

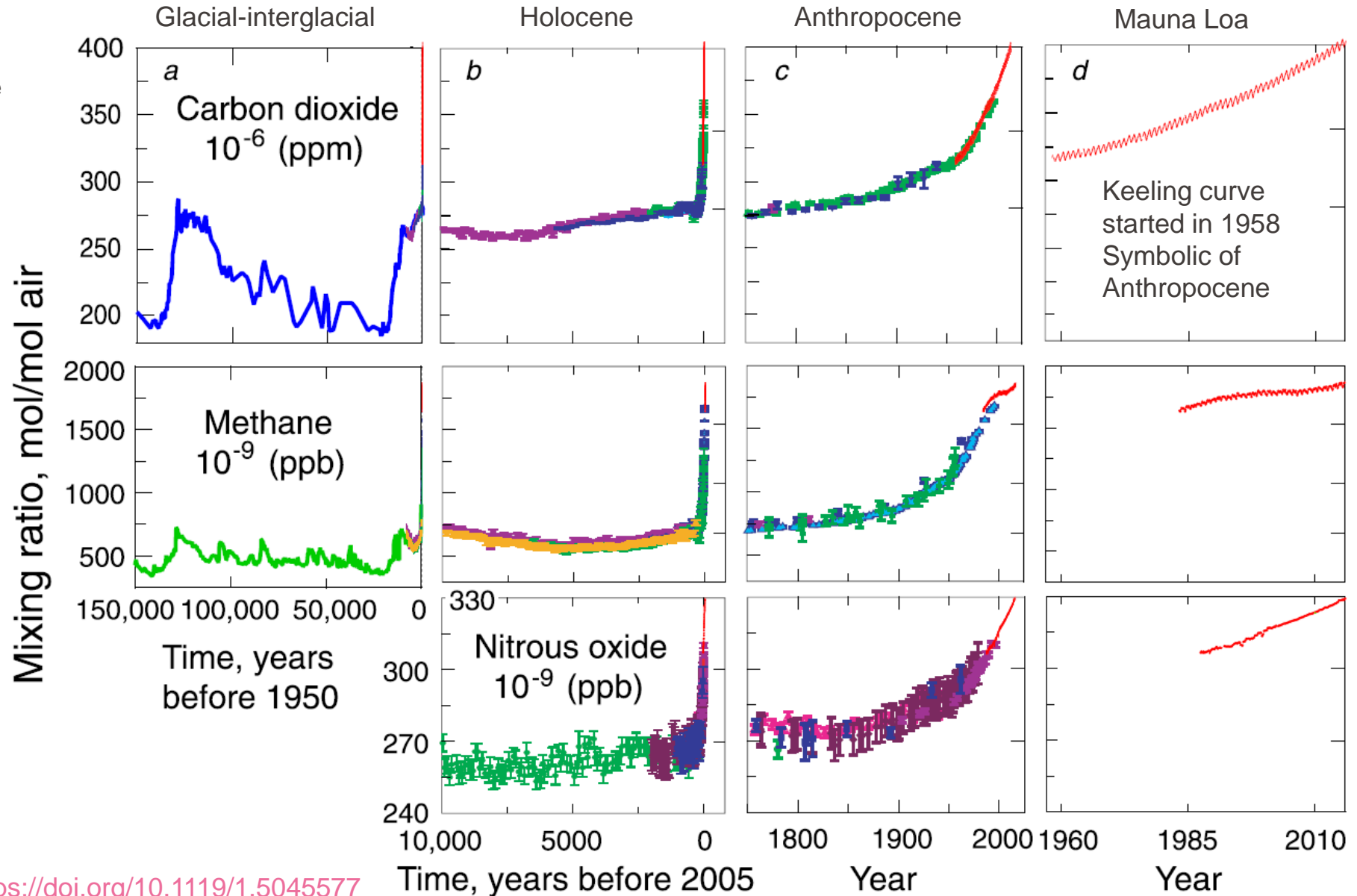
Anthropogenic greenhouse effect and radiative forcing



