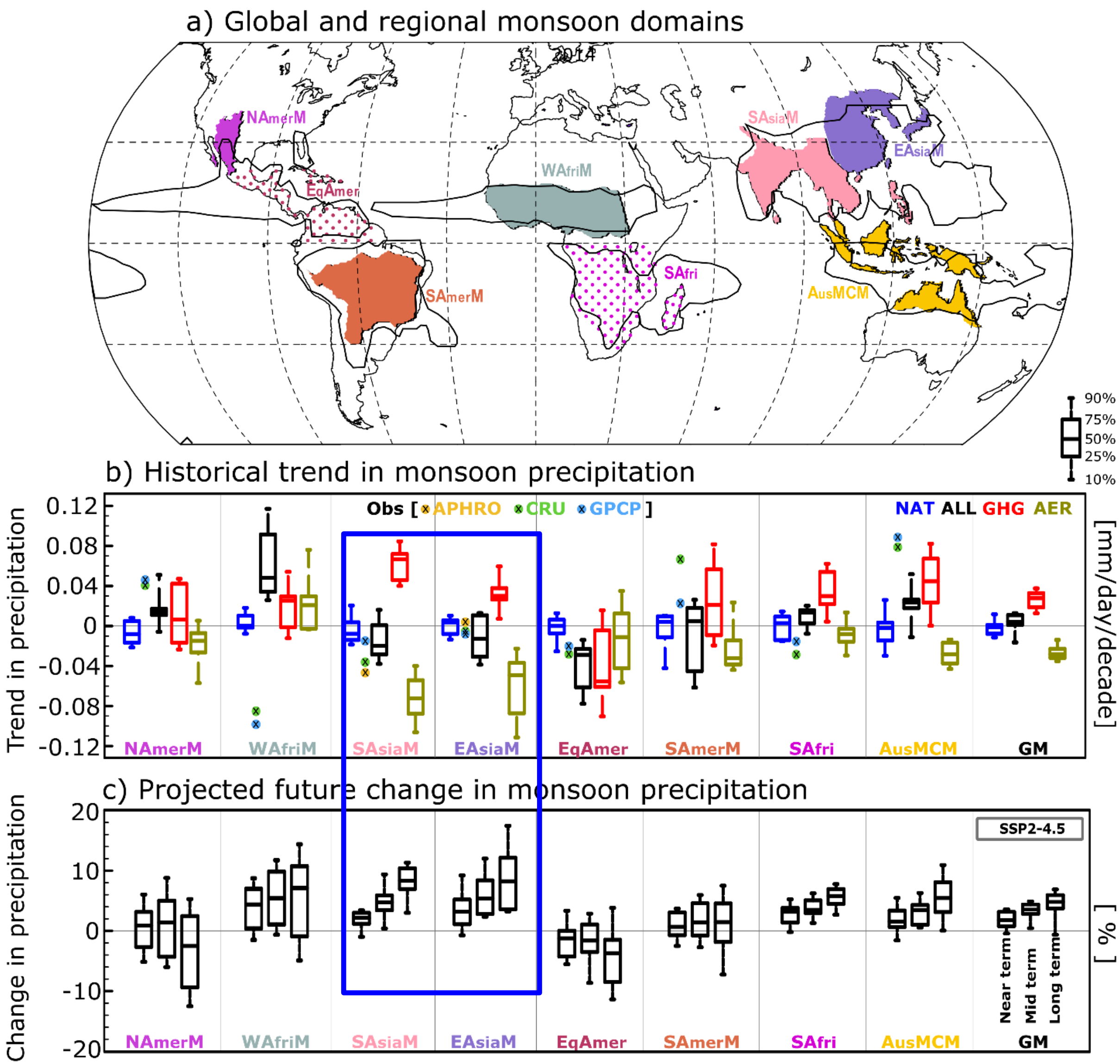
Global Precipitation Anomaly



Changes in Global Monsoon Precipitation



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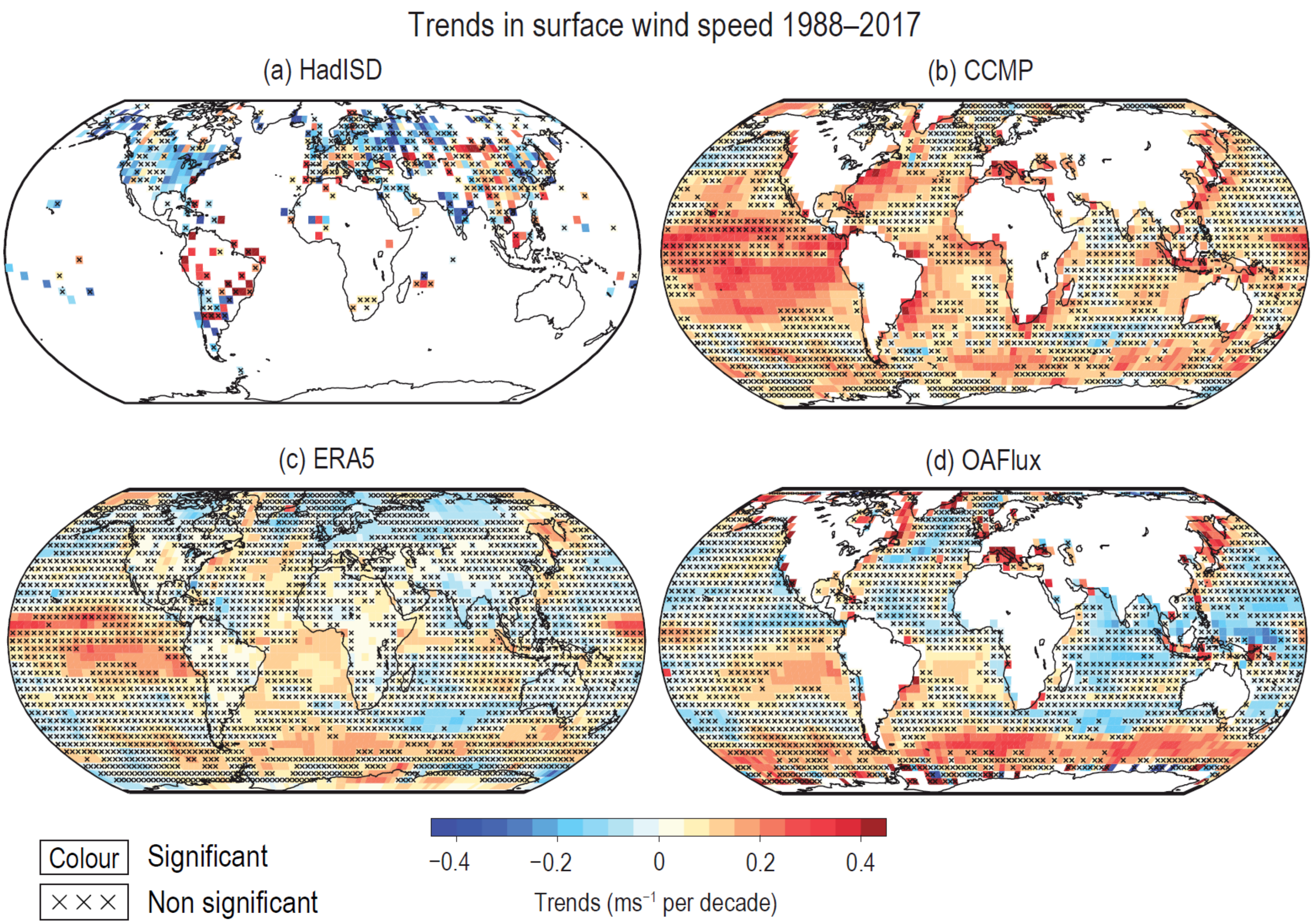
Surface Wind Speed Change: 1988–2017



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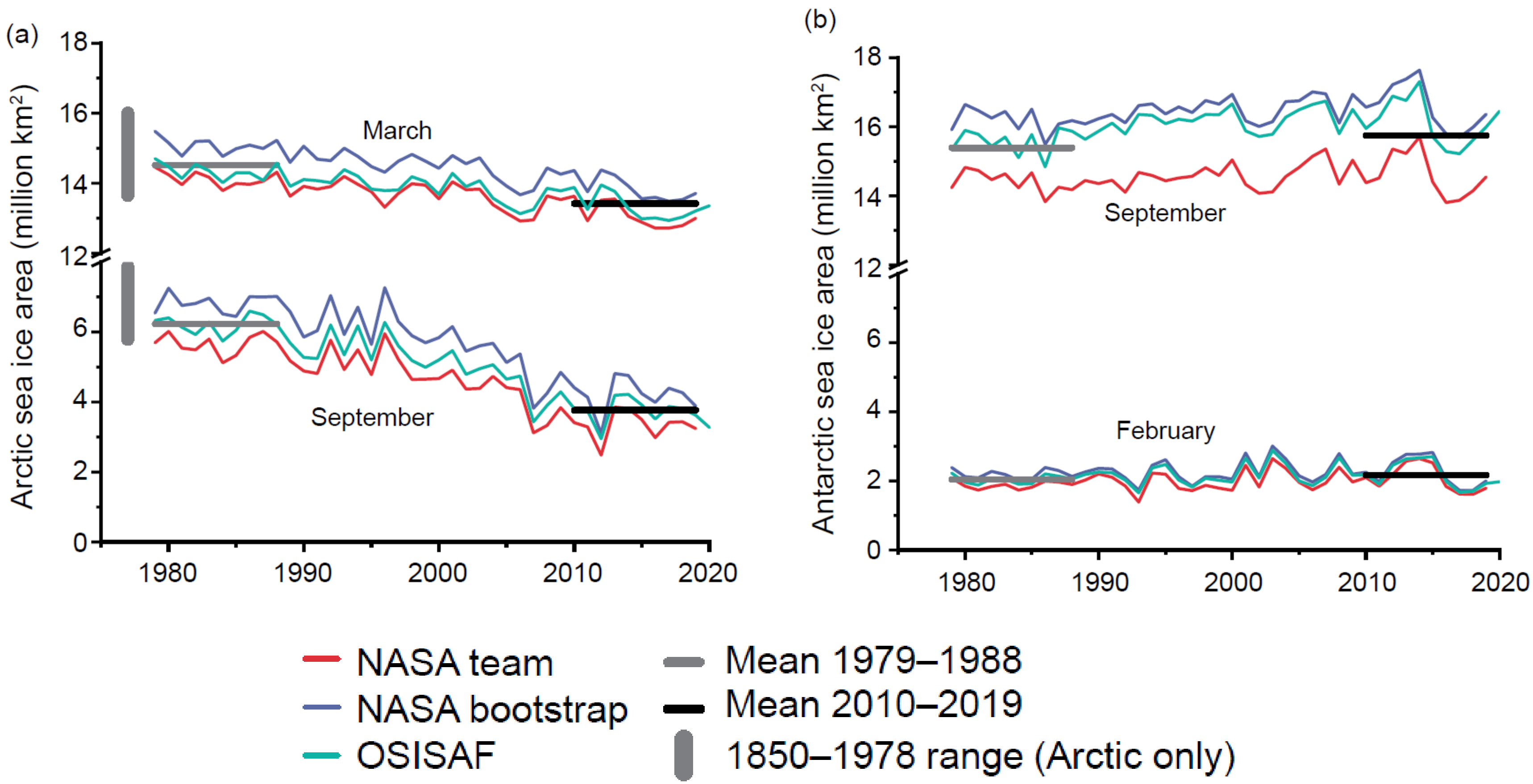
Snow and Ice Change



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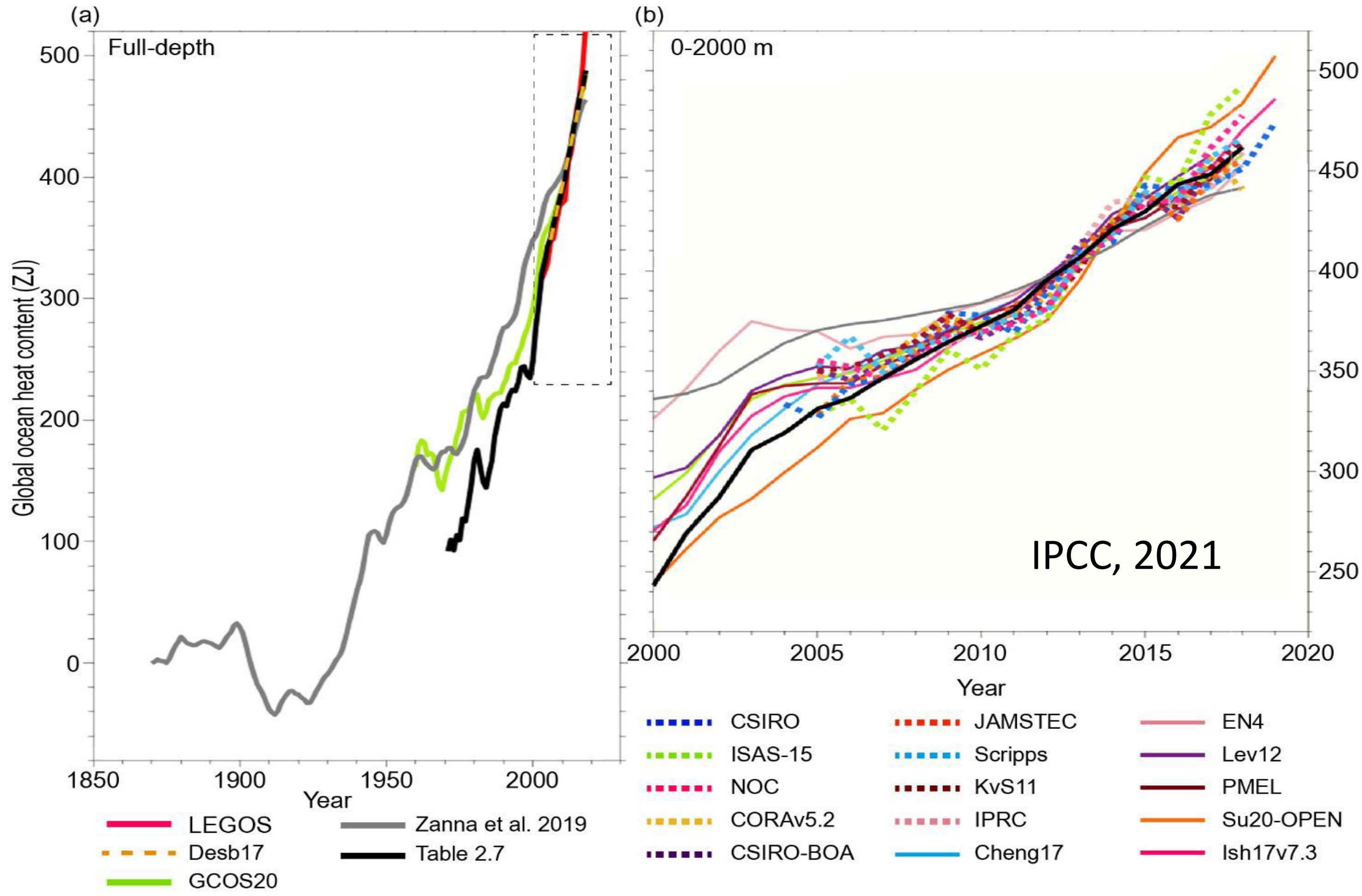
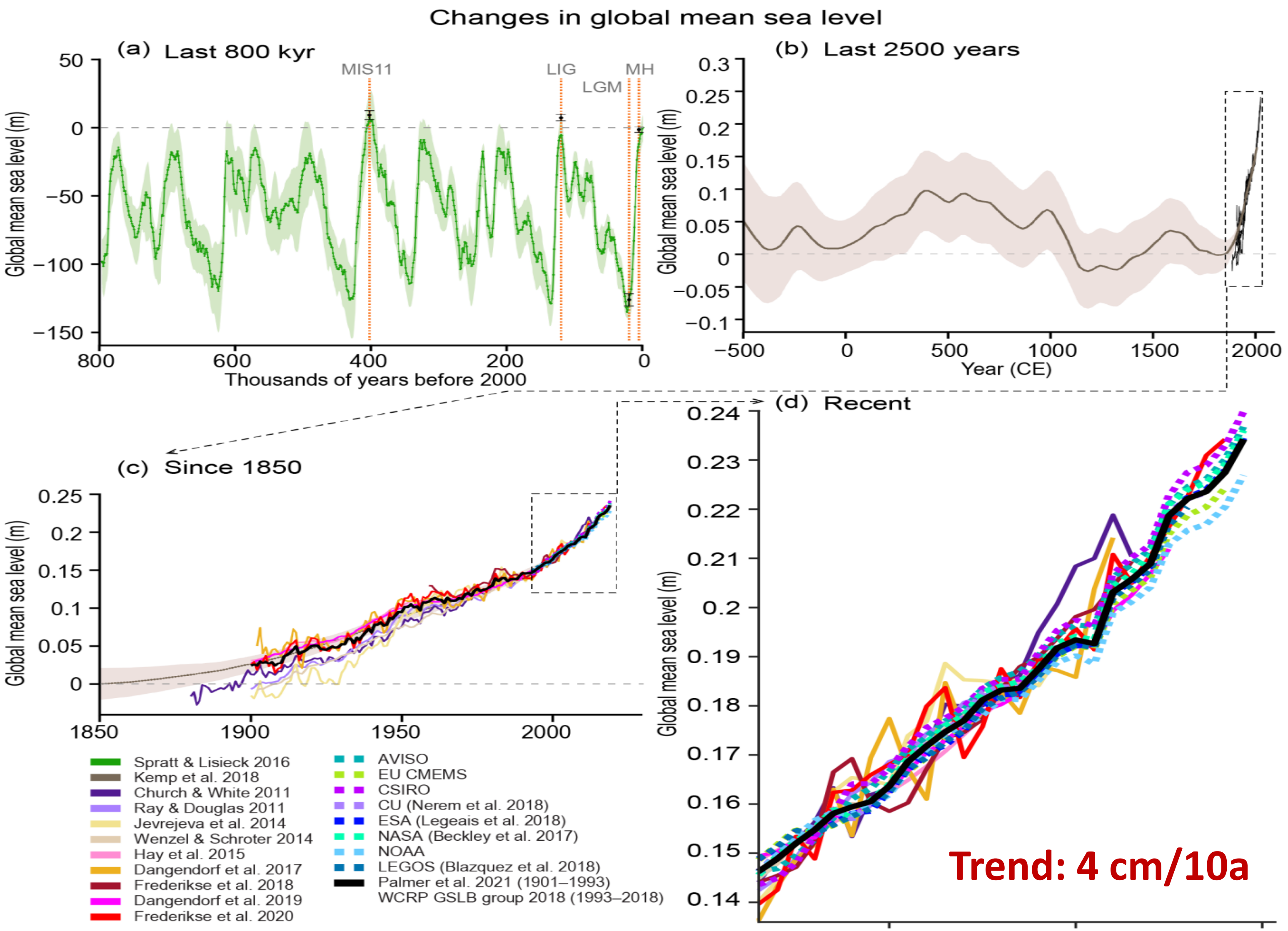
Ocean Heat Content Change



