

# Global warming - physicist's perspective

## 02 – measurements and modelling

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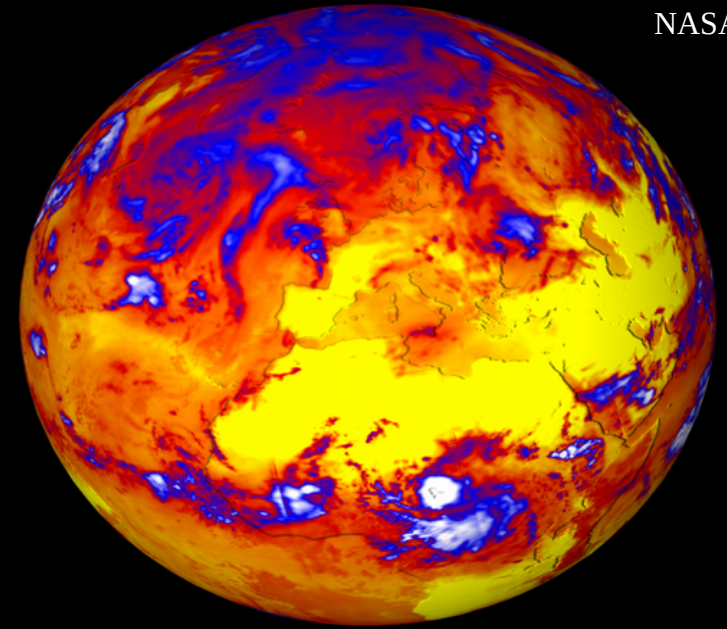


## Outline:

1. Physical properties and principles of climate system
2. Measurements and observations
3. Climate modeling

# Energy Balance

NASA



**THE EARTH is illuminated by shortwave SOLAR radiation, which is partially absorbed and partially reflected.**

**In (quasi) equilibrium energy of absorbed radiation is balanced by emission in thermal infrared.**

**Deflections from the equilibrium result in climate system heating/cooling.**

## **ENERGY IN CLIMATE SYSTEM**

1. Solar energy flux =  $\frac{1}{4}$  of Solar constant  
 $\frac{1}{4} * 1362 \text{W/m}^2 \approx 341 \text{W/m}^2$ .
2. Earth's surface albedo, mean  $\approx 0.3$ , highly variable,  
from 0.9 (fresh snow) to 0.07 (clean ocean).
3. Geothermal energy flux  $\approx 0.092 \text{W/m}^2$ .
4. Heat flux from fossil fuel combustion  $\approx 0.026 \text{W/m}^2$ .

## **BASIC PROPERTIES OF THE CLIMATE SYSTEM**

1. Air: surface pressure  $\approx 1000 \text{hPa}$  (10m of water),  
 $c_p = 1004 \text{J/kg} \cdot \text{K}$ .
2. Water: global average depth  $\approx 3000 \text{m}$ ,  $c_w = 4192 \text{J/kg} \cdot \text{K}$ .
3. Ground - only a shallow layer responding to radiative fluxes.
4. Greenhouse gases:  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{O}_3$ , many others.



## **Forcings and feedbacks** in climate system.

Climate **forcings** are the **initial drivers** of a climate shift.

Examples: solar irradiance, changes in the planetary orbit, anthropogenic or volcanic emissions of greenhouse gases.

Climate **feedbacks** are processes that **change as a result of a change in forcing**, and **cause additional climate change**. Examples : ice-albedo feedback, CO<sub>2</sub> solubility.

**Feedbacks** can be positive or negative.

Positive feedbacks, when exceeding thresholds, may lead to rapid climate changes. There are indications in paleoclimatological data that such changes occurred in geological history of the planet.