Intensified or anthropogenic greenhouse effect

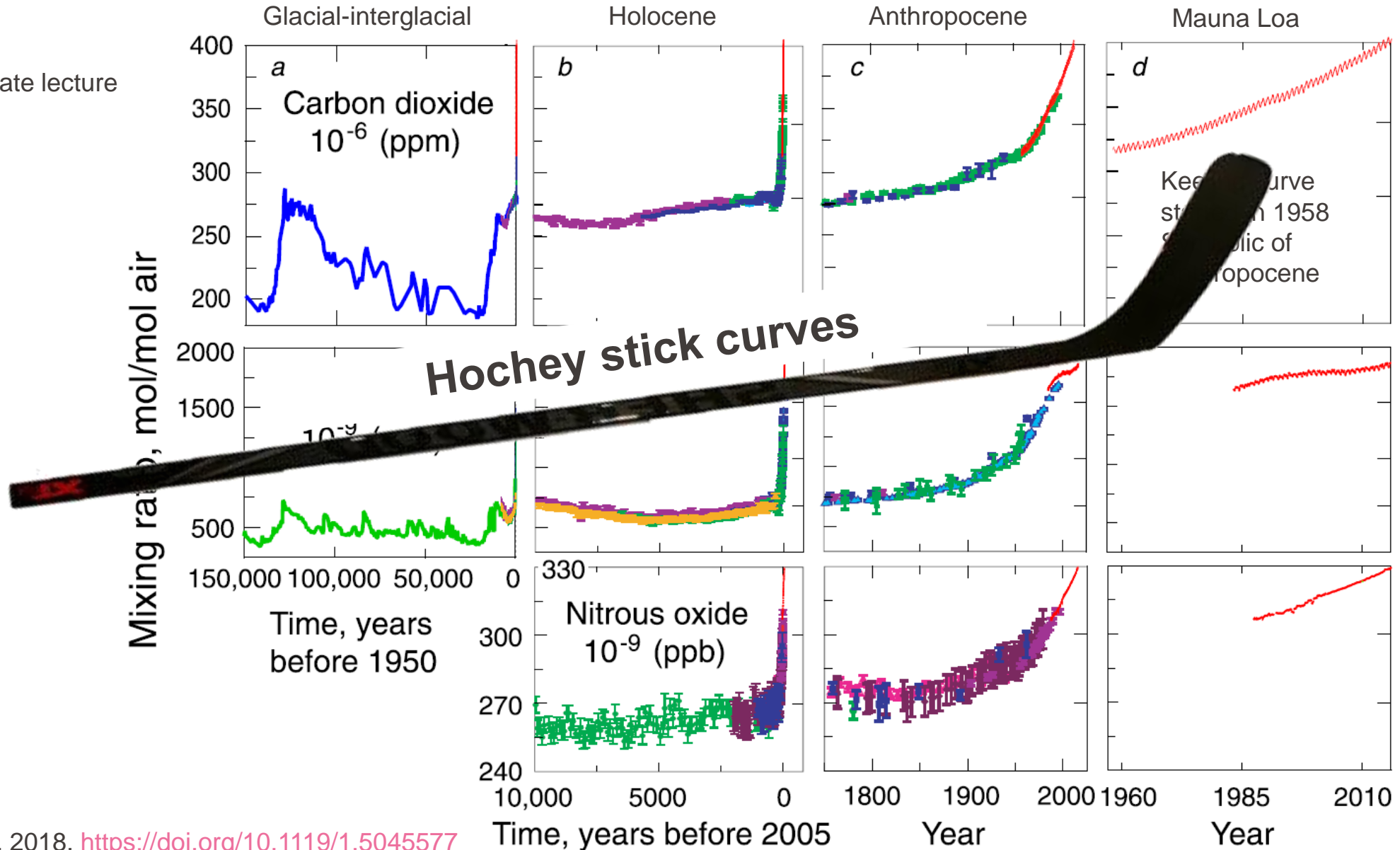
- Remember: **natural GHG** effect is responsible for a temperature effect of +32°C
- The intensified or **anthropogenic GHG** effect results from an increase in greenhouse gases, changes in the aerosol concentrations and composition due to human activities.

see paleoclimate lecture for more



Increase in greenhouse gases due to anthropogenic activity

see paleoclimate lecture for more



■ Schwartz, 2018, <https://doi.org/10.1119/1.5045577>

Greenhouse gas	Chemical formula	Major sources	Preindustrial concentration (ppm)	2020 concentration (ppm)	Atmospheric Lifetime (years)	Lifetime governed by
Carbon Dioxide	CO ₂	Fossil fuel combustion; Deforestation; Cement production	278	414.24	100*	*
Methane	CH ₄	Fossil fuel production; Agriculture; Landfills	700	1.879	12	Atmospheric decomposition
Nitrous Oxide	N ₂ O	Fertilizer application; Fossil fuel and biomass combustion; Industrial processes	270	333	121	Atmospheric decomposition
Chlorofluorocarbon-12 (CFC-12)	CCl ₂ F ₂	Refrigerants	0	0.527*10 ⁻³ (2011)	100	Atmospheric decomposition
Hydrofluorocarbon-23 (HFC-23)	CHF ₃	Refrigerants	0	0.024*10 ⁻³ (2011)	222	Atmospheric decomposition
Sulfur Hexafluoride	SF ₆	Electricity transmission	0	0.0073*10 ⁻³ (2011)	3,200	Atmospheric decomposition
Nitrogen Trifluoride	NF ₃	Semiconductor manufacturing	0	0.00086*10 ⁻³ (2011)	500	Atmospheric decomposition

* No single lifetime can be given for carbon dioxide because it moves throughout the earth system at differing rates. Some carbon dioxide will be absorbed very quickly, while some will remain in the atmosphere for thousands of years.

IPCC AR5, and <https://gml.noaa.gov/>

Major GHG properties

Which gas is missing here?