- 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

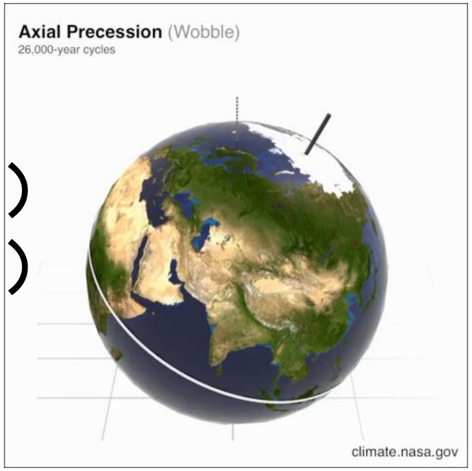


Contributors to sea level rise:
https://youtu.be/Q15gTMXjwCc

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

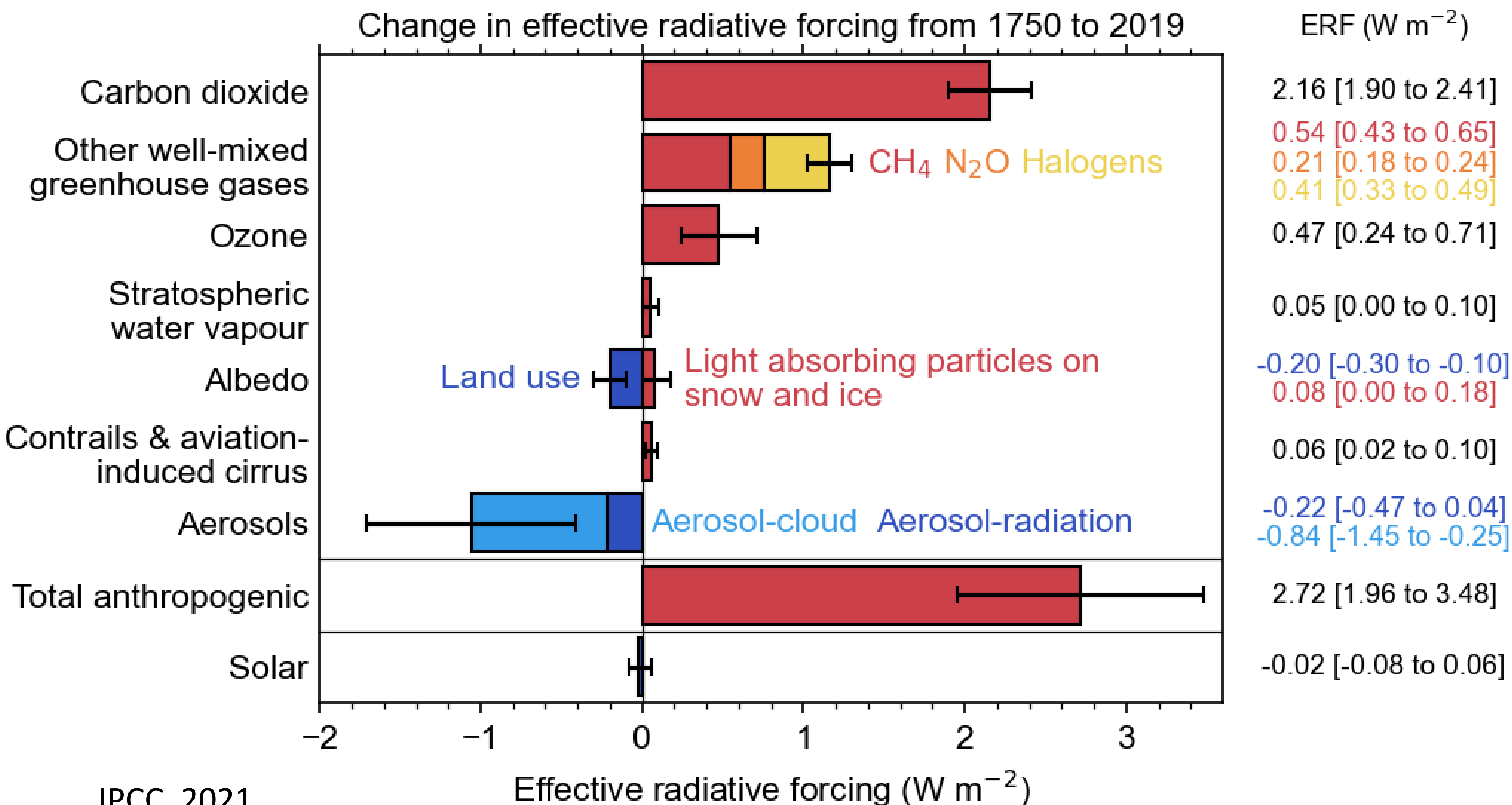


- 内部变率：气候系统自身动态演化
- 自然（外部）因素：
  - 地质运动（板块运动、火山活动、陨石等）
  - 地球轨道变化（偏心率、黄赤交角、岁差）
  - 太阳活动（太阳黑子等）
- 人为强迫：
  - 长寿命温室气体：CO_2、CH_4、N_2O、halocarbons
  - O_3（与NO_x、CO、VOC相关）
  - 气溶胶：BC、OC、sulfate、nitrate、ammonium、dust
  - 植被改变
- 反馈过程：热力、动力、碳循环等

Effective Radiative Forcing

What is ERF?

[Concentration based]

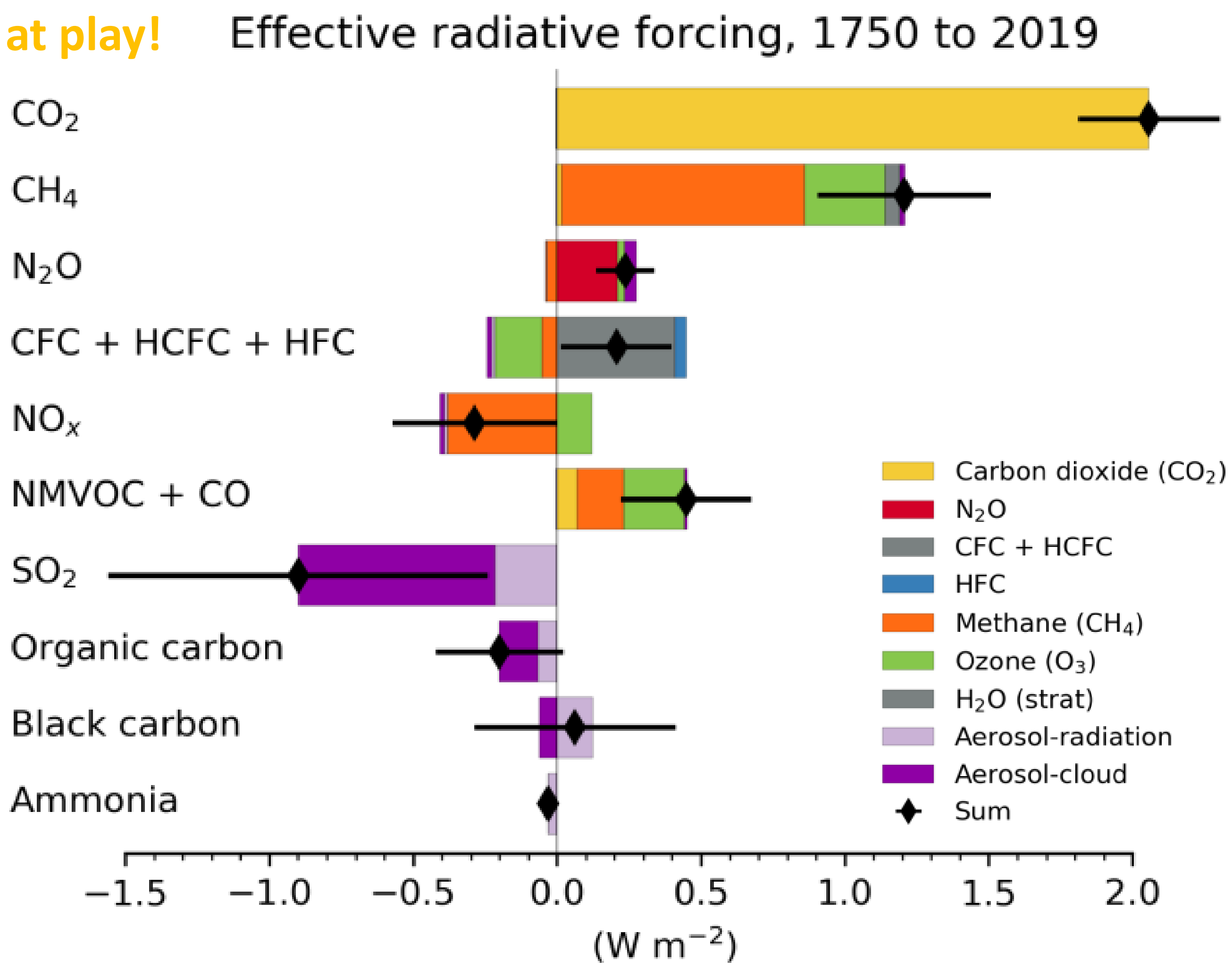


IPCC, 2021

Effective Radiative Forcing

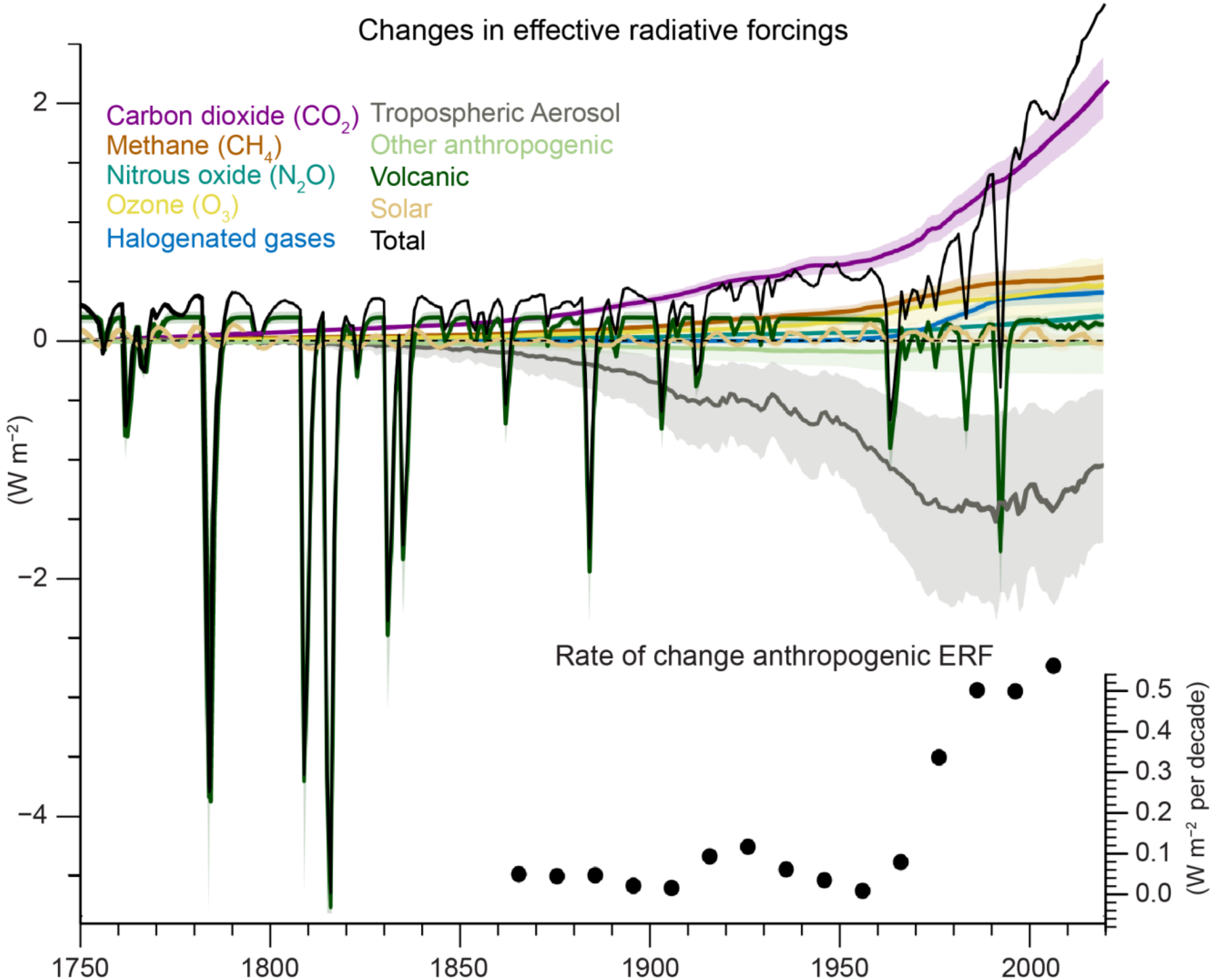
Climate-chemistry interactions at play!

[Emission based]



IPCC, 2021

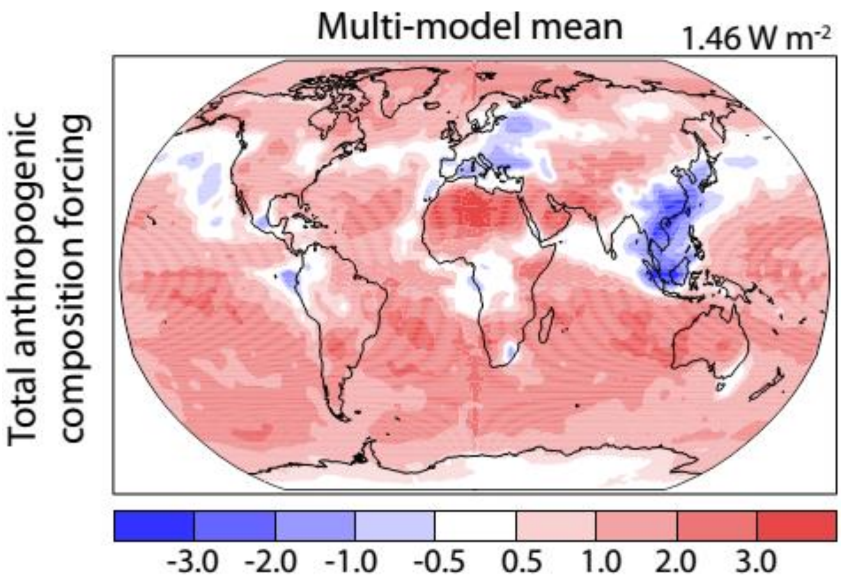
Effective Radiative Forcing



IPCC, 2021

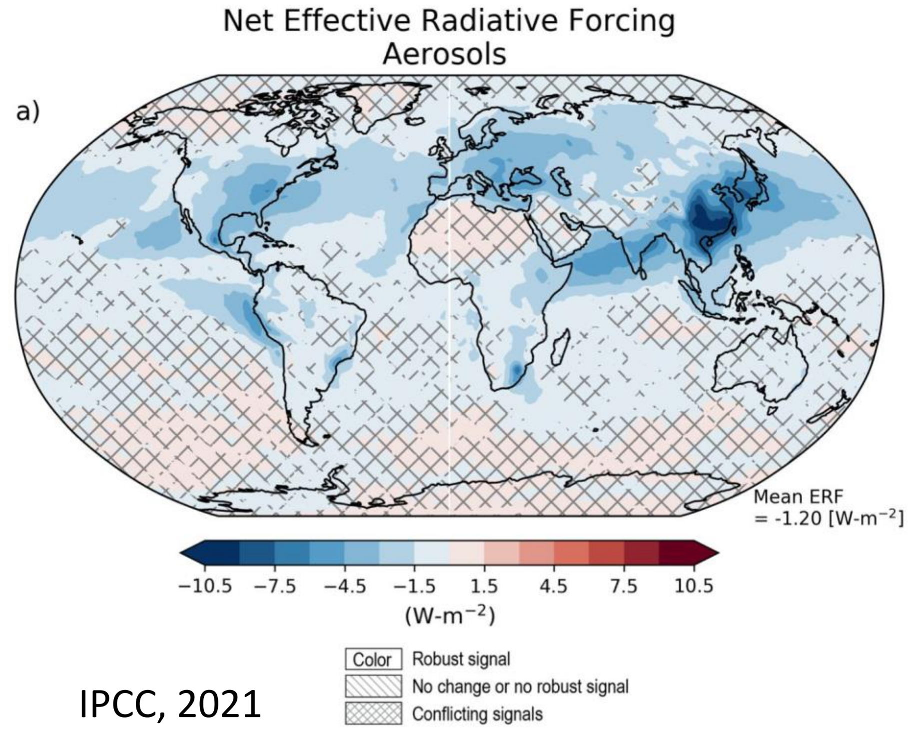
Radiative Forcing: Spatial Distribution

Total RF: 1850–2000



IPCC, 2013

Aerosol ERF: 1850–[1995-2014 mean]