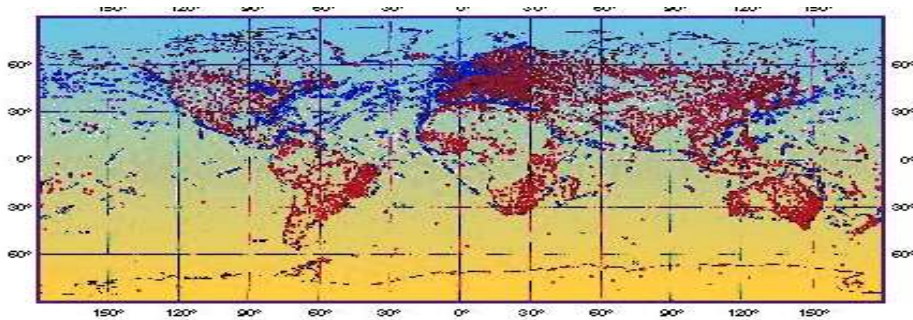
## Outline:

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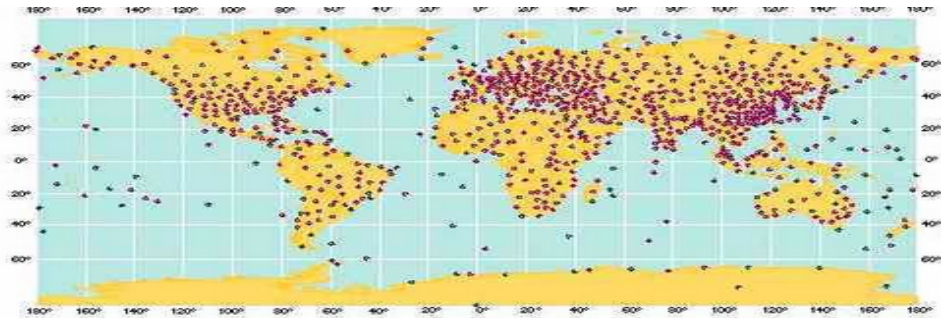
**Atmosphere:** Over 11,000 weather stations, as well as satellites, ships and aircraft take measurements.

1040 of stations are selected to provide high quality climate data.

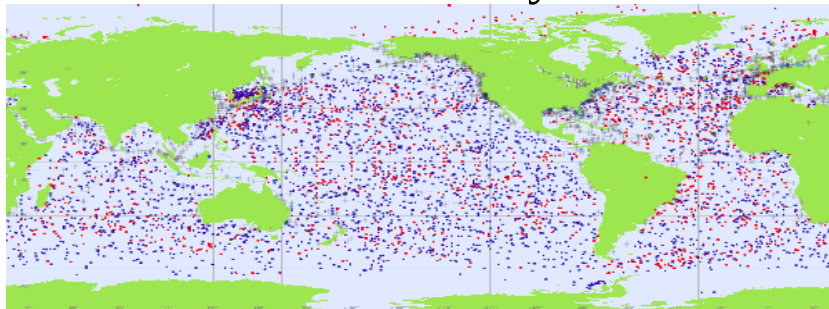
There are special networks at national (e.g. Reference Climate Stations), regional (e.g. Regional Basic Climatological Network) and global scales. (e.g. the Global Climate Observing System - GCOS - Surface Network, GSN).