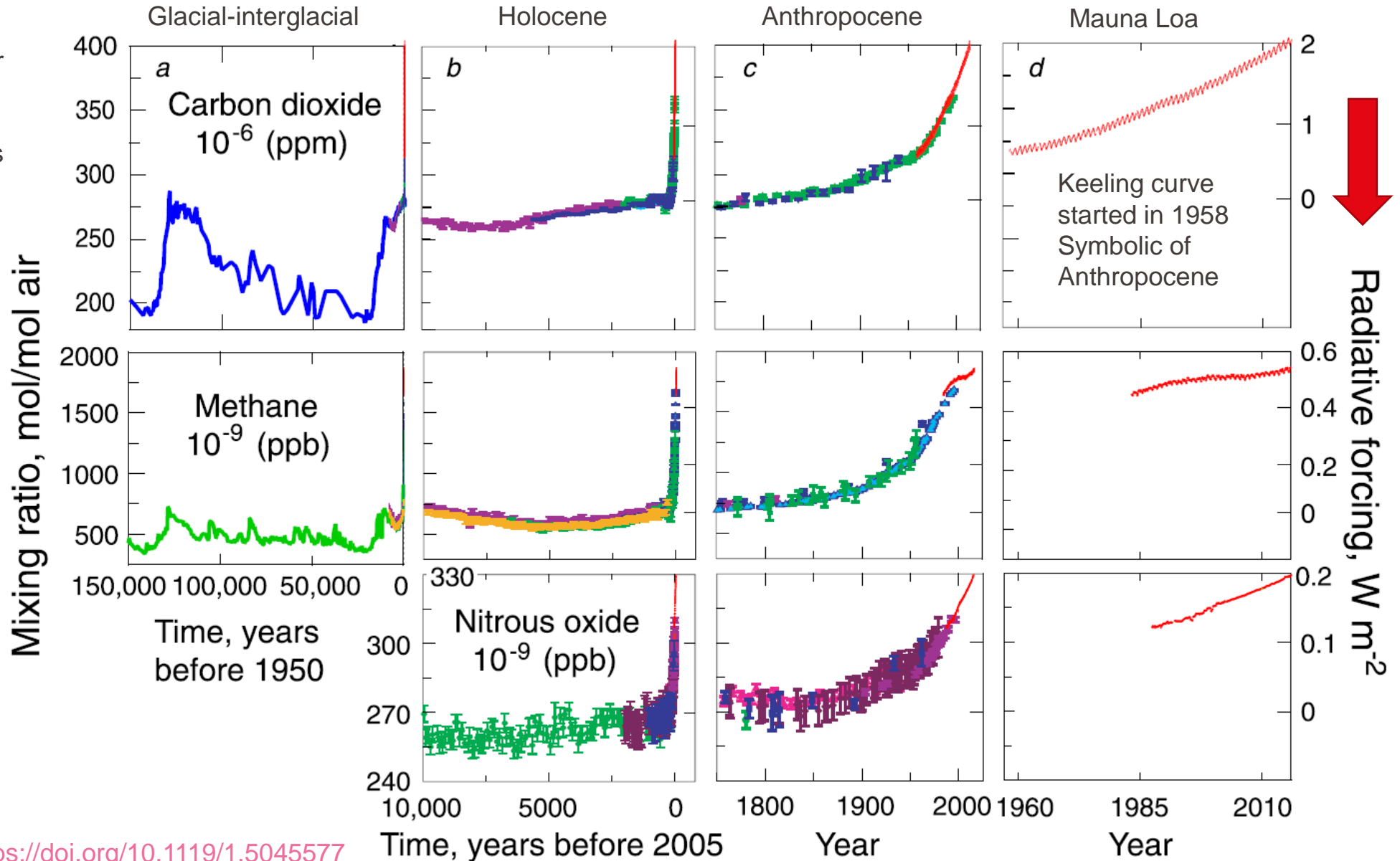
Greenhouse gas	Chemical formula	Major sources	Preindustrial concentration (ppm)	2020 concentration (ppm)	Atmospheric Lifetime (years)	Lifetime governed by
Carbon Dioxide	CO ₂	Fossil fuel combustion; Deforestation; Cement production	278	414.24	100*	*
Methane	CH ₄	Fossil fuel production; Agriculture	700	1.879	12	Atmospheric decomposition
Nitrous Oxide	N ₂ O	Fertilizer; Fossil fuel combustion; Industrial processes	319	333	121	Atmospheric decomposition
Chlorofluorocarbon-12 (CFC-12)	CCl ₂ F ₂	Refrigerants	0	0.00011 (2011)	100	Atmospheric decomposition
Hydrofluorocarbon-23 (HFC-23)	CHF ₃	Refrigerants	0	0.00011 (2011)	222	Atmospheric decomposition
Sulfur Hexafluoride	SF ₆	Electricity transmission	0	0.0073*10 ⁻³ (2011)	3,200	Atmospheric decomposition
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Aerosol lifetimes are much shorter (hours – days) since they are removed by precipitation and gravitational settling.

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Increase in greenhouse gases due to anthropogenic activity

Any *perturbation* (internal or external) to Earth's energy system is called *forcing*. Same unit as energy fluxes (W m^{-2}).



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Concentration change and effectiveness

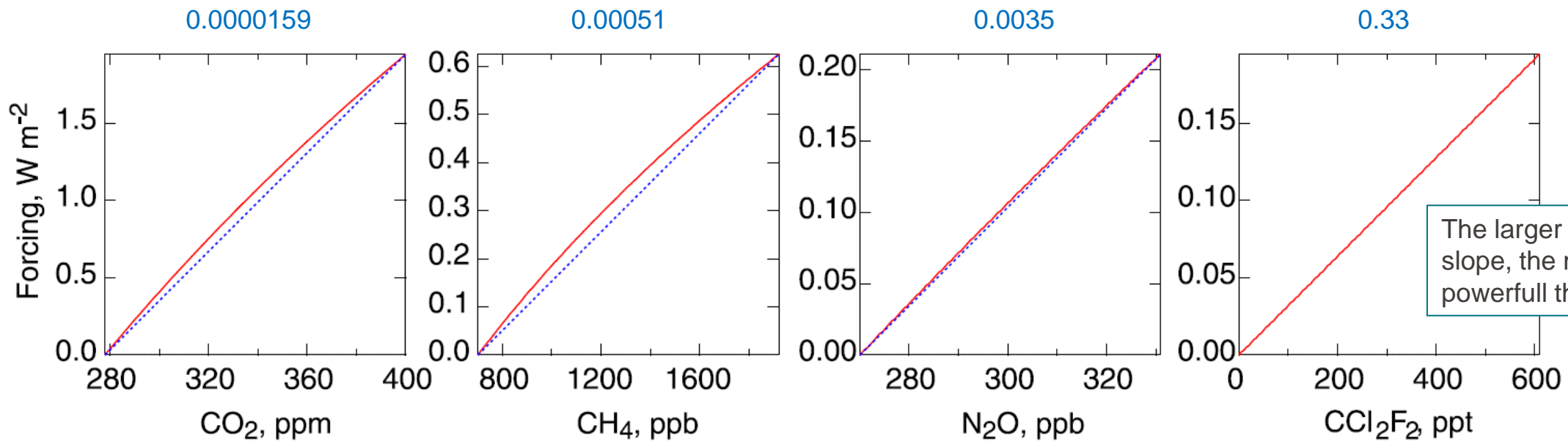
Which GHG had the smallest RF contribution in 2016? → exercises