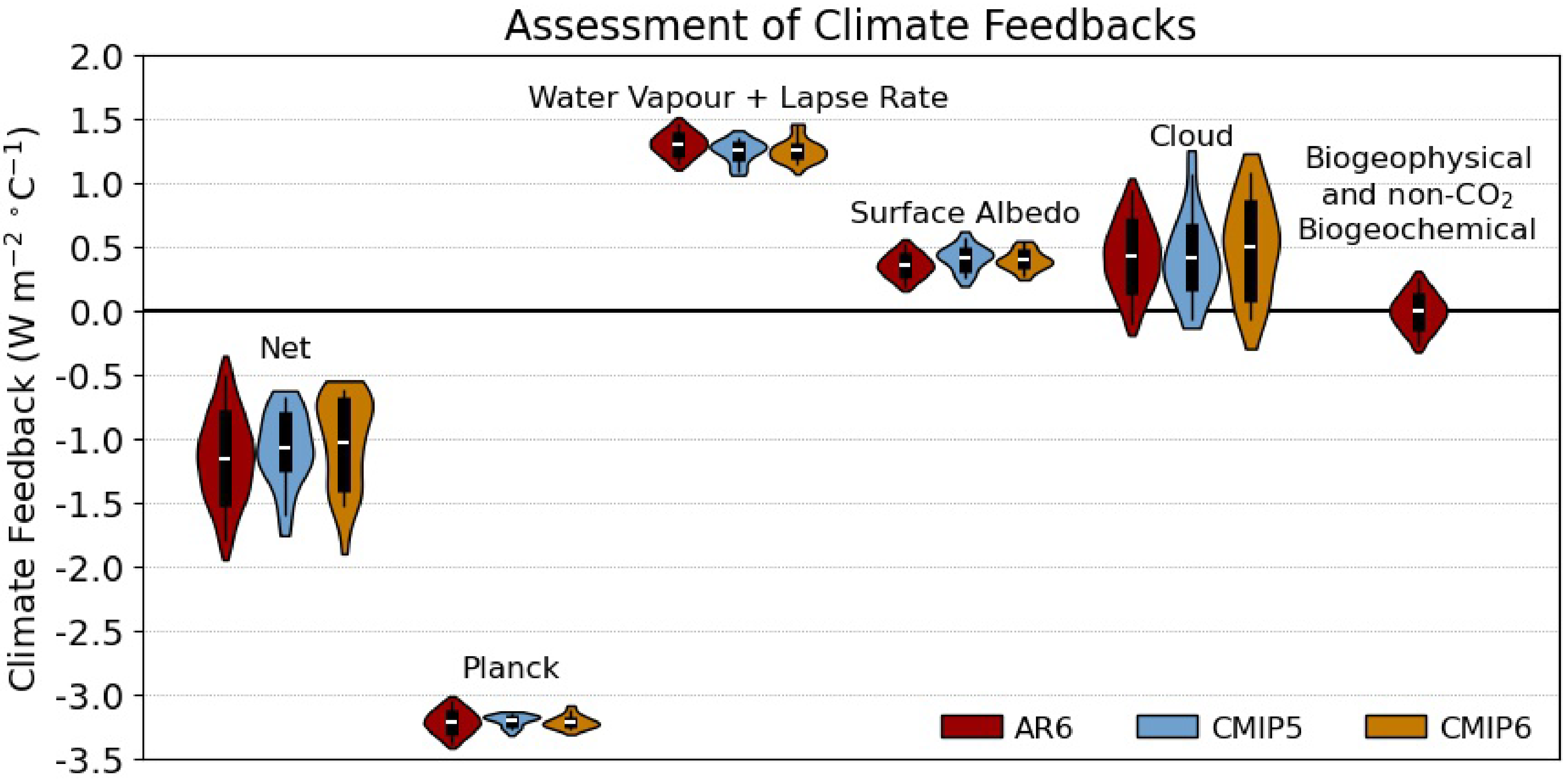


IPCC, 2021

与气候变化相关的反馈过程

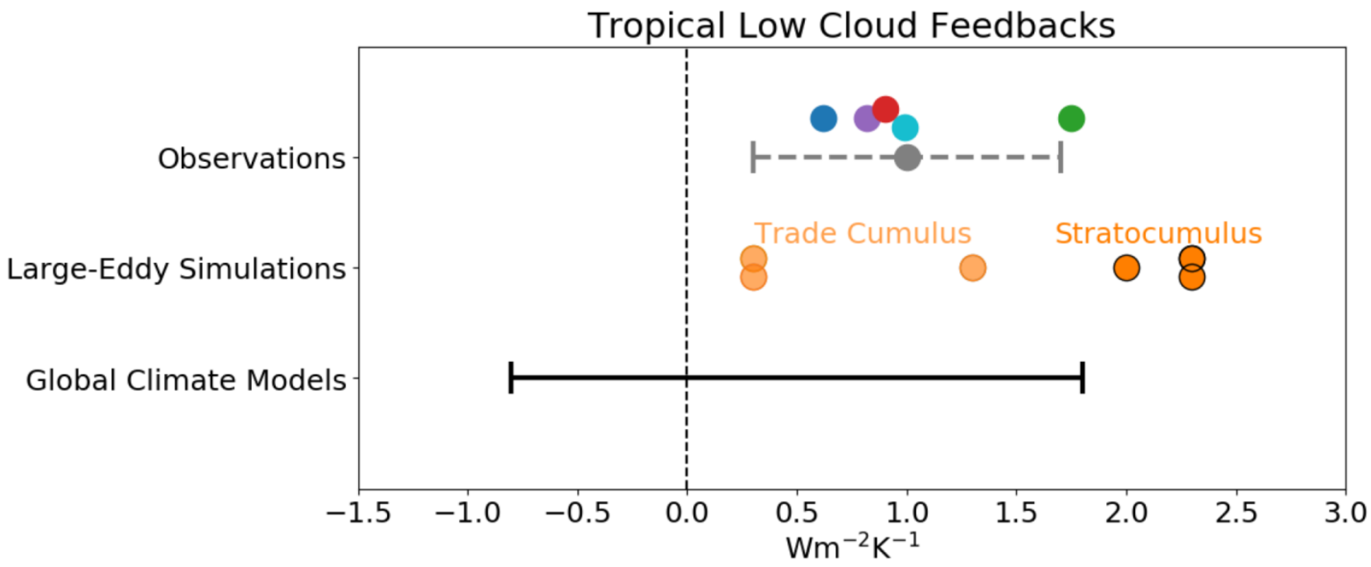
- 温度（热辐射）：（-）
- 水汽：温室效应（+）
- 温度递减率：（-）
- 冰雪圈：返照率（+）
- 云水：返照率（-）、温室效应（+）
- 海洋：CO_2含量（+,-）、AMOC（?）
- 生物圈：光合作用（-）、呼吸（+）

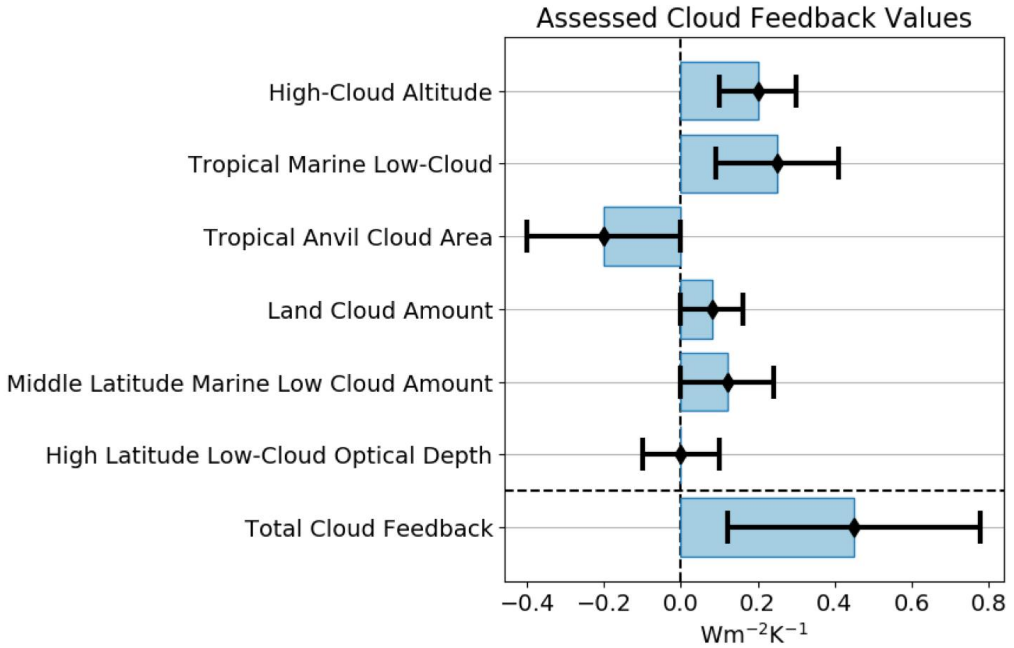
Summary of Feedbacks



IPCC, 2021

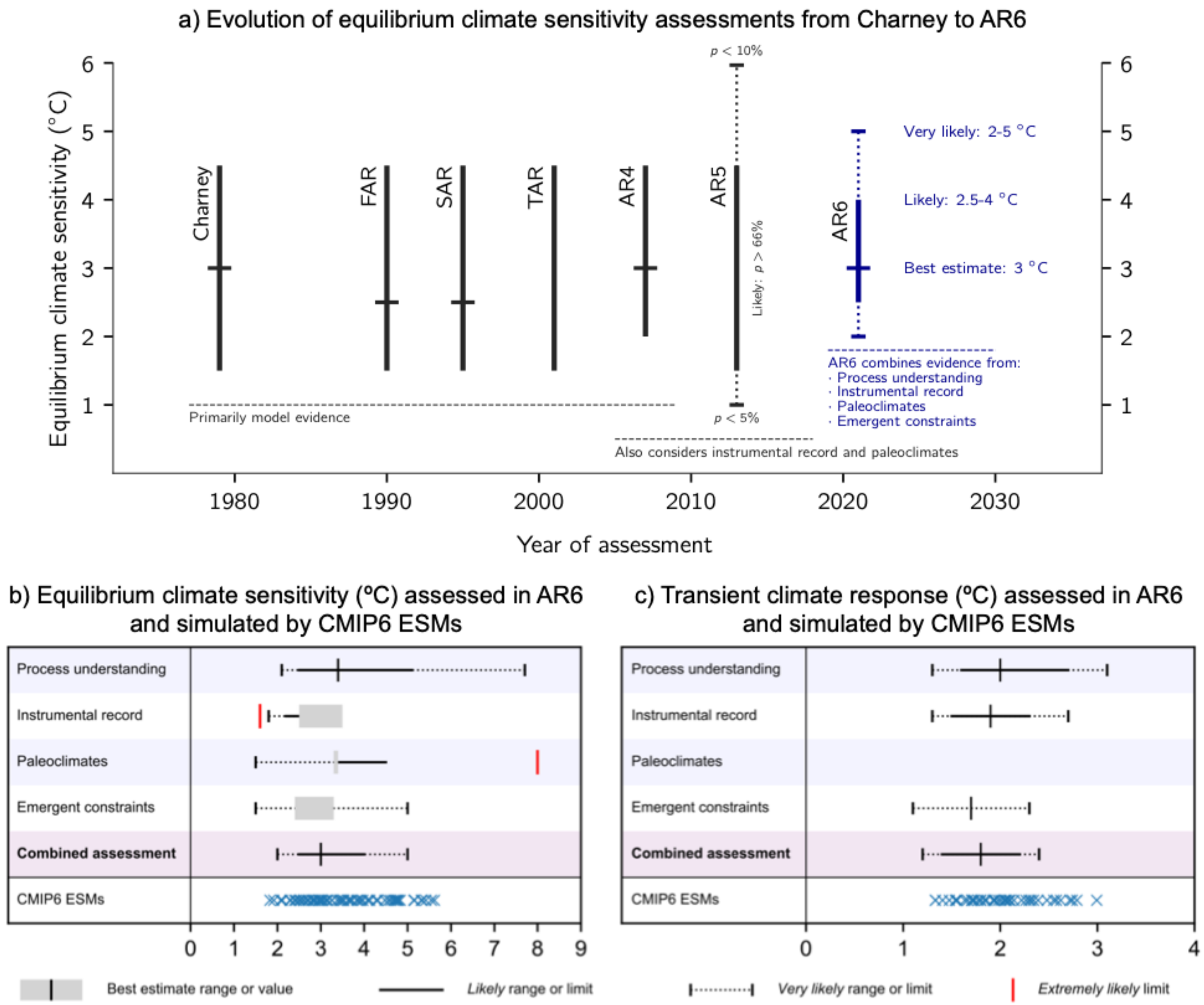
Cloud Feedbacks

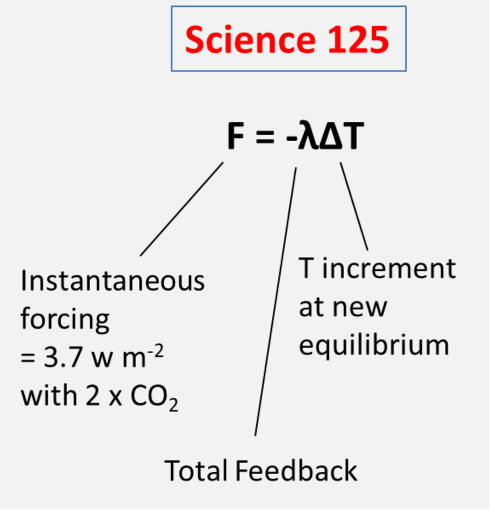




Sherwood et al., 2020 RoG

Climate Sensitivity





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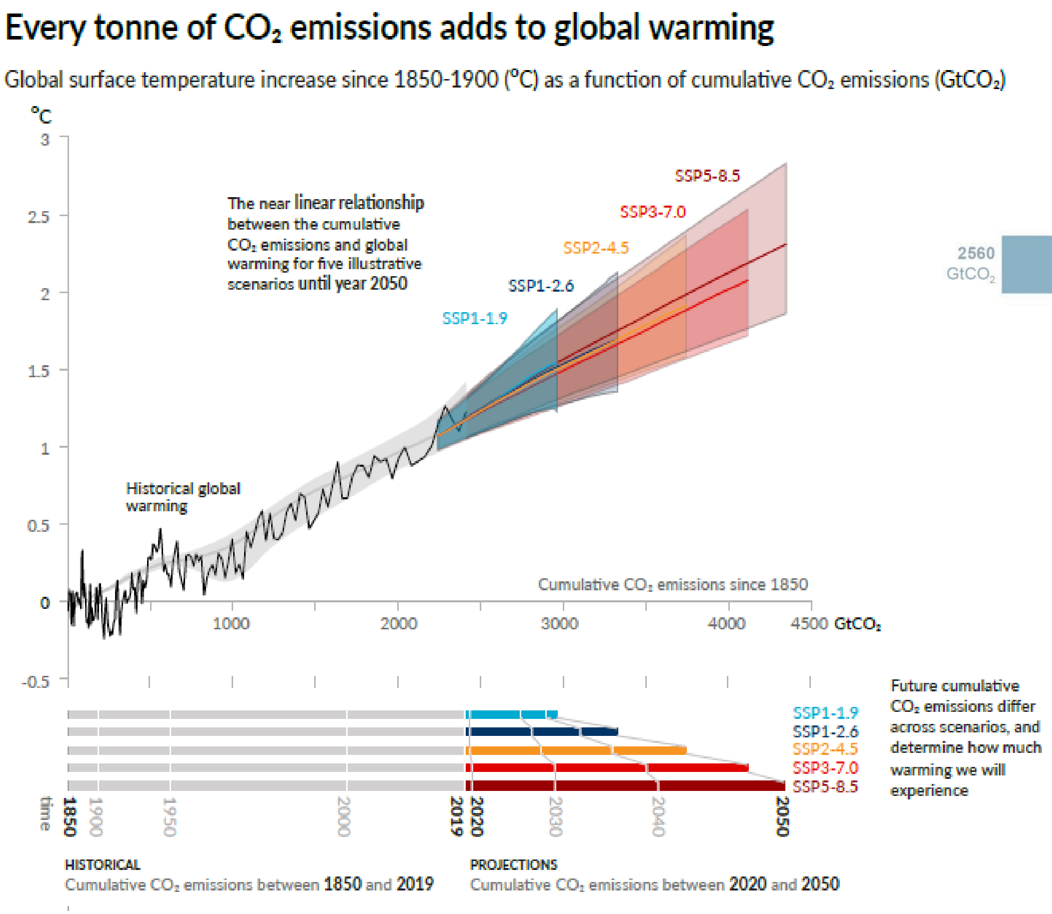
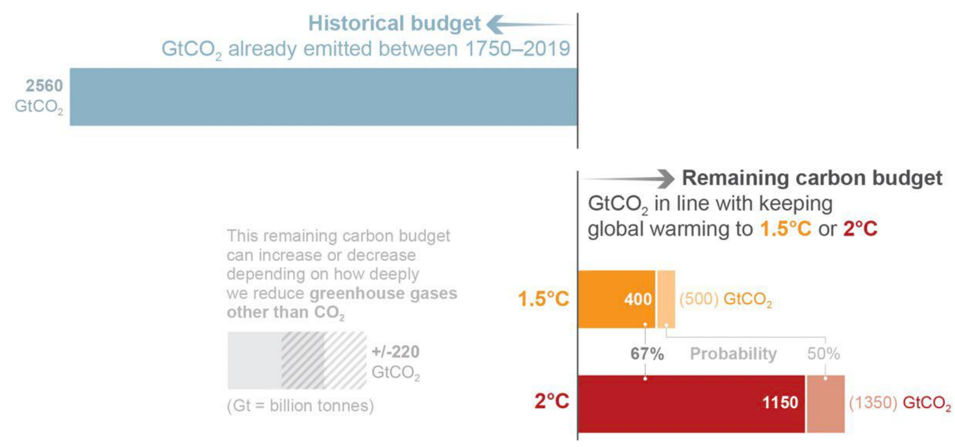
Cumulative CO_2 Emissions and Warming