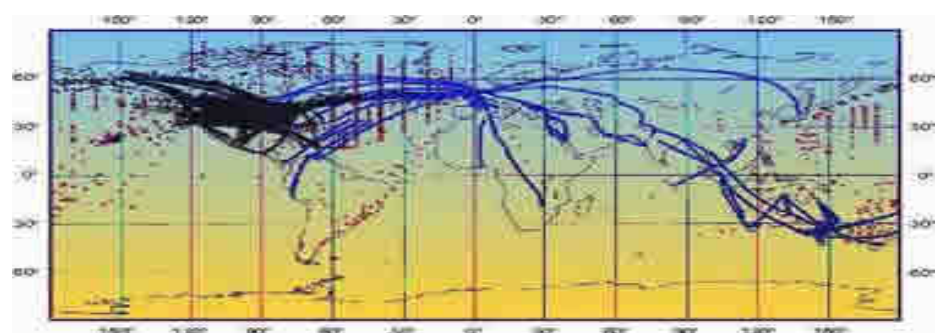
Weather stations and buoys



Upper air soundings



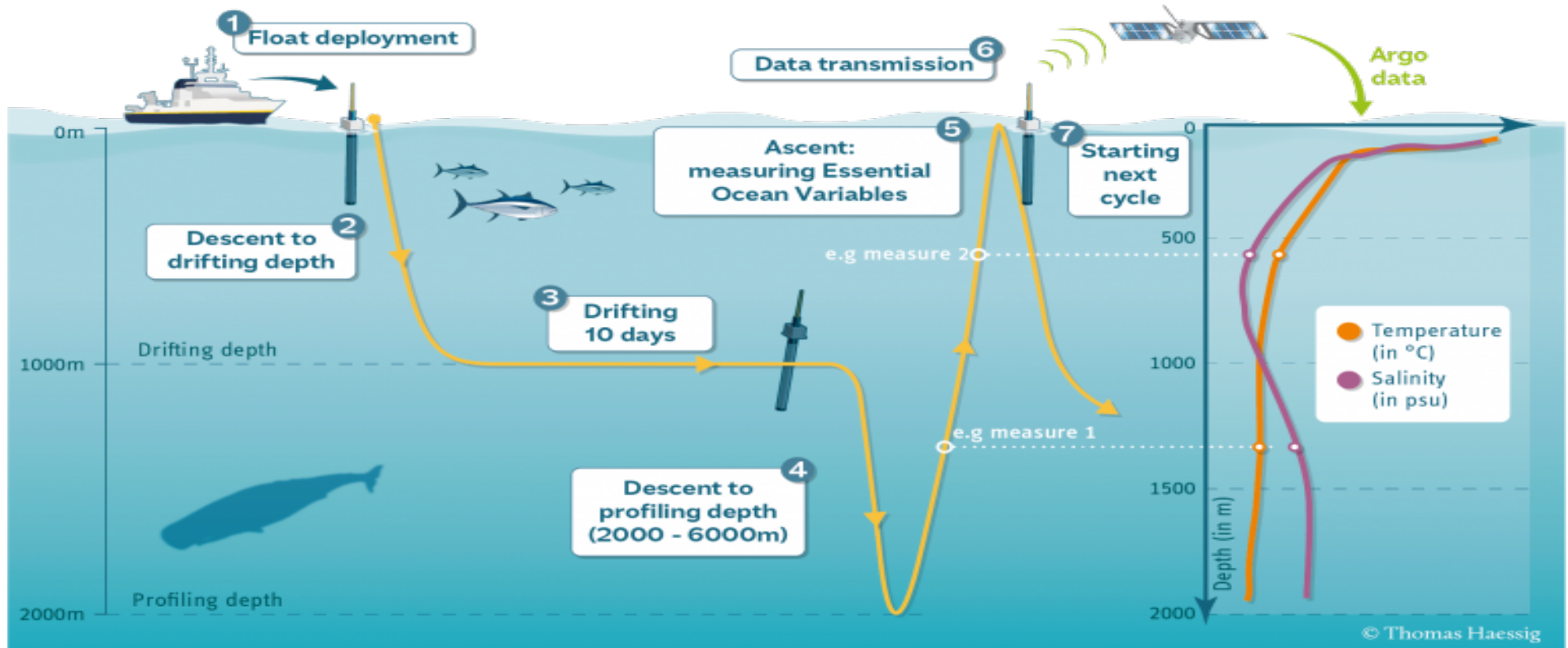
Voluntary ship observations



Aircraft based observations

# OCEAN:

ARGO project: temperature and salinity profiling, deep sea currents.