Trace gas	Preindustrial mixing ratio, x_0 , ppb	2016 mixing ratio, x , ppb	Expression for forcing, $W \cdot m^{-2}$
CO ₂	278×10^3	403×10^3	$5.35(\ln x - \ln x_0)$
CH ₄	700	1843	$0.036(\sqrt{x} - \sqrt{x_0})$
N ₂ O	270	329	$0.12(\sqrt{x} - \sqrt{x_0})$
CCl ₂ F ₂	0	0.512	$0.33(x - x_0)$

sublinear
sublinear
sublinear
linear

Used to calculate red lines in graphs.

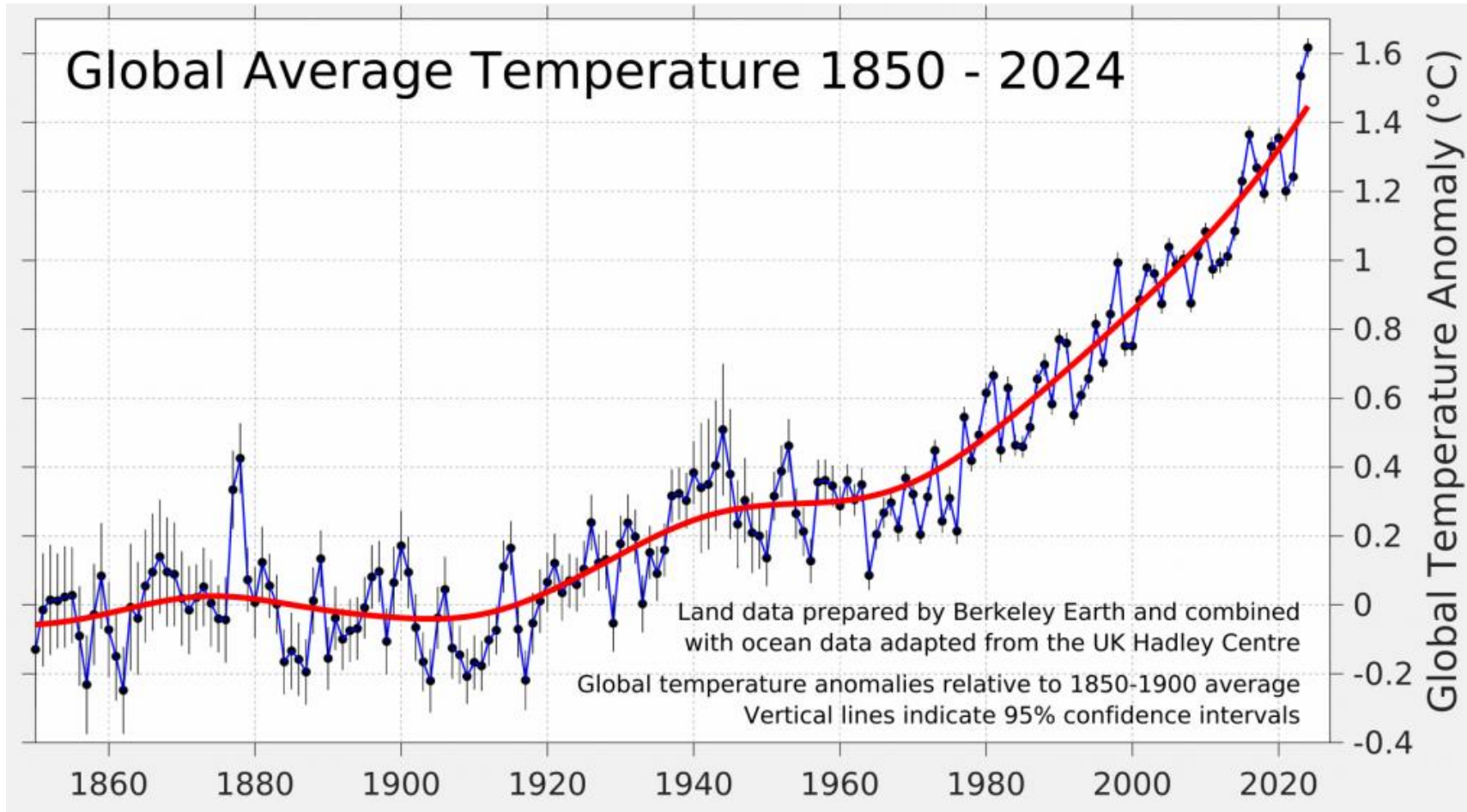
Slopes of linear fits (blue dotted): units in $W m^{-2} ppb^{-1}$



The larger the slope, the more powerful the GHG.

■ Schwartz, 2018, <https://doi.org/10.1119/1.5045577>

What does this mean for the global mean surface temperature (GMST)?