Carbon budget



IPCC, 2021

思考题

讨论：地表气温的日变化、云和气溶胶的影响

讨论：气候变化与极端天气的关系

讨论：气溶胶对气候的影响的不确定性及原因

讨论：云反馈作用的不确定性及原因

讨论：气候-化学相互作用及生物圈影响

讨论：碳中和背景下污染-气候协同控制

BACKUP SLIDES

Changes in Climate Indicators During Earth Evolution

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

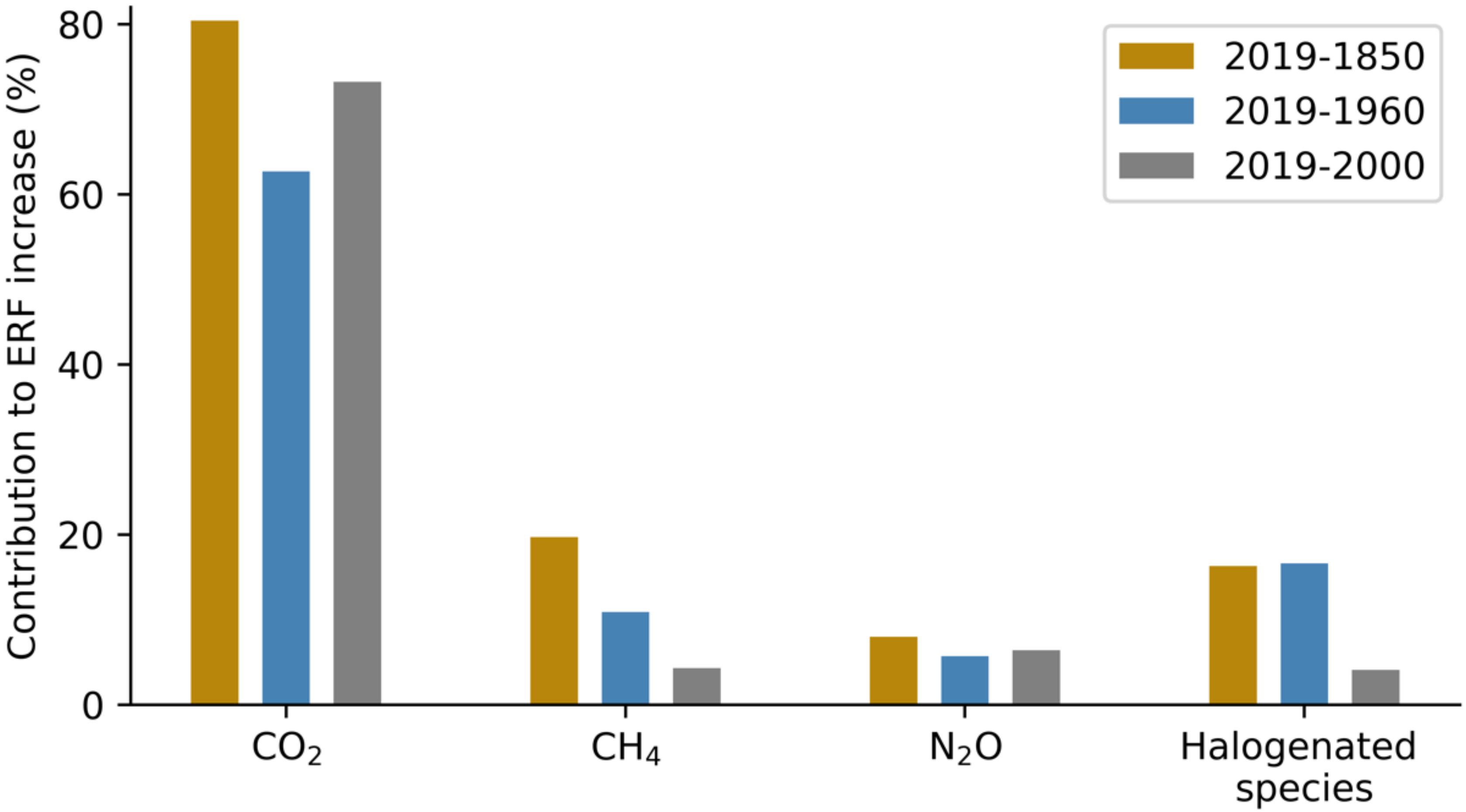
Colder, Lower sea level, More ice

Warmer, Higher sea level, Less ice

Insufficient data or not assessed

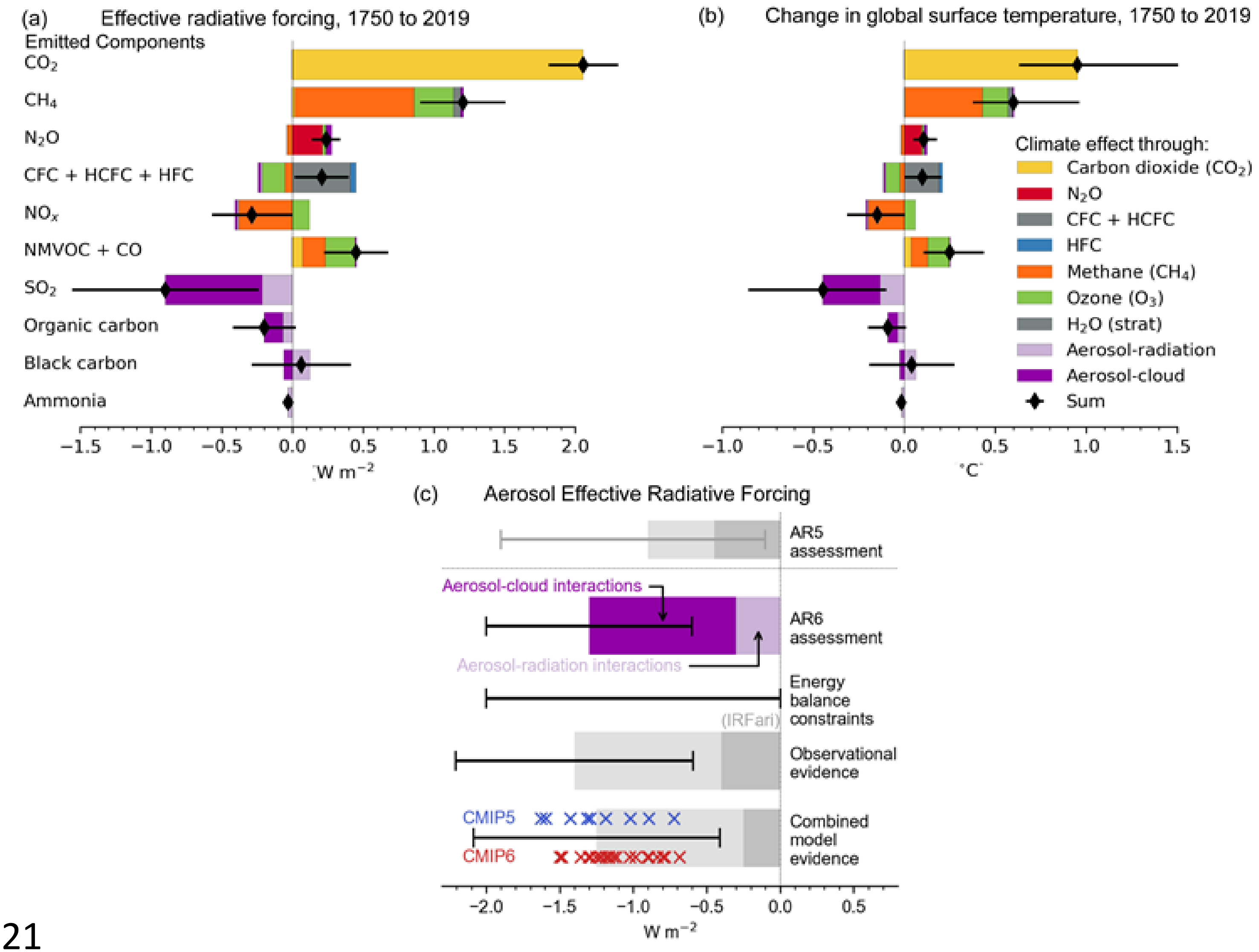
IPCC, 2021

Contributions of Long-lived GHGs to Total (GHG+AER) ERF



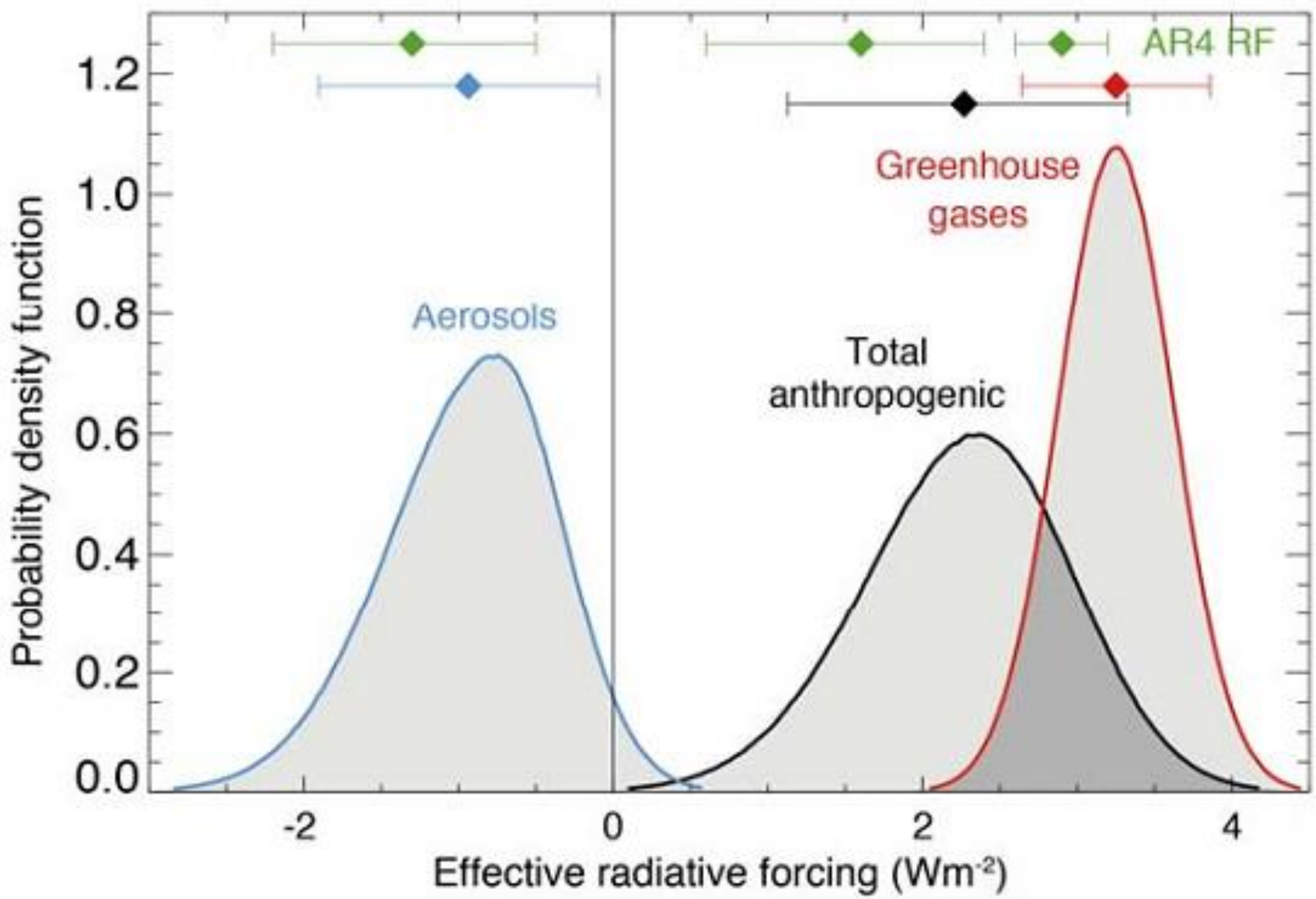
IPCC, 2021

Effective Radiative Forcing



IPCC, 2021

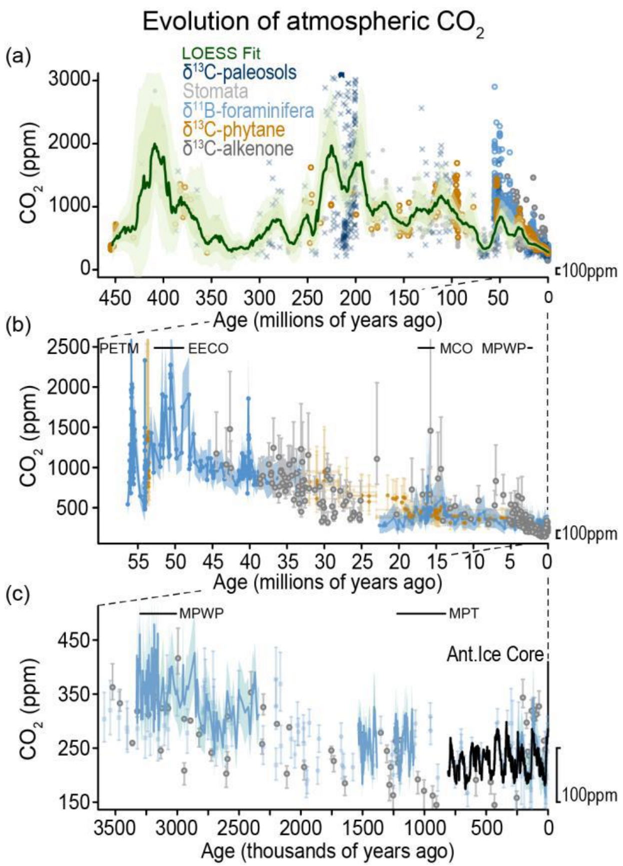
Effective Radiative Forcing