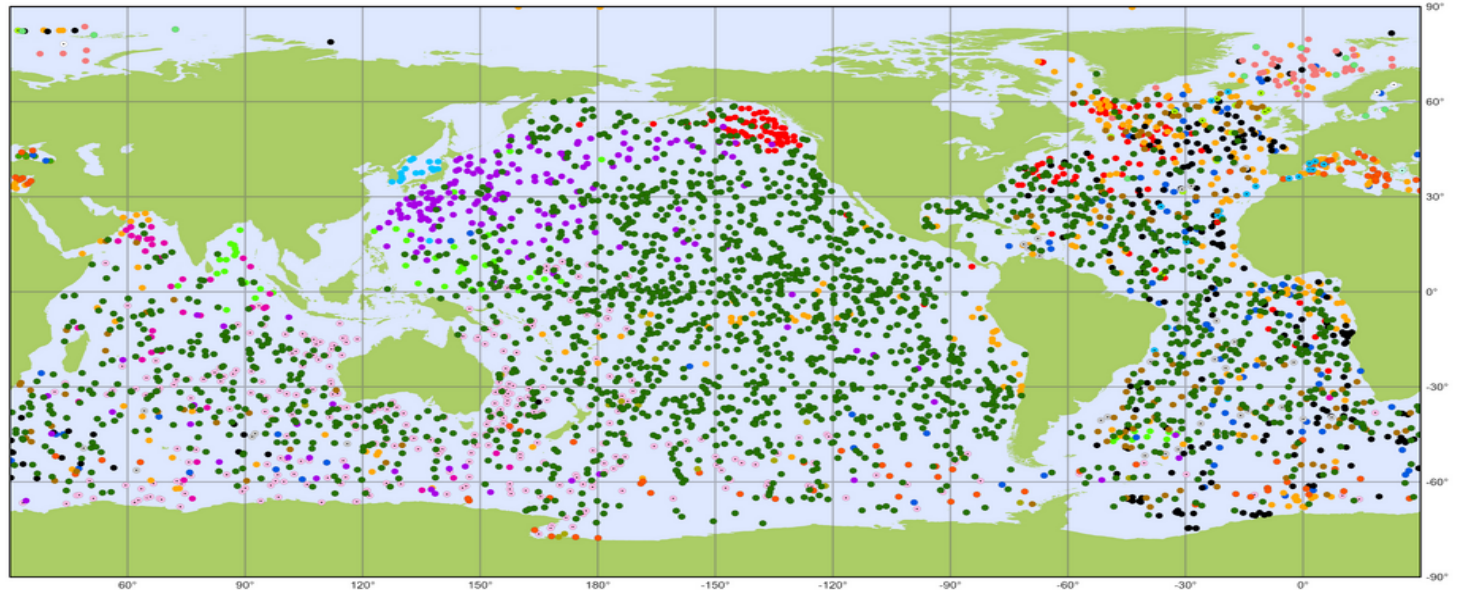


<http://www.argo.ucsd.edu/>

# OCEAN:

ARGO project: temperature and salinity profiling, deep sea currents.

Thousands of automatic profilers provide actual data from the world ocean.



Argo

National contributions - 3885 operational floats  
Latest location of operational floats (data distributed within the last 30 days)

September 2022



• AUSTRALIA (313)	• FINLAND (4)	• IRELAND (17)	• NEW ZEALAND (17)	• SPAIN (21)
• BULGARIA (6)	• FRANCE (269)	• ITALY (85)	• NORWAY (47)	• UK (135)
• CANADA (149)	• GERMANY (229)	• JAPAN (202)	• PERU (1)	• USA (2127)
• CHINA (57)	• GREECE (3)	• MOROCCO (1)	• POLAND (12)	
• EUROPE (100)	• INDIA (40)	• NETHERLANDS (33)	• KOREA, REPUBLIC OF (17)	



Generated by ocean-ops.org, 2022-10-01  
Projection: Plate Carree (-150,0000)