Estimate based on the new IPCC AR6 summary for policy makers:

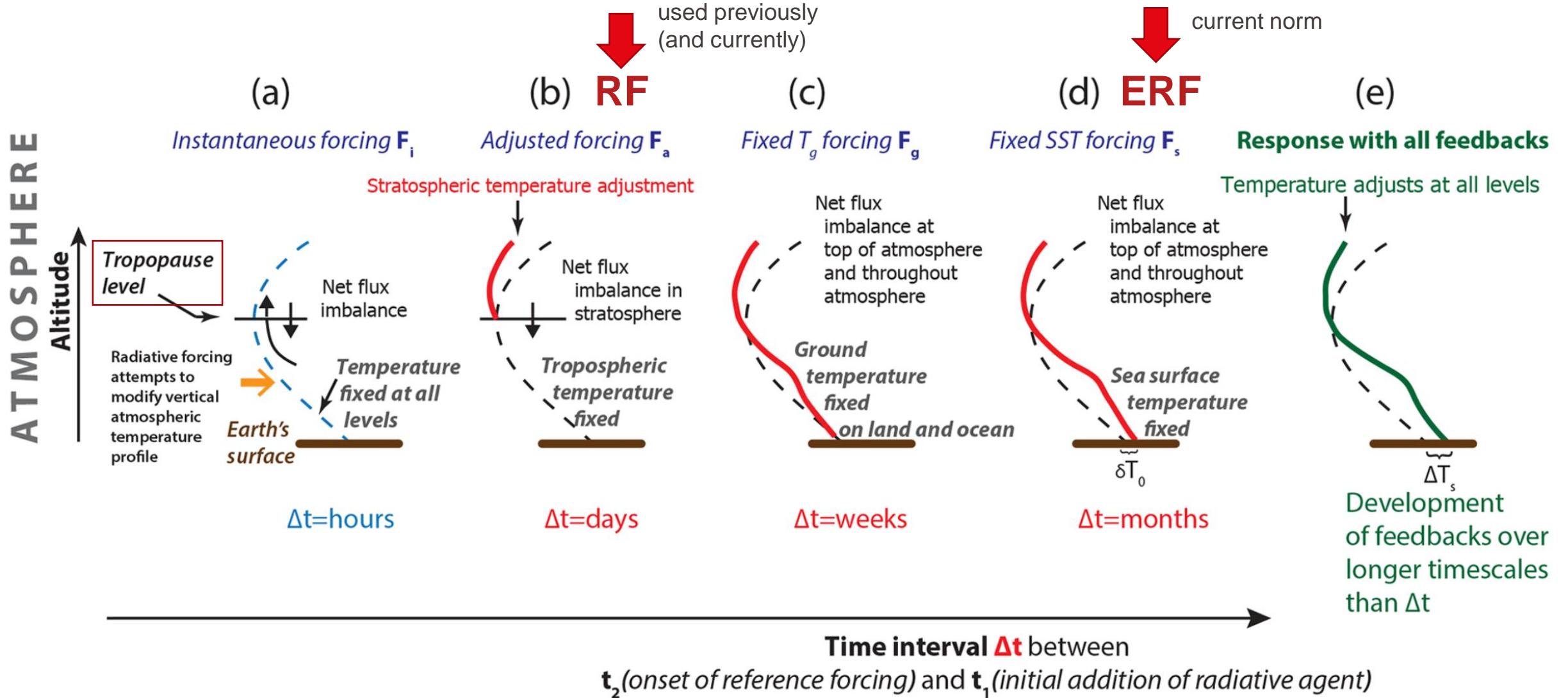
“The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8 $^{\circ}\text{C}$ to 1.3 $^{\circ}\text{C}$, **with a best estimate of 1.07 $^{\circ}\text{C}$.**”

Today the best estimate is 1.3 $^{\circ}\text{C}$

- A forcing that changes the radiation balance of Earth.
- Fundamental definition: Warming of Earth's surface and lower atmosphere is driven by radiative forcing, the difference between the flux of thermal radiant energy from a black surface through a hypothetical, transparent atmosphere, and the flux through an atmosphere with greenhouse gases, particulates and clouds, but with the same surface temperature.
- Climate science definition: Radiative forcing in climate science is commonly compared against the preindustrial time (not hypothetical atmospheres).
- Because GHG and aerosols change the thermal IR radiative flux at the TOA (net smaller flux) they induce radiative forcing.