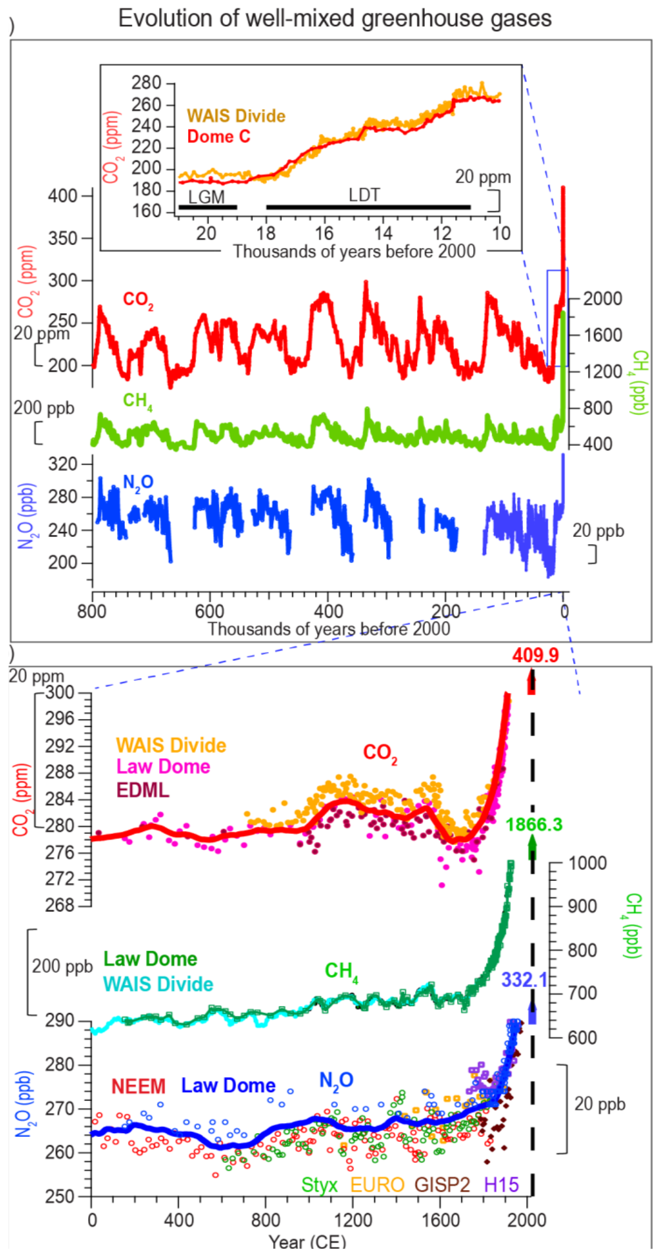


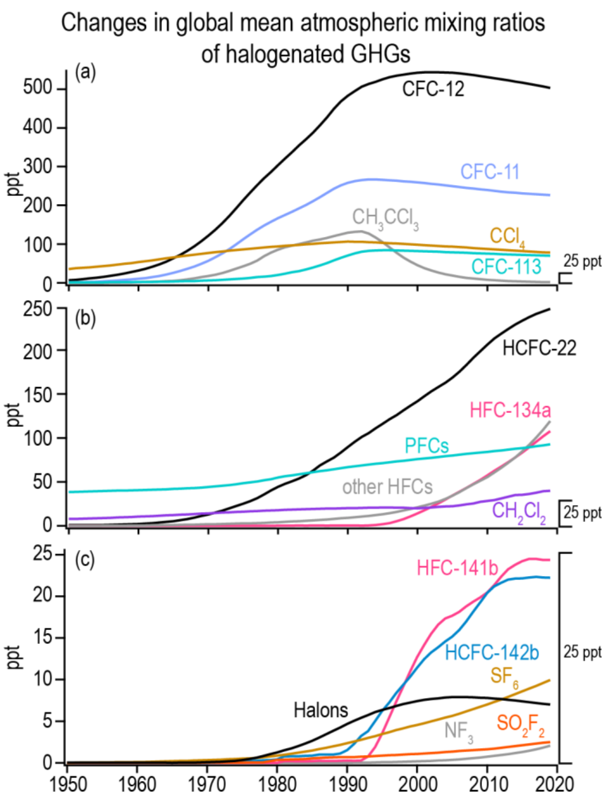
IPCC, 2013

Trends in Long-lived GHGs Concentrations

[CO_2] in 2022: 417 ppm

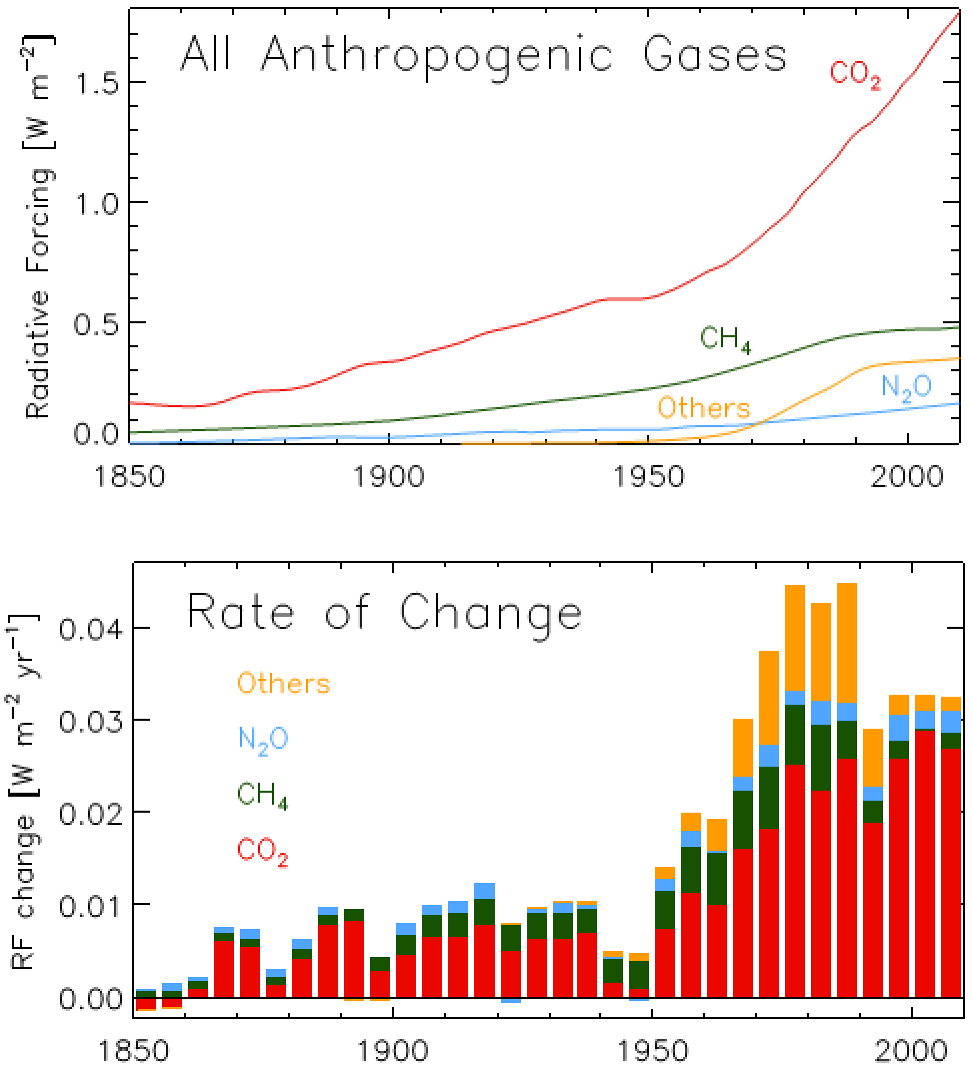






IPCC, 2021

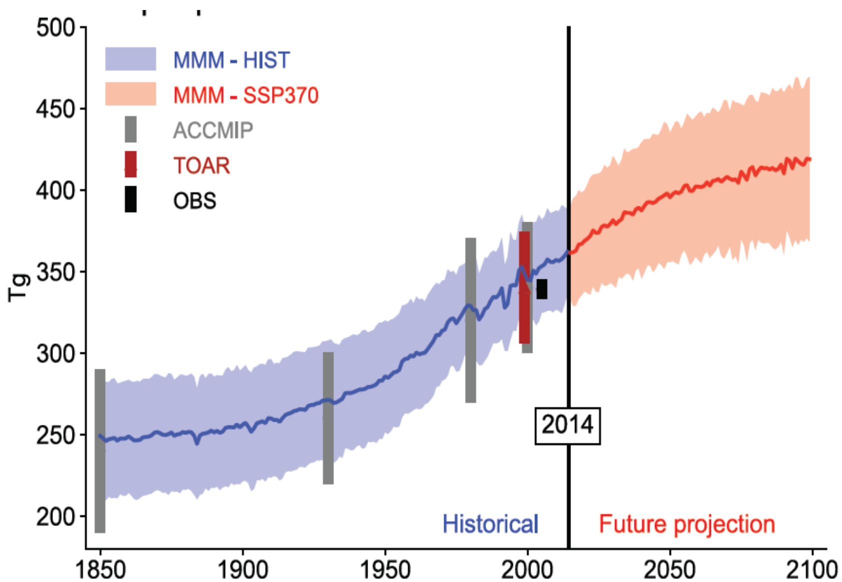
Trends in Long-lived GHG Radiative Forcing



IPCC, 2013

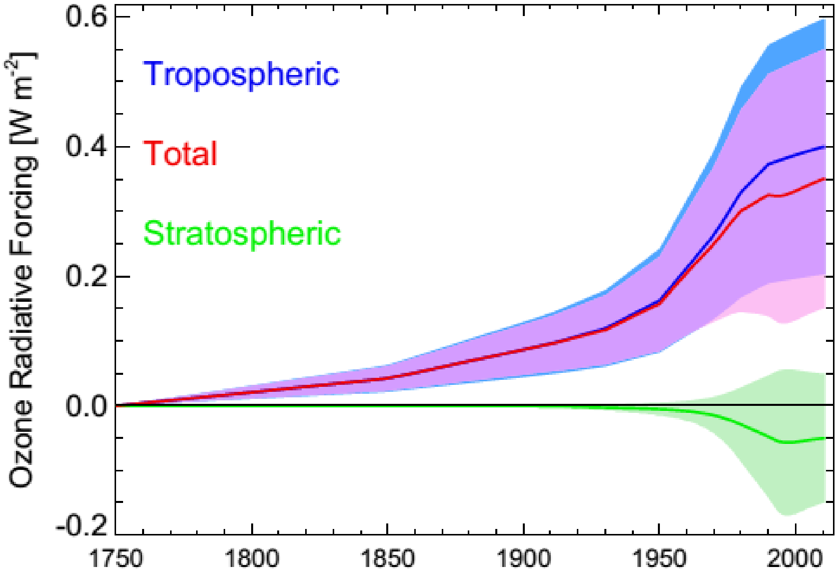
Ozone Radiative Forcing

Tropospheric ozone burden



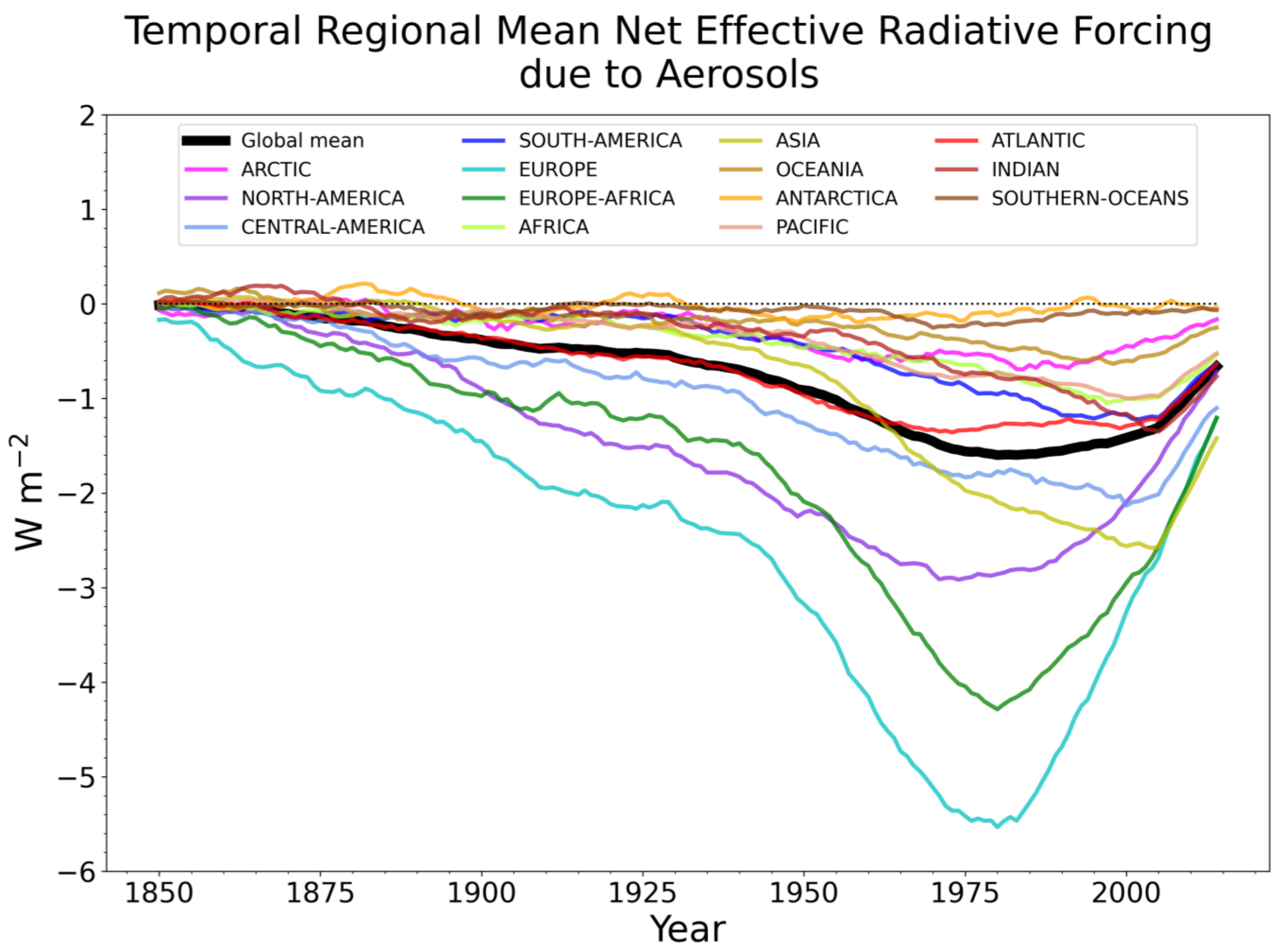
IPCC, 2021

Ozone RF



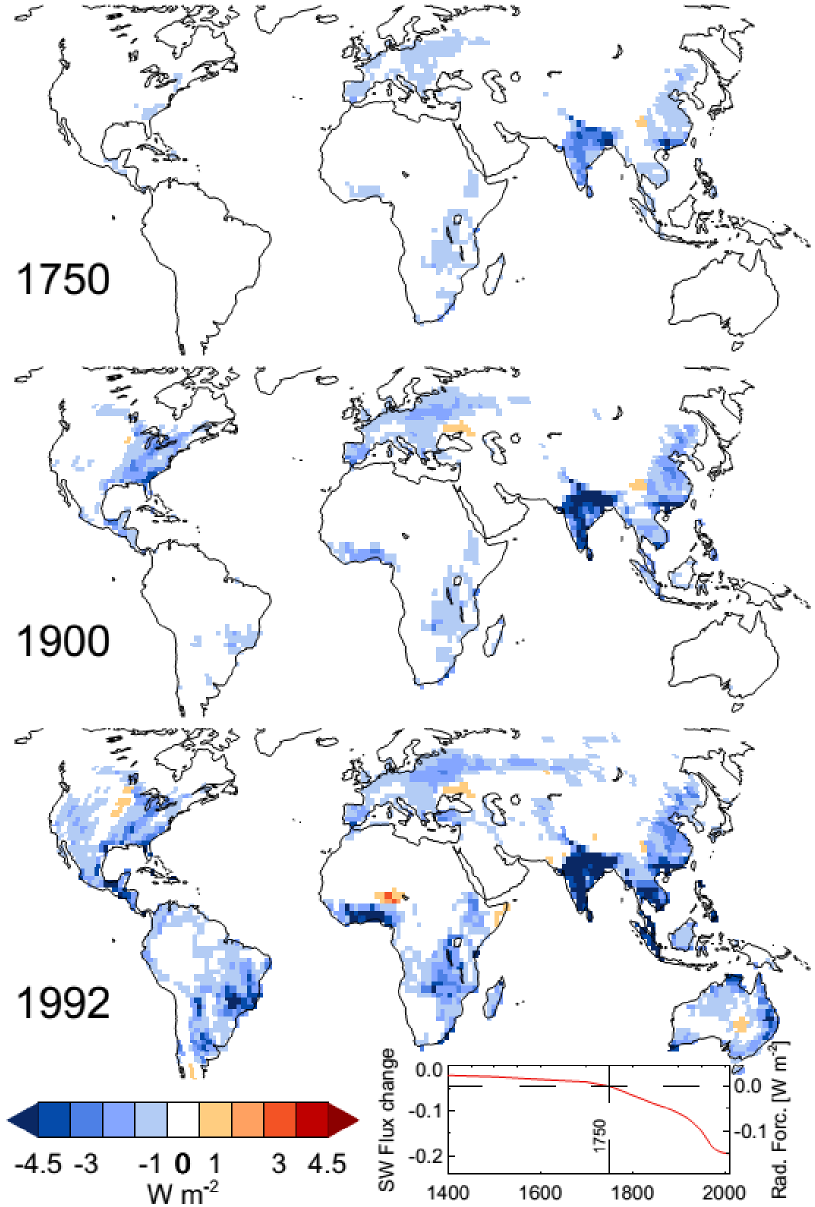
IPCC, 2013

Aerosol Effective Radiative Forcing



IPCC, 2021

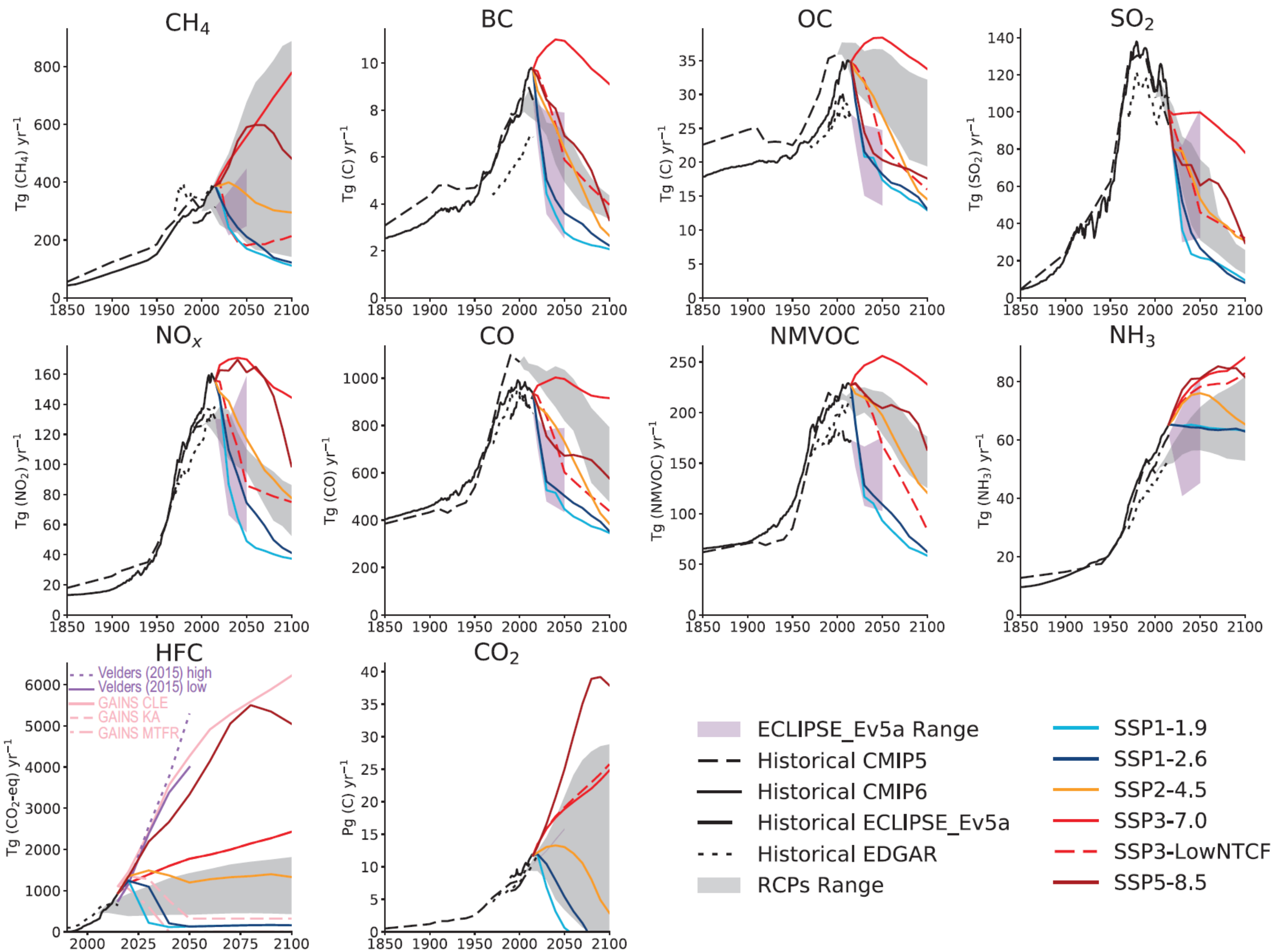
LUC-related Surface Albedo Radiative Forcing