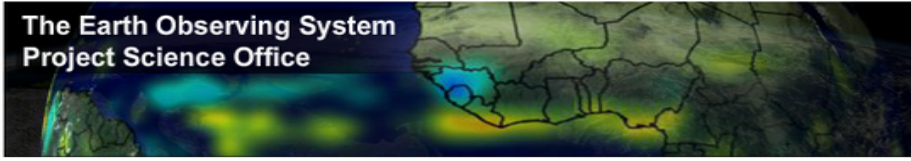
<http://www.argo.ucsd.edu/> , <https://www.aoml.noaa.gov/argo/>




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  - Earth Observation
    - Operation >
      - SHIZUKU (GCOM-W1)
      - IBUKI (GOSAT)
      - Aqua
      - TRMM
    - REIMEL (INDEX)
    - Akebono (EXOS-D)
    - GEOTAIL
    - Development >
      - DAICHI-2 (ALOS-2)
      - SPM/DPB
      - GCOM-C
      - Earth-CARE
      - Completed >
        - DAICHI (ALOS)
    - Communication, Positioning & Engineering Test
      - Operation >

### Satellites and Spacecraft


Satellites offer a wide variety of valuable services. These include communications and weather observation, which are essential to modern life, as well as astronomical observation and space development. Japanese satellites now in orbit are performing missions in a wide range of areas. For example, they have been playing an important role in assessing and analyzing abnormal weather patterns. For the purpose of planetary exploration, plans are under way for sending probes to the Moon and Mars.

#### Earth Observation Satellites


In Operation




Global Change Observation Mission 1st - Water "SHIZUKU" (GCOM-W1)



Greenhouse gases Observing SATellite "IBUKI" (GOSAT)



"Aqua" Earth Observation Satellite



Tropical Rainfall Measuring Mission "TRMM"

#### About NASA's Earth Observing System

The Earth Observing System (EOS) is a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans. EOS is a major component of the Earth Science Division of NASA's Science Mission Directorate. EOS enables an improved understanding of the Earth as an integrated system. The EOS Project Science Office (EOSPSO) is committed to bringing program information and resources to program scientists and the general public alike.

Download 2012 NASA Science Mission Directorate Calendar Screen Saver **NEW!**

#### EOS Announcements

The Earth Observer Newsletter online is now available in color!  
February 17, 2011

#### Earth Observatory's Image of the Day



## observing the earth



ESA
OBSERVING THE EARTH
UNDERSTANDING OUR PLANET
SECURING OUR ENVIRONMENT
BENEFITING OUR ECONOMY

+ About Observing the Earth

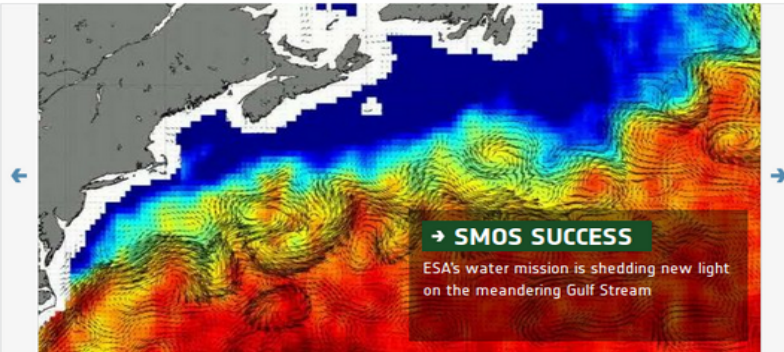
EO programmes

- The Living Planet
- GMES

ESA's Earth Observing missions

- Envisat overview
- ERS overview
- Earth Explorers overview
- Sentinels overview
- MSG overview
- MetOp overview
- Proba-1 overview
- Third Party Missions overview