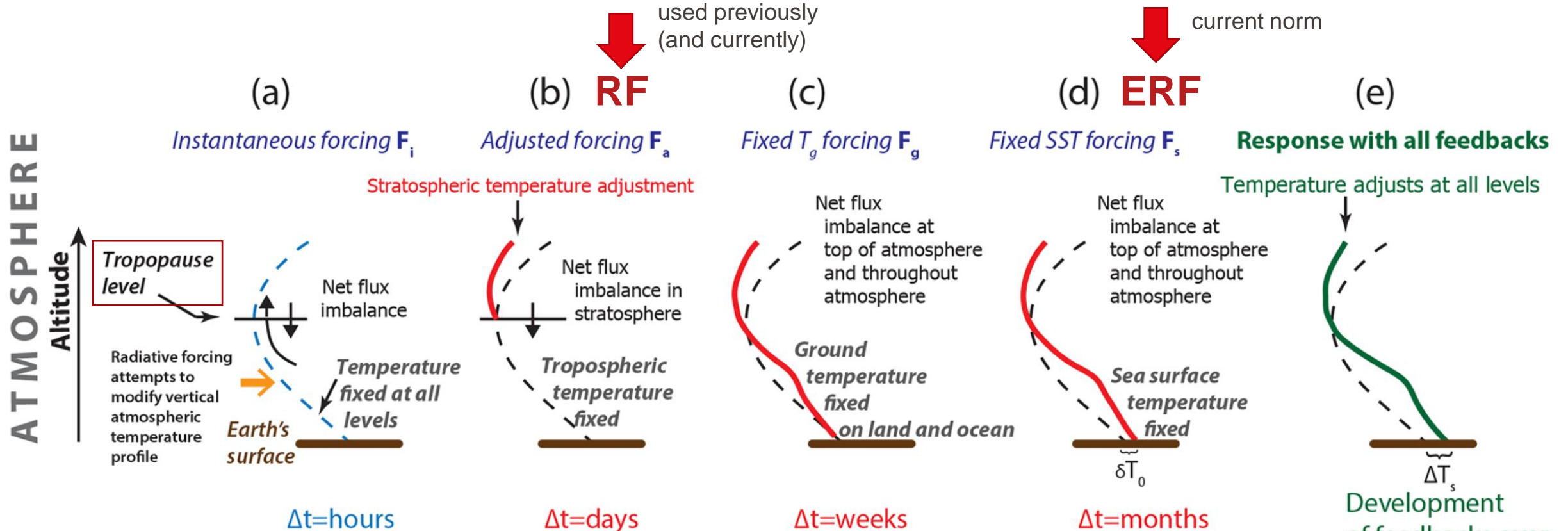
Types of RF

RF = Radiative Forcing
ERF = Effective Radiative Forcing



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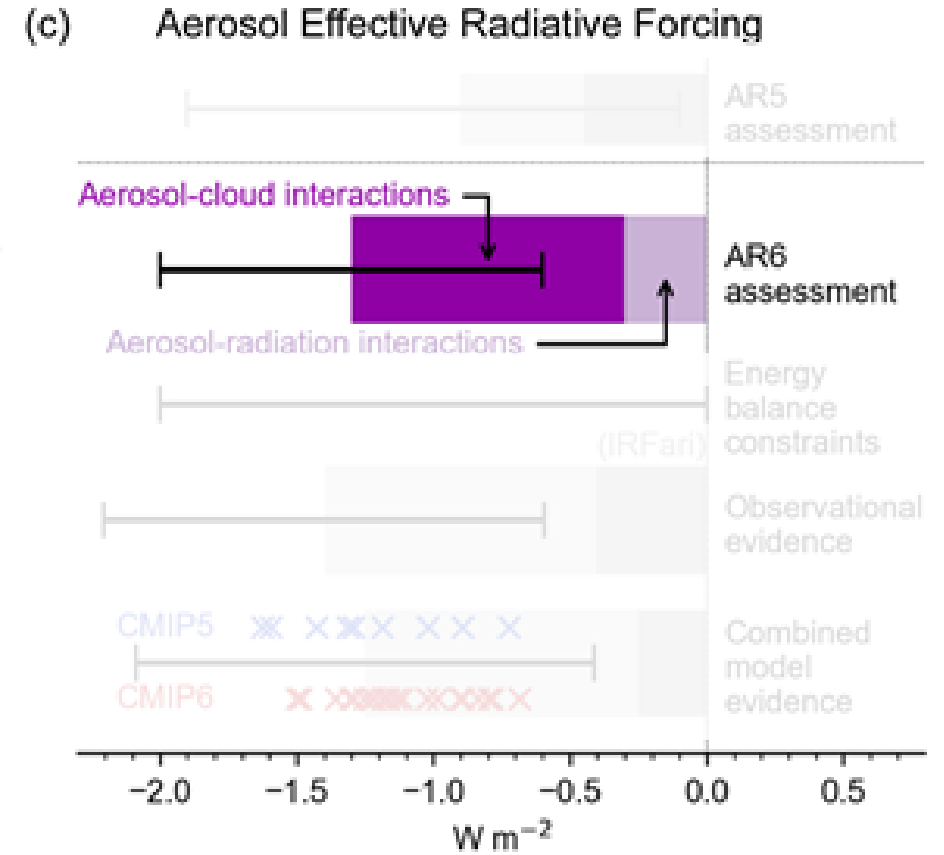
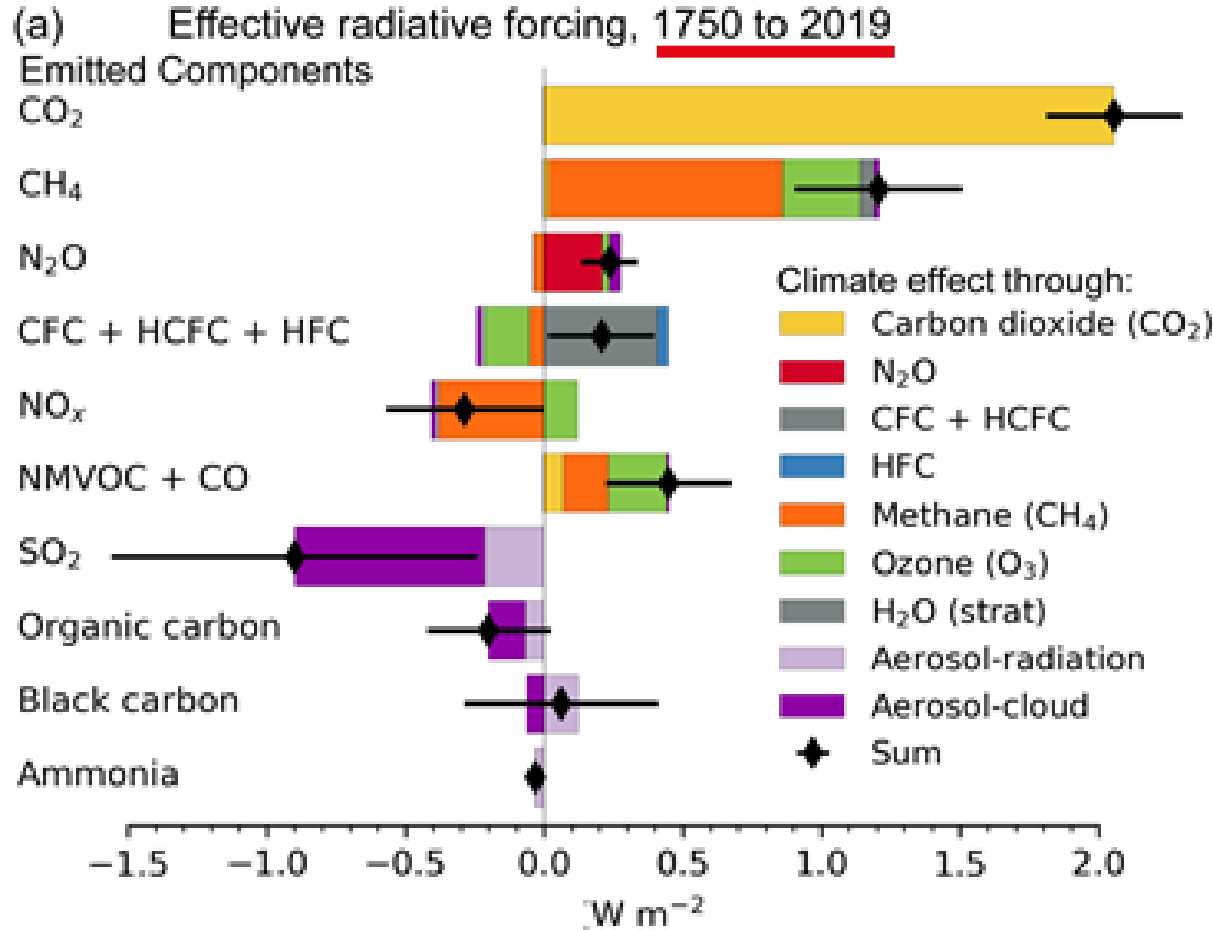