Effects already occurred in 1750

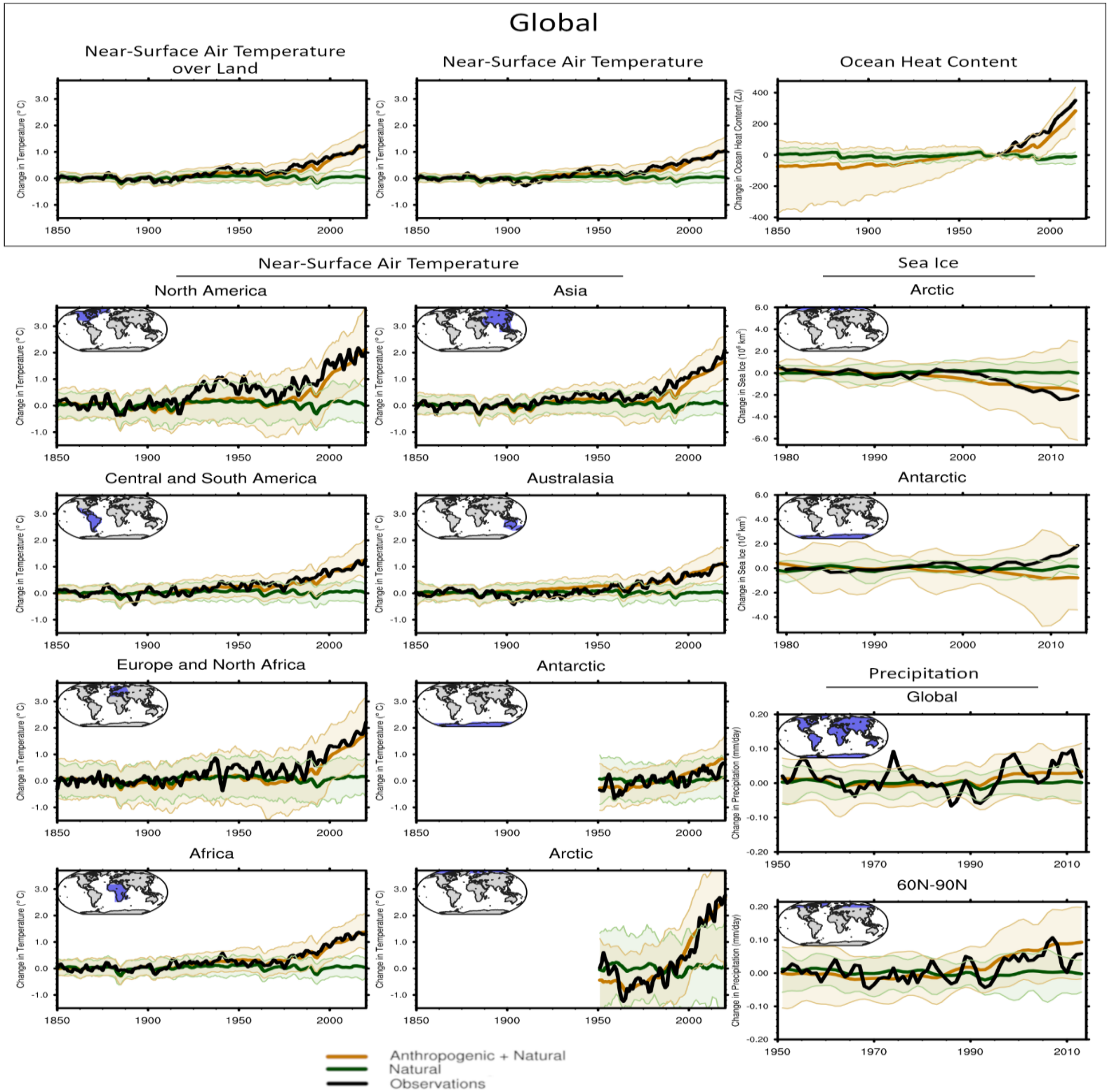
IPCC, 2013

Future Projection of Climate Forcers



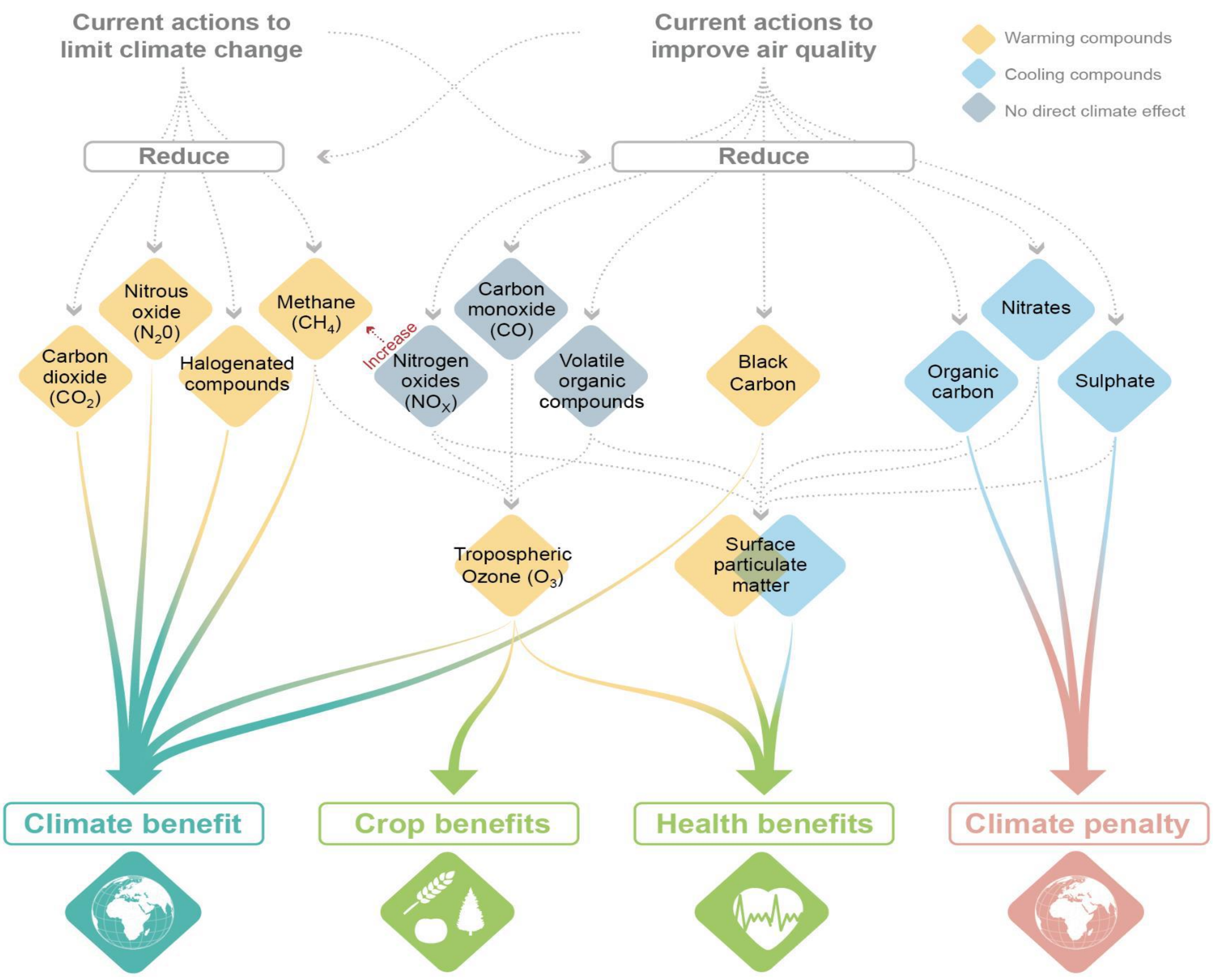
IPCC, 2021

Modeled Anthropogenic versus Natural Impacts



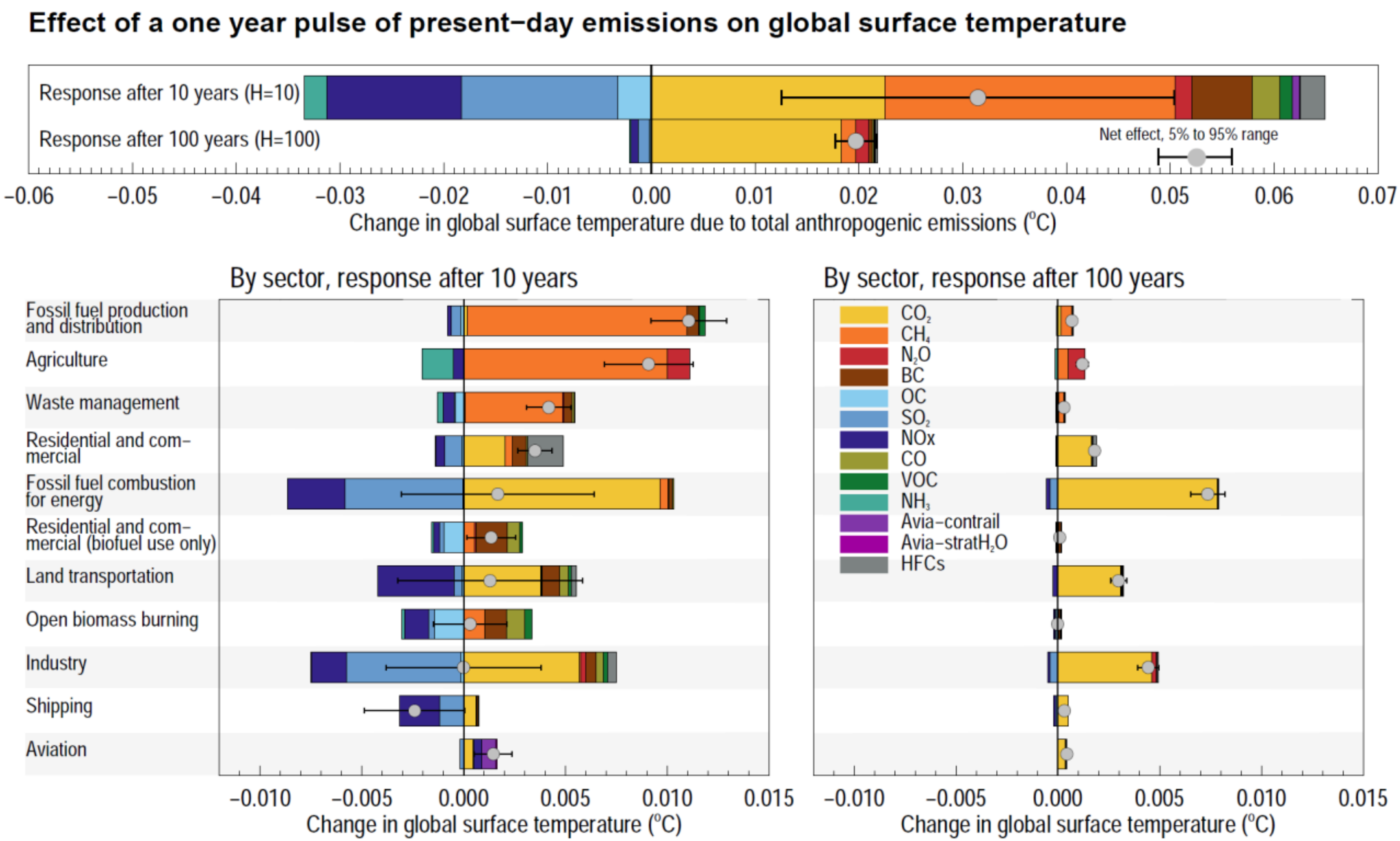
IPCC, 2021

Climate-Pollution Nexus



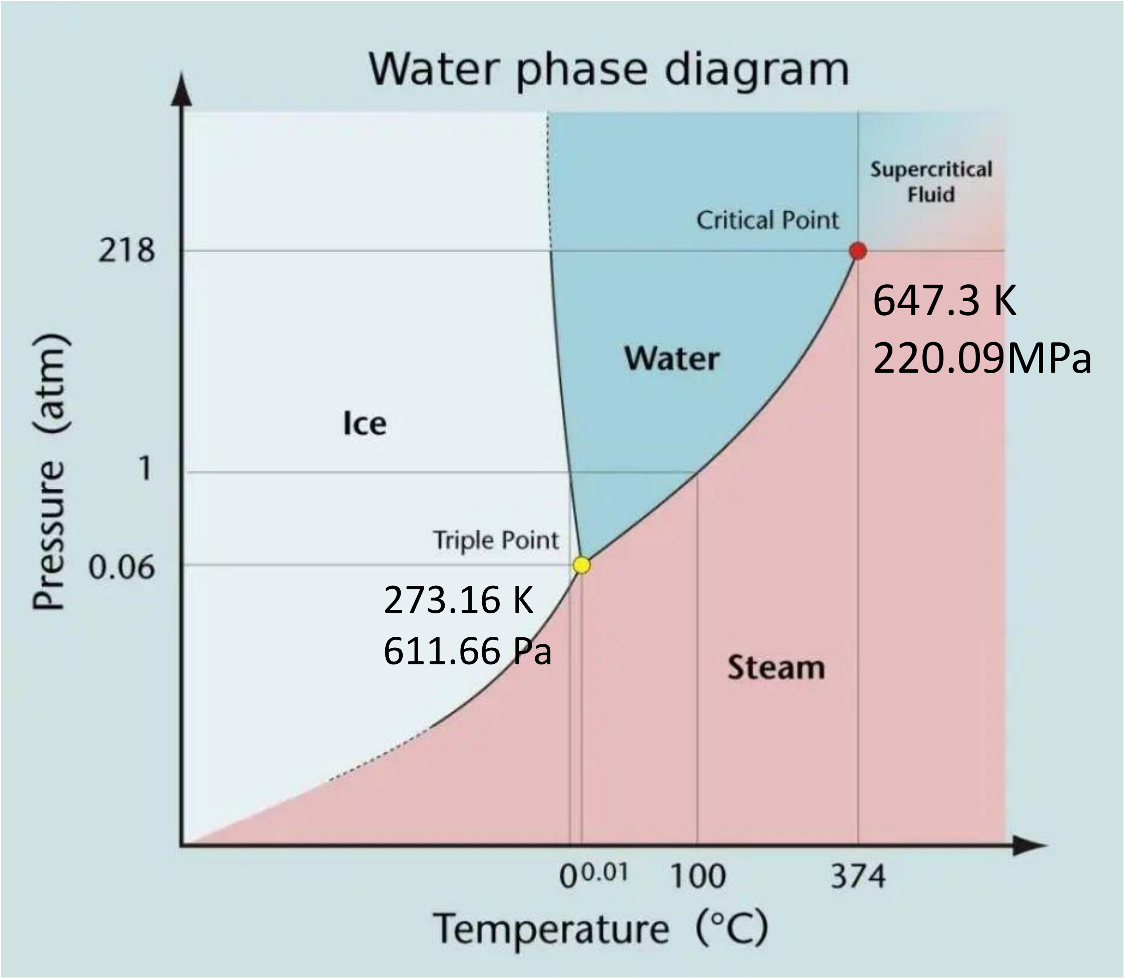
IPCC, 2021

Temperature Response to Perturbed Emissions by Sector



IPCC, 2021

H_2O Feedback

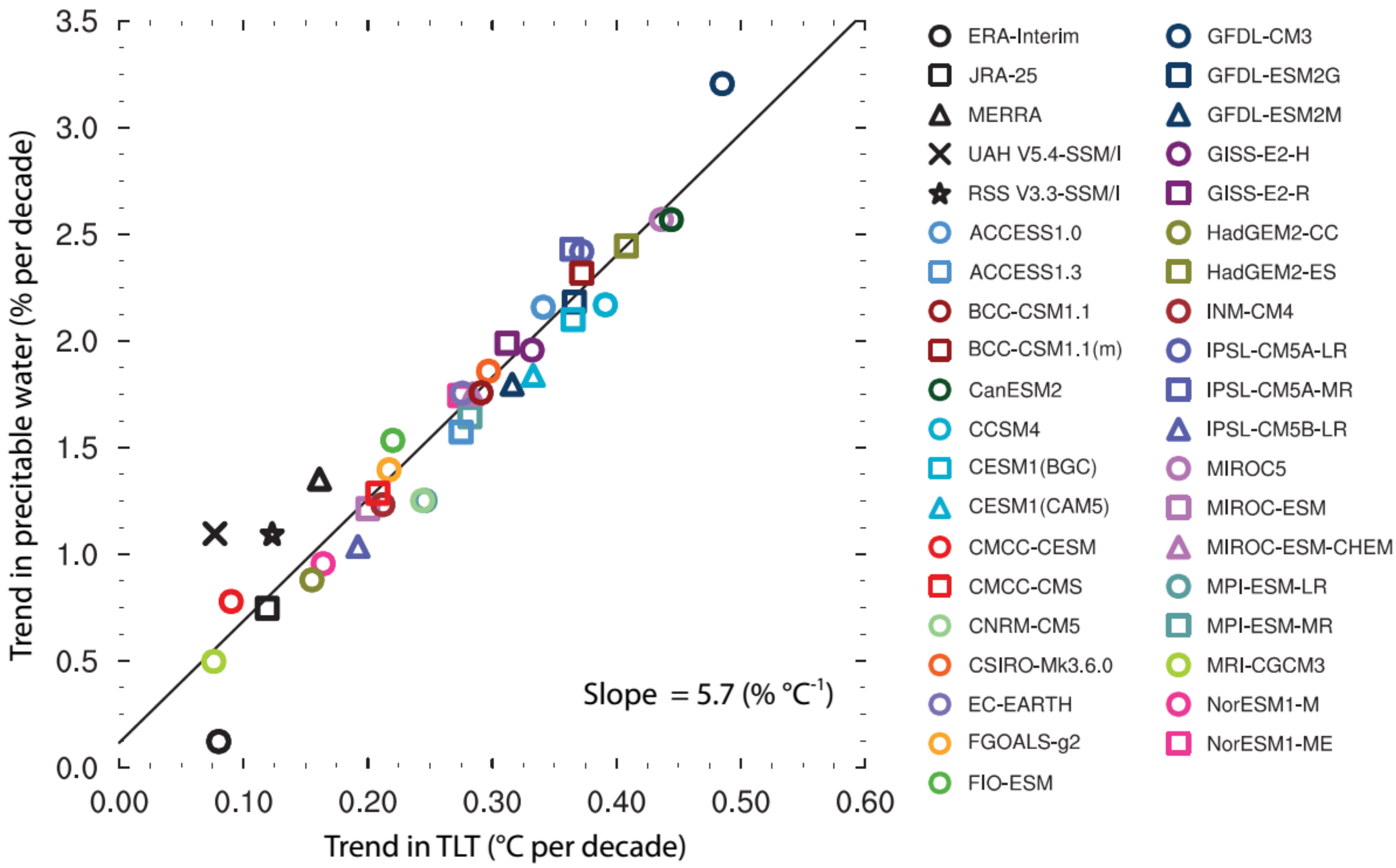


Clausius–Clapeyron Eq.:

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

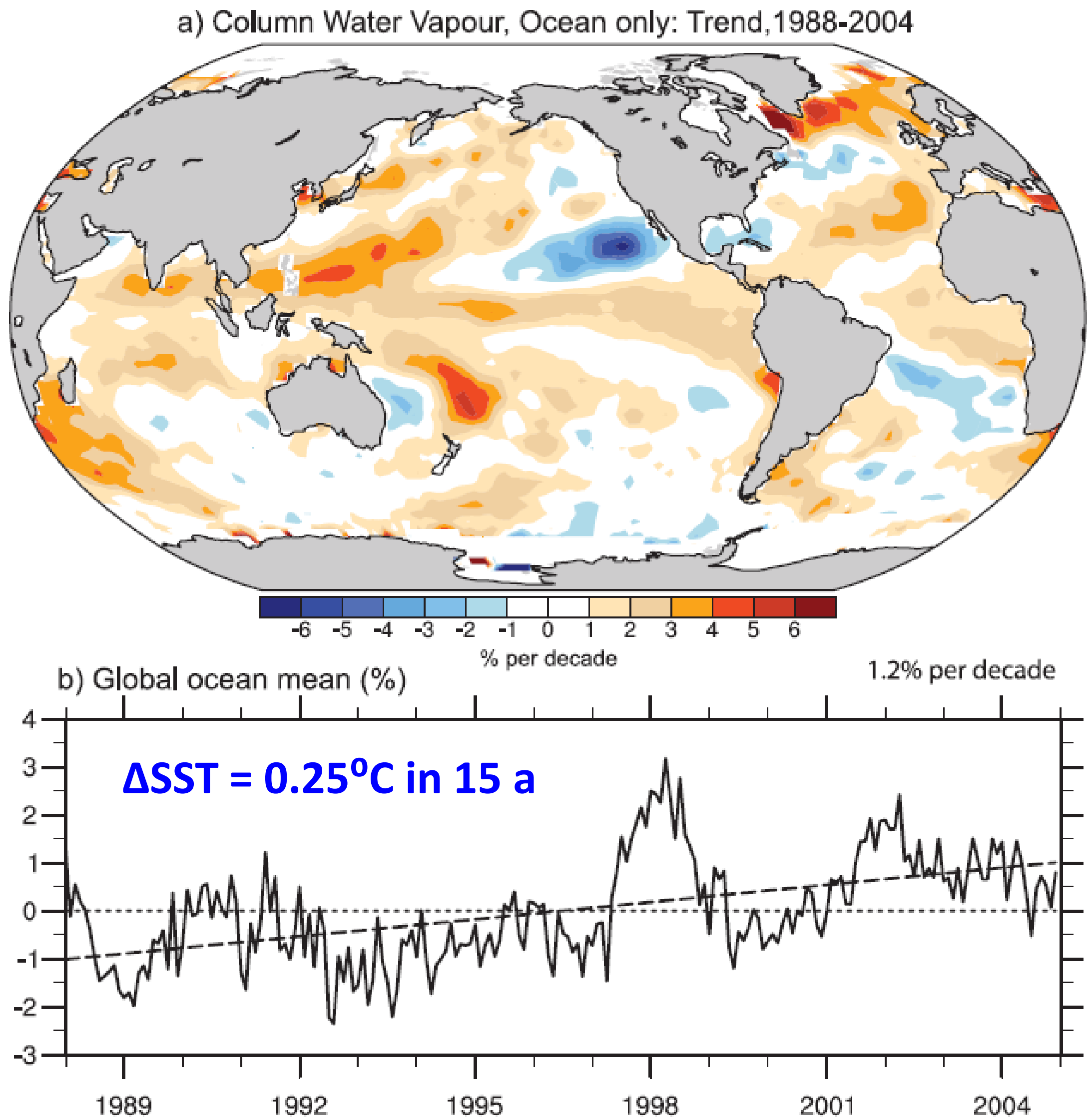
With constant RH **T ↑ → H_2O ↑ → GH effect ↑ → T ↑**