ESA > Our Activities > Observing the Earth



→ SMOS SUCCESS

ESA's water mission is shedding new light on the meandering Gulf Stream

Archive

Search here

Image of the week archive

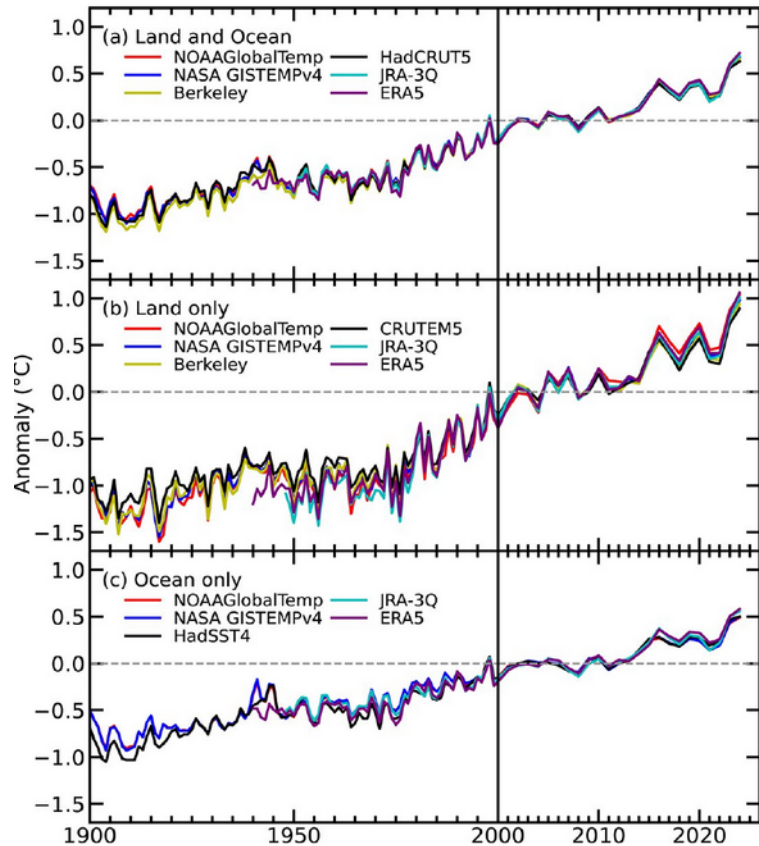
Earth from Space on ESA Web-TV

Living Planet Symposium 2013

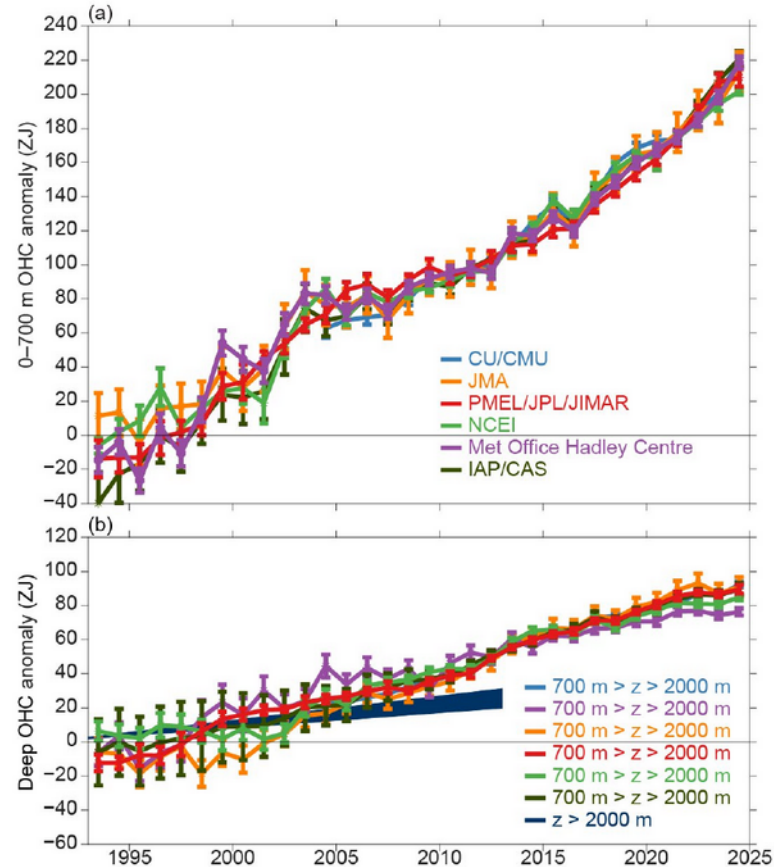
Satellite systems of NASA, ESA, JAXA and others.