ERF is the ensuing radiative forcing once all rapid adjustments for temperature (including the stratospheric domain), water vapour, surface albedo (snow and ice cover, vegetation), and clouds are taken into account in response to a change in a forcing agent such as increasing GHG concentrations. Sea surface temperatures and sea ice cover are fixed at climatological values unless otherwise specified. Hence ERF includes both the effects of the forcing agent itself and the rapid adjustments to that agent.

Time interval Δt between forcing) and t_1 (initial addition of radiative agent)

ERF by component

GHG make up roughly 3.7 W m⁻² radiative forcing
 Compare: to TOA outgoing LW of -240 W m⁻²



Negative leads to temperature decrease Positive forcing leads to temperature increase

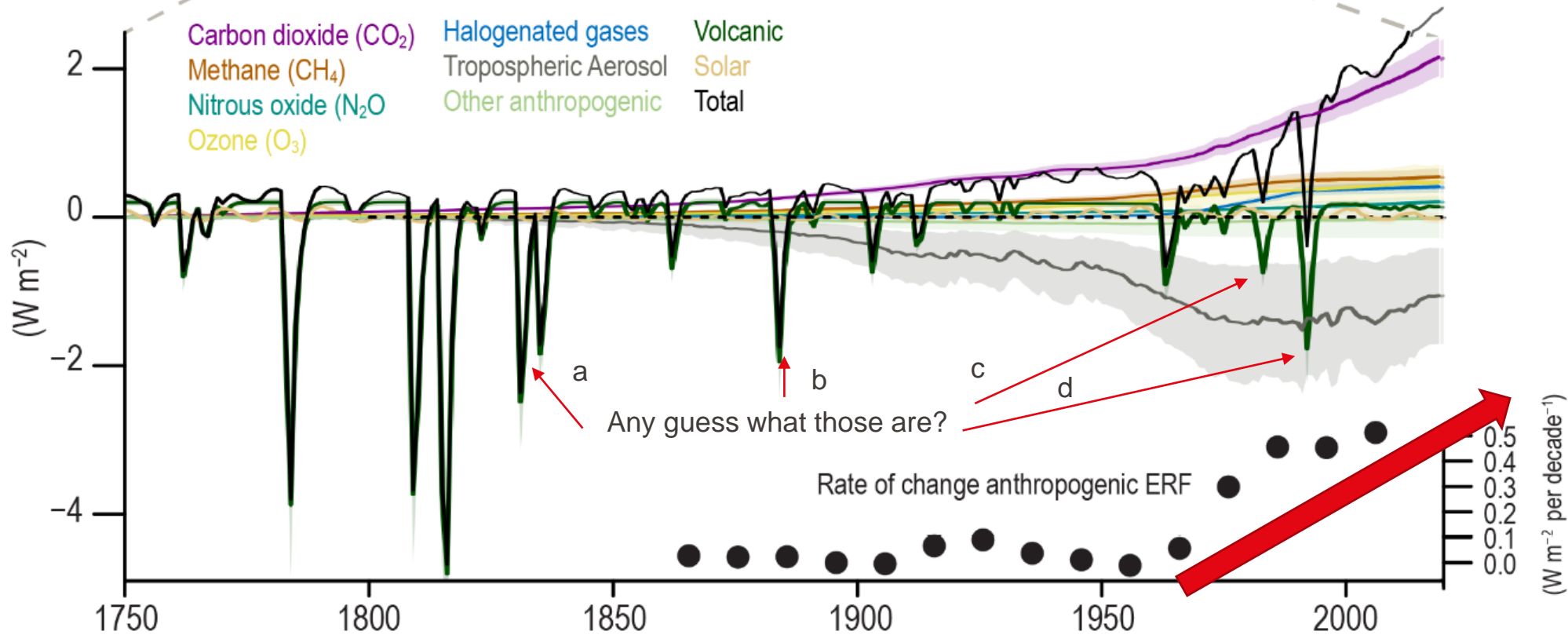
■ IPCC AR6, Fig. TS.15

Effects of most important GHG are well understood, the largest uncertainties are with aerosols and clouds.