Water Vapor Increase Driven by Warming



IPCC, 2013

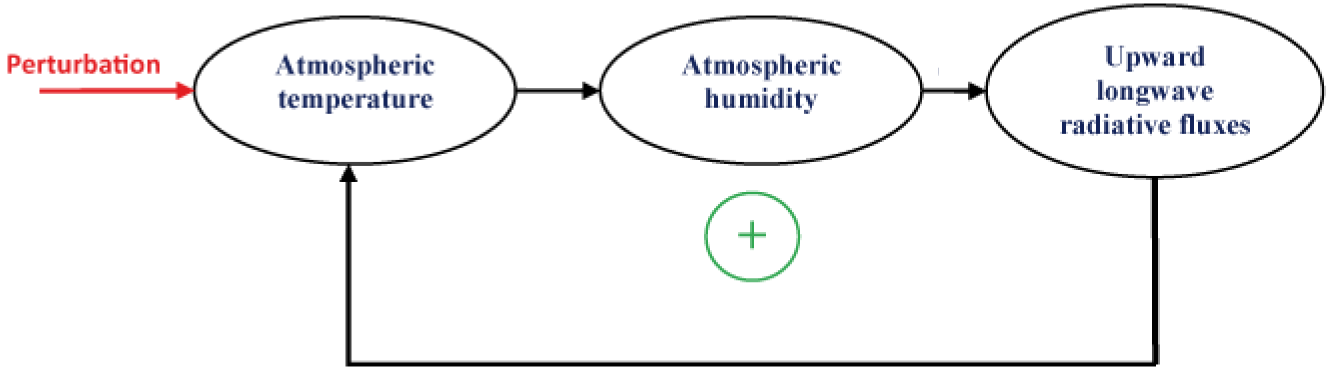
Water Vapor Change: 1988-2004



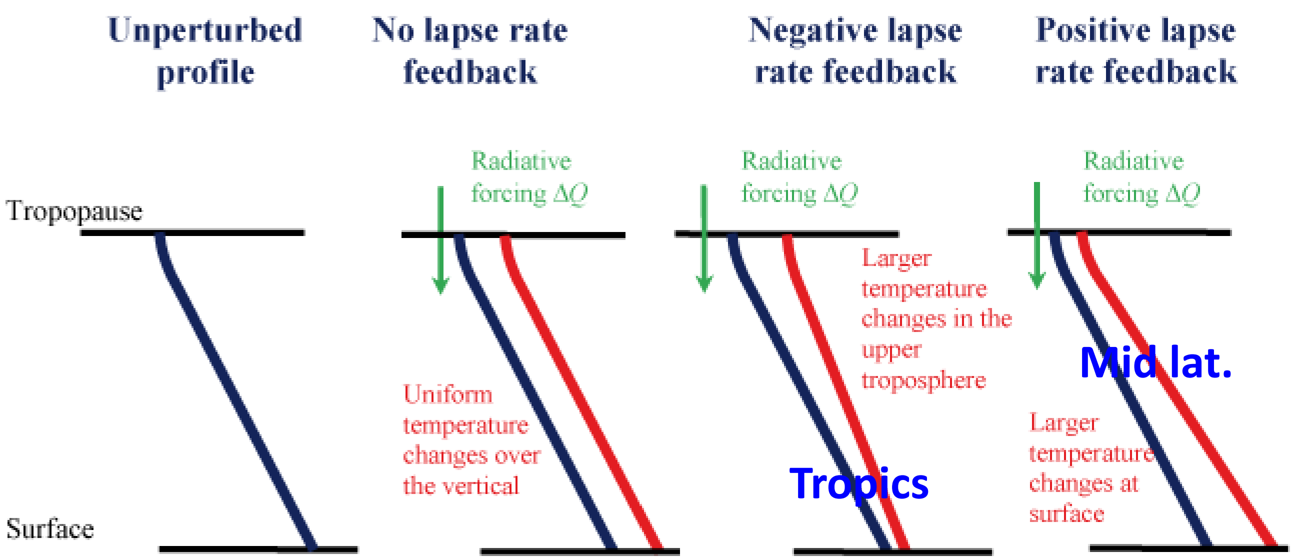
IPCC, 2007

Water Vapor – Lapse Rate Feedback

Water vapor feedback



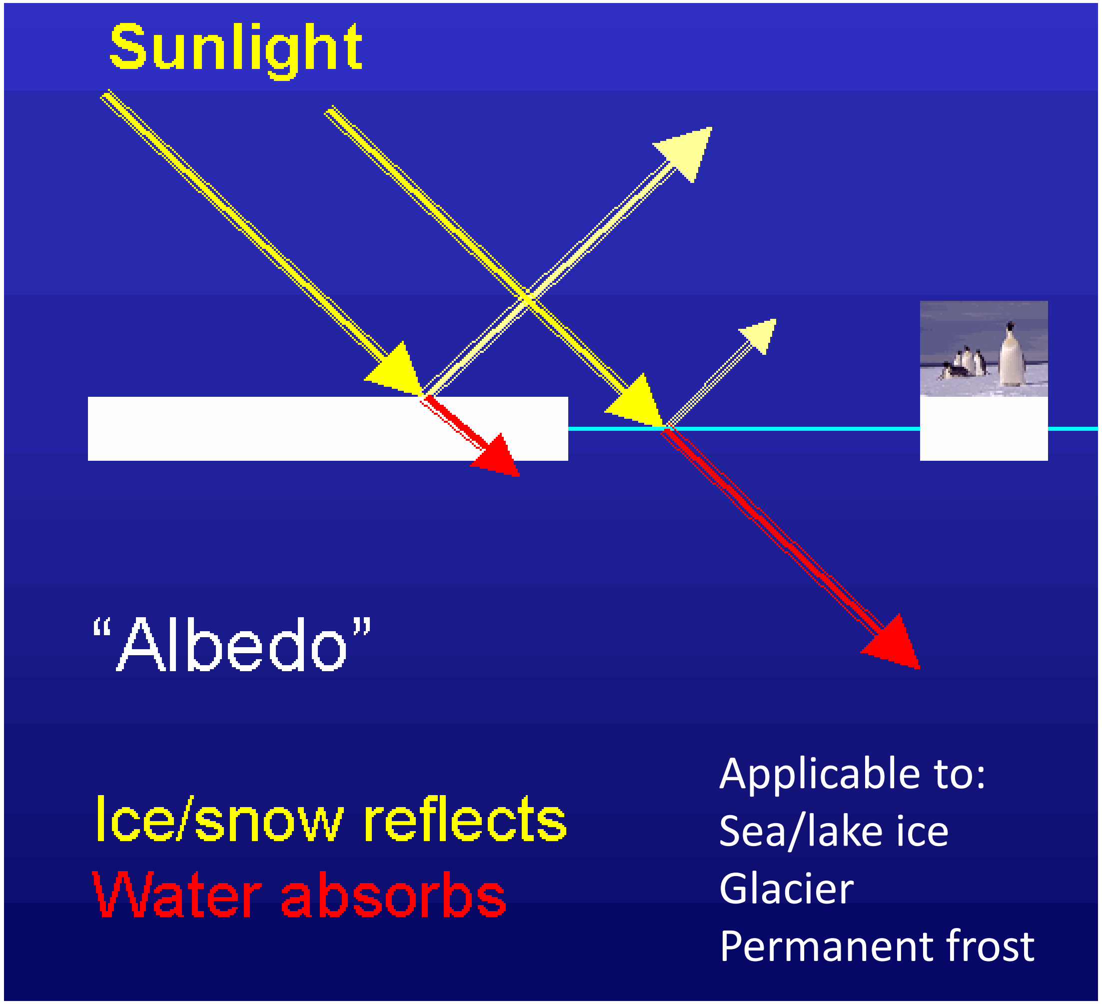
Lapse rate feedback



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

IPCC, 2007

Ice Albedo Feedback

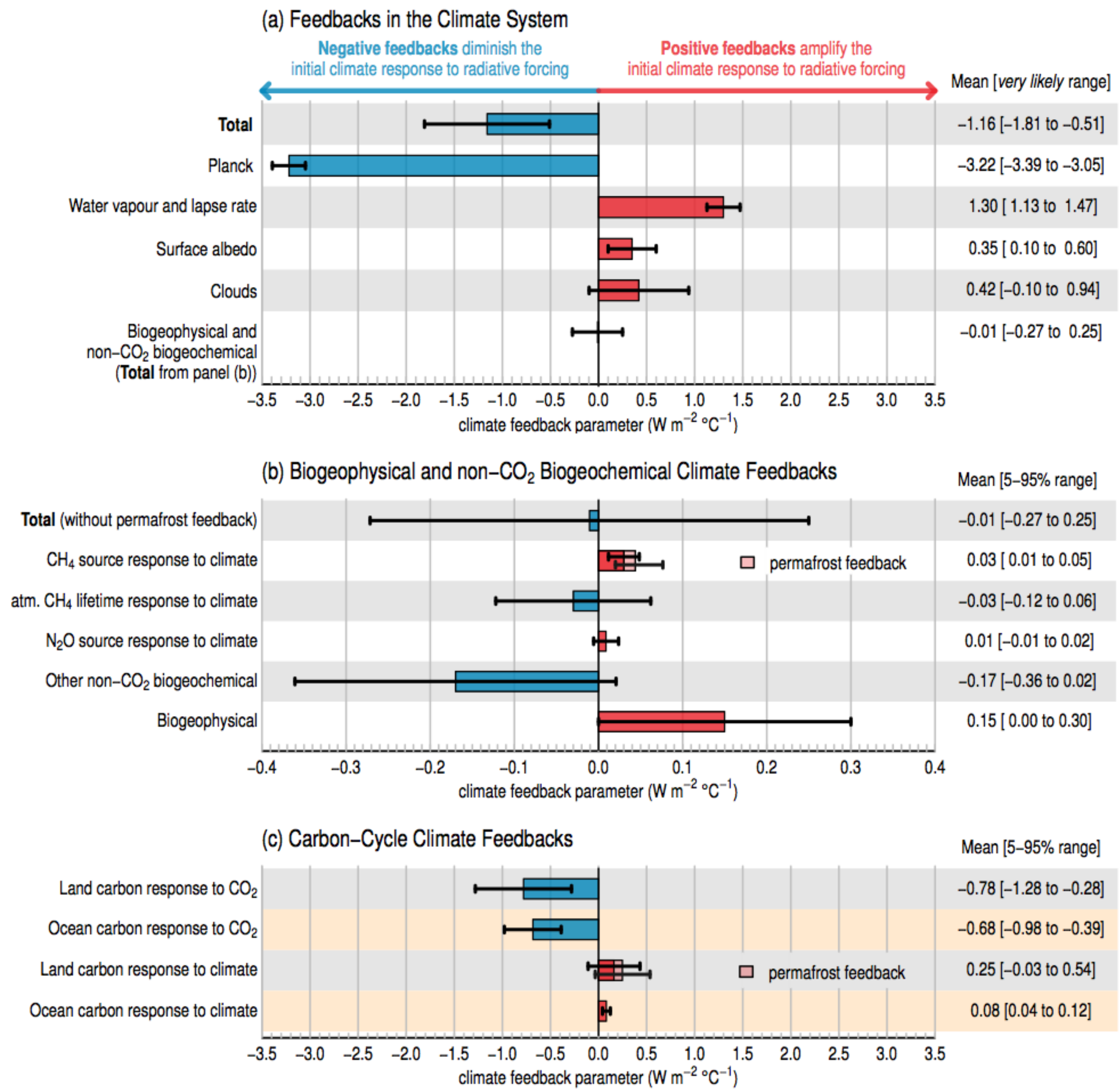


T ↑ → Ice ↓ → Albedo ↓ → T ↑

Cloud Types and Radiative Effects

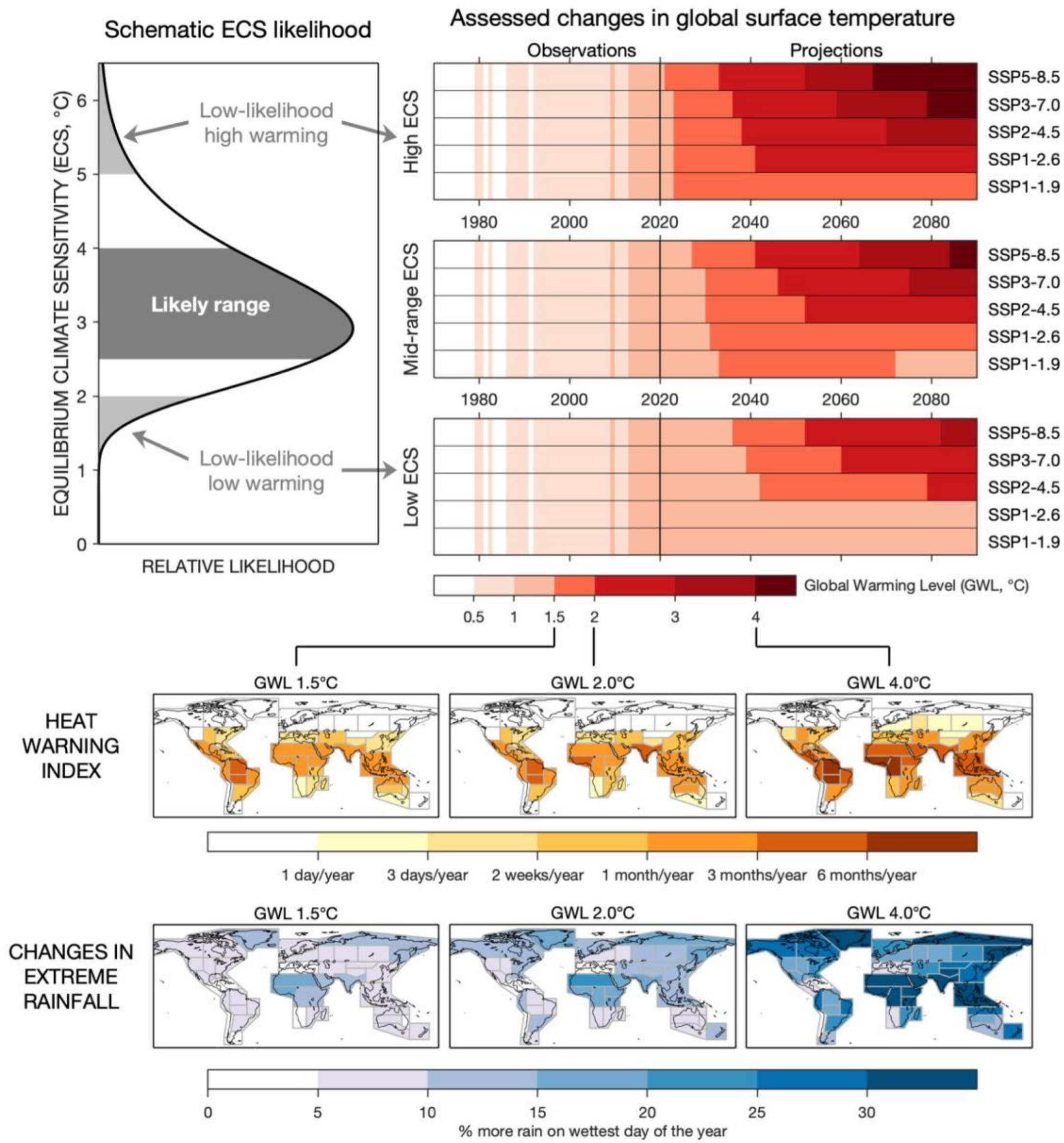
- **High-level clouds: weak reflectance of SW, strong GH effect on LW**
- **Low-level clouds: strong reflectance of SW, weak GH effect on LW**
- **Convective clouds: strong SW and LW effects**
- **Polar clouds in different seasons?**
- **How to affect clouds: height, fraction, thickness, droplet size,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

Summary of Feedbacks



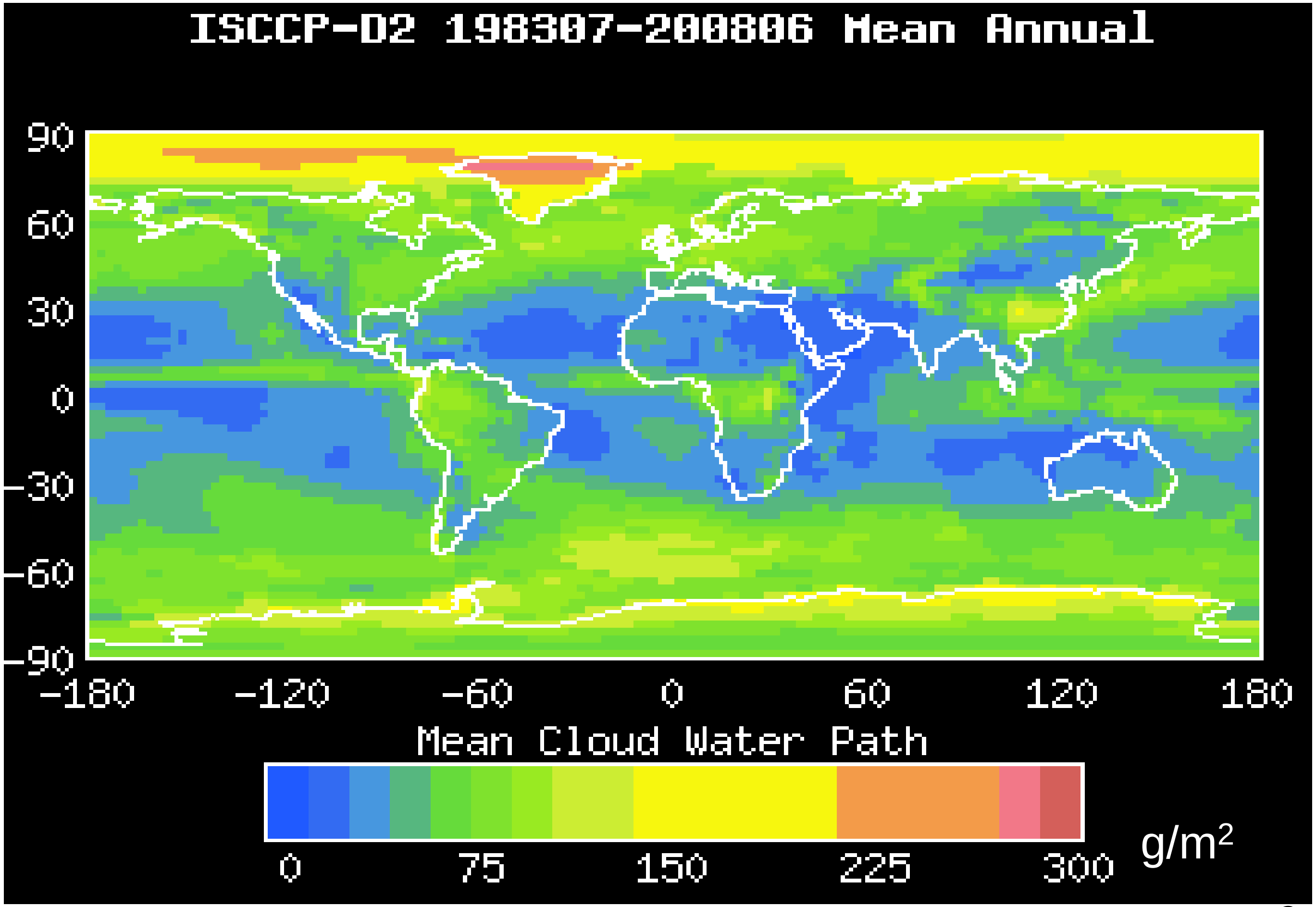
IPCC, 2021

Climate Sensitivity and Warming



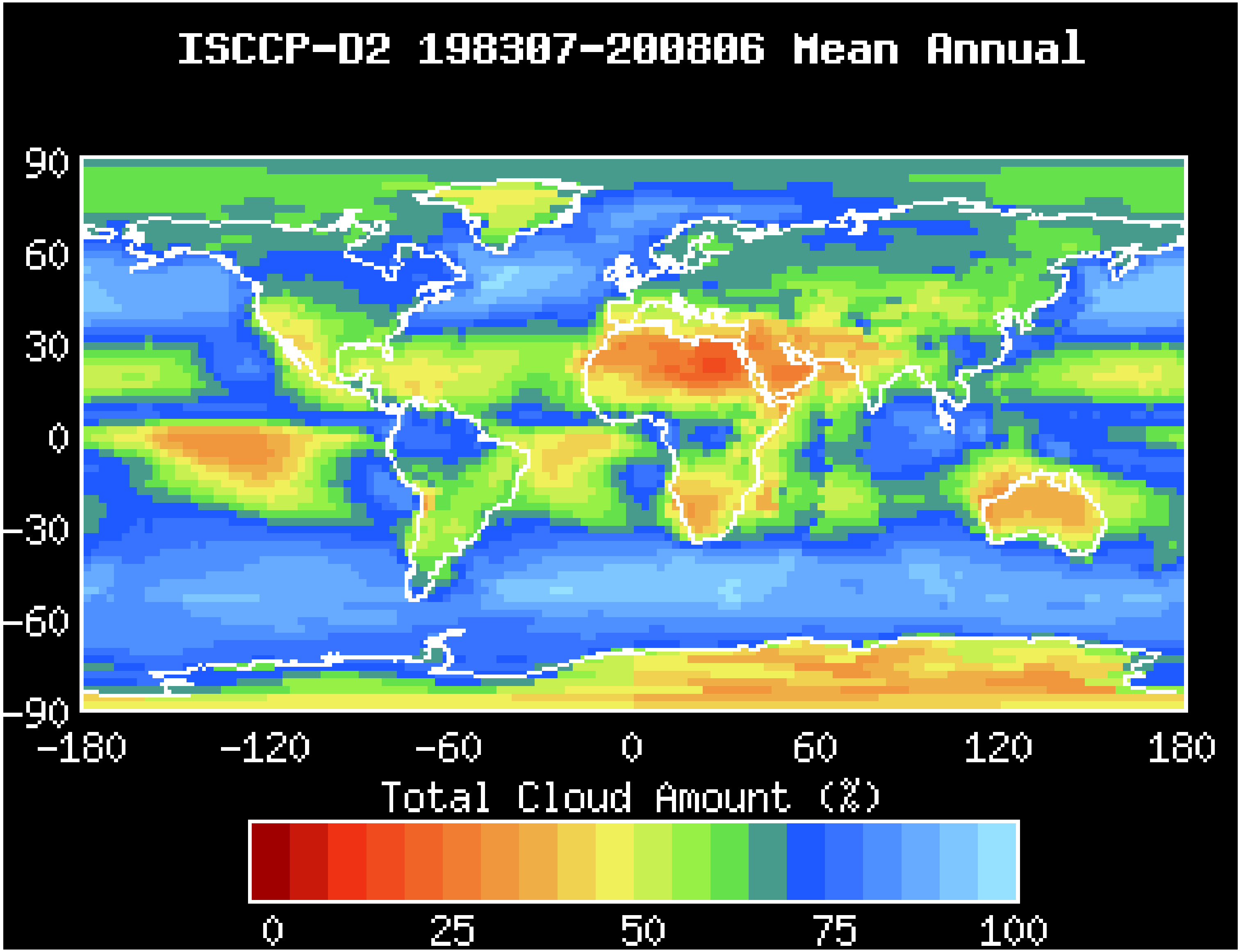
IPCC, 2021

Global Cloud Water Content: 1983-2008

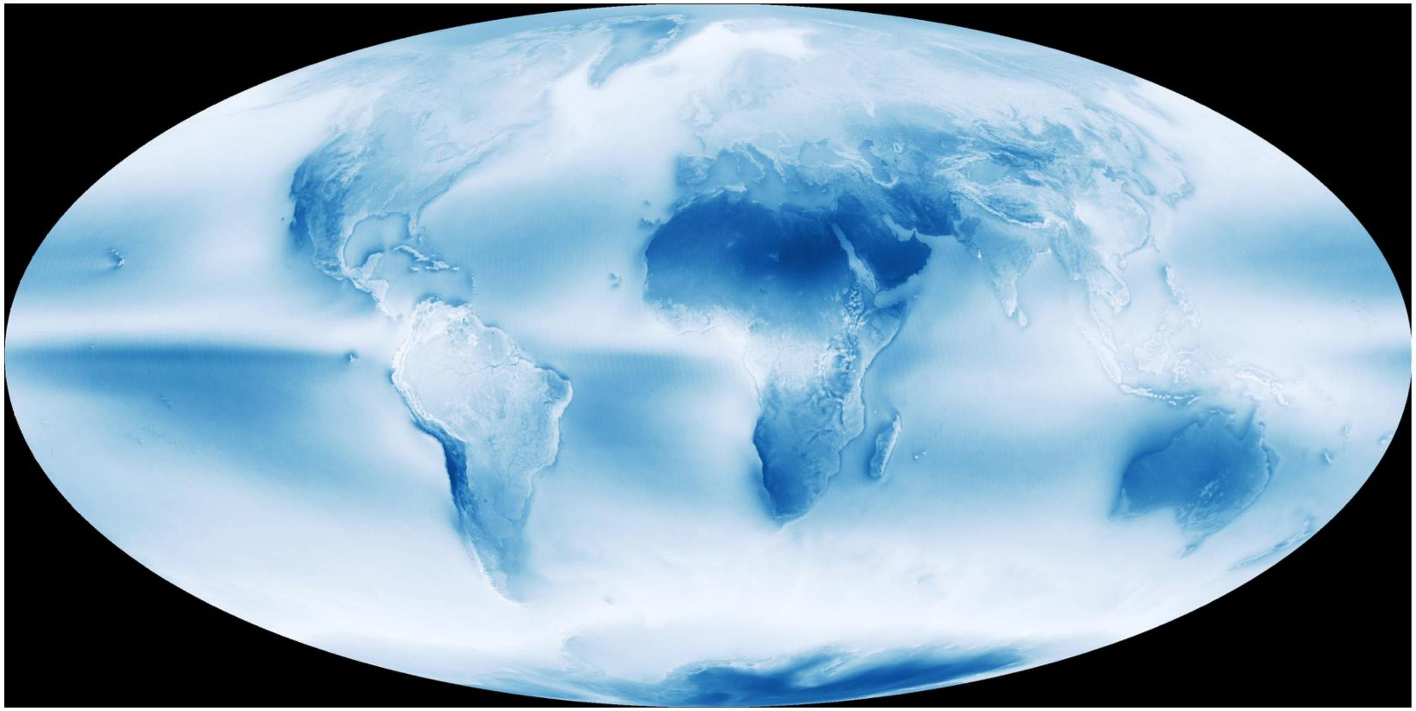


0 7.5 15 22.5 30 x 10^{-3} cm

Global Cloud Cover: 1983-2008

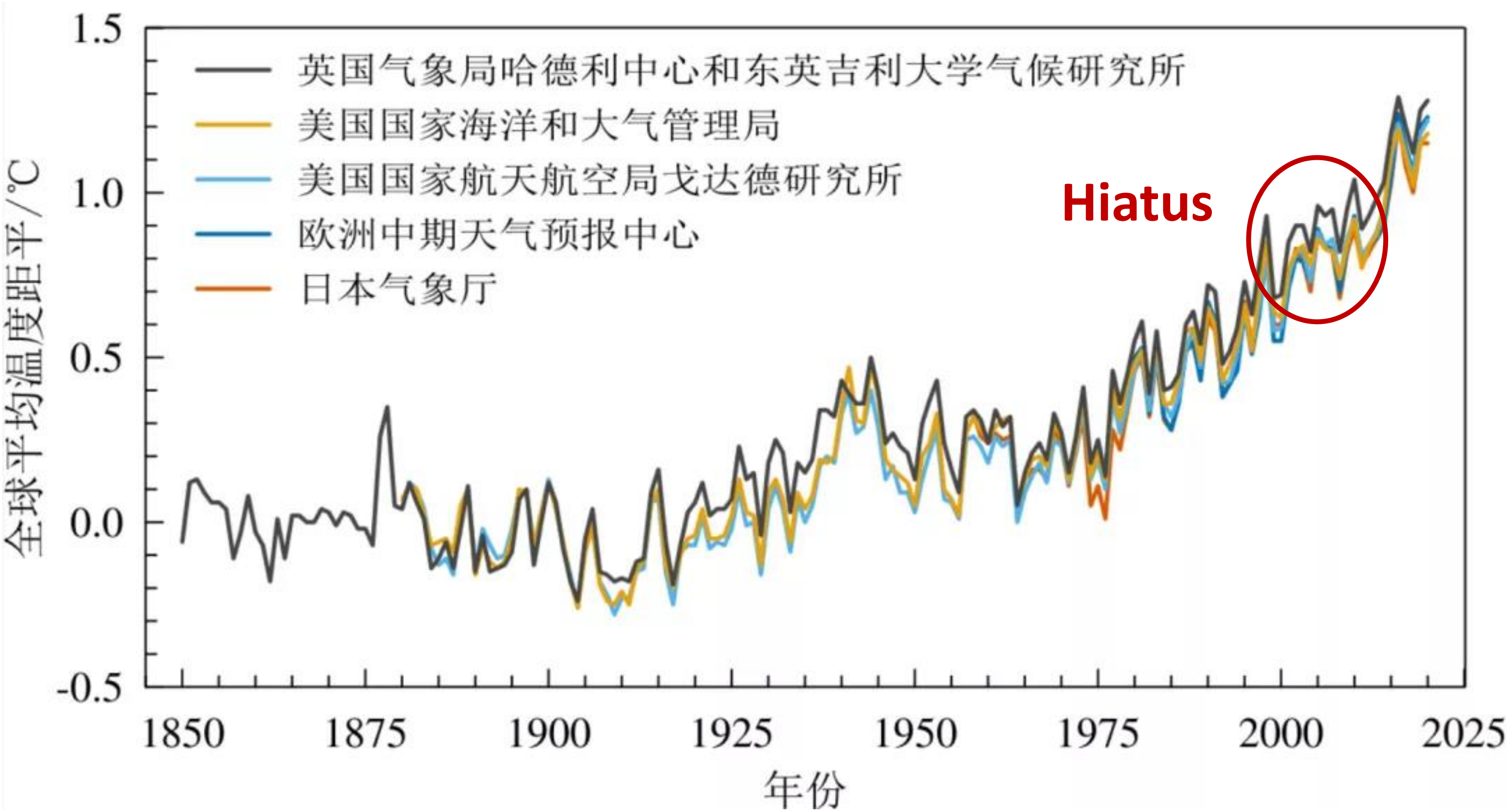


Global Cloud Coverage: 2002-2015



Credit: NASA Earth Observatory image by Jesse Allen and Kevin Ward, using data provided by the MODIS between July 2002 and April 2015. Colors range from dark blue (no clouds) to light blue (some clouds) to white (frequent clouds).

Global Temperature Anomaly: 1850-2020



中国气候变化蓝皮书（2021）