ERF longterm perspective

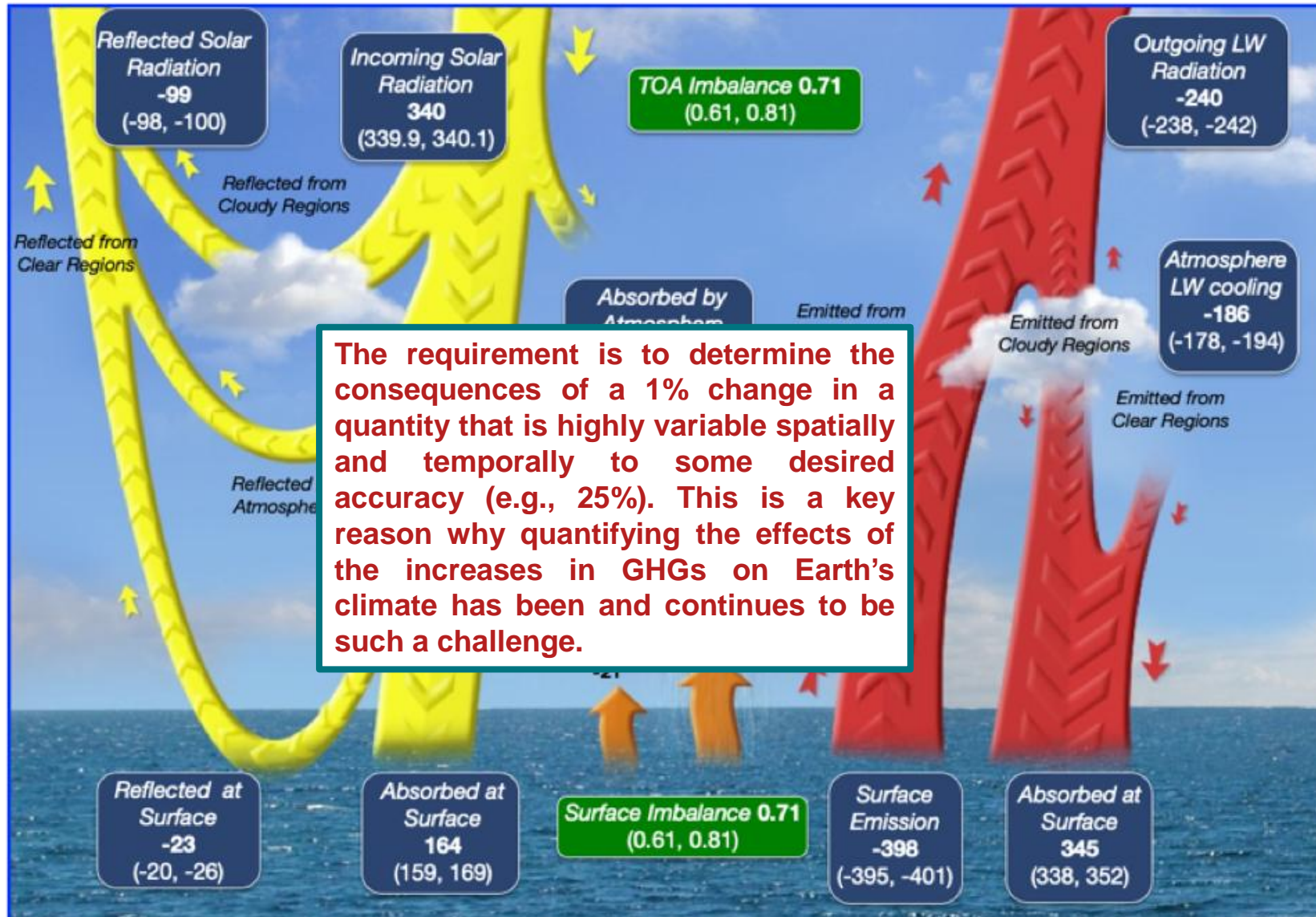
- a – Kelud 1826, Indonesia
- b – Krakatoa 1883, Indonesia
- c – El Chichón 1982, Mexico
- d – Pinatubo 1991, Philippines

(d) The increase in effective radiative forcing since the late 19th century is driven predominantly by warming GHGs and cooling aerosol. ERF is changing at a faster rate since the 1970s.



Rate of forcing is increasing as well!

GHG ERF cannot be measured



The requirement is to determine the consequences of a 1% change in a quantity that is highly variable spatially and temporally to some desired accuracy (e.g., 25%). This is a key reason why quantifying the effects of the increases in GHGs on Earth's climate has been and continues to be such a challenge.

- TOA fluxes as well as most other fluxes within the atmosphere are one or several two orders of magnitude larger than the perturbation by GHG and aerosols.
- Hence, the RF by GHG and aerosols cannot be measured directly, but needs to be calculated.
- Calculation needs several ingredients:
 - Knowledge of concentration change (measurements)
 - Greenhouse gas properties: lifetime, effectiveness (next)
 - Models with realistic clouds, temperature and water vapor (upcoming)