# Observations - summary

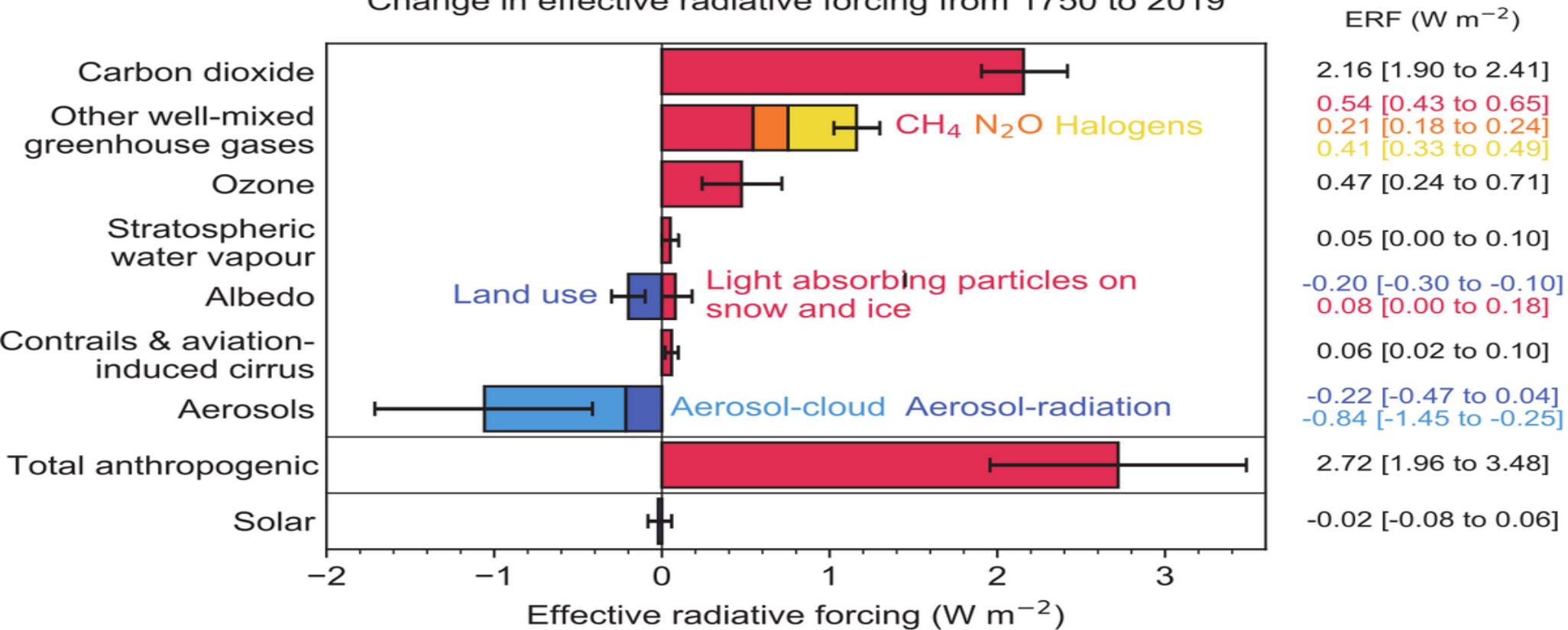
## Temperature anomaly



## OHC change



## Change in effective radiative forcing from 1750 to 2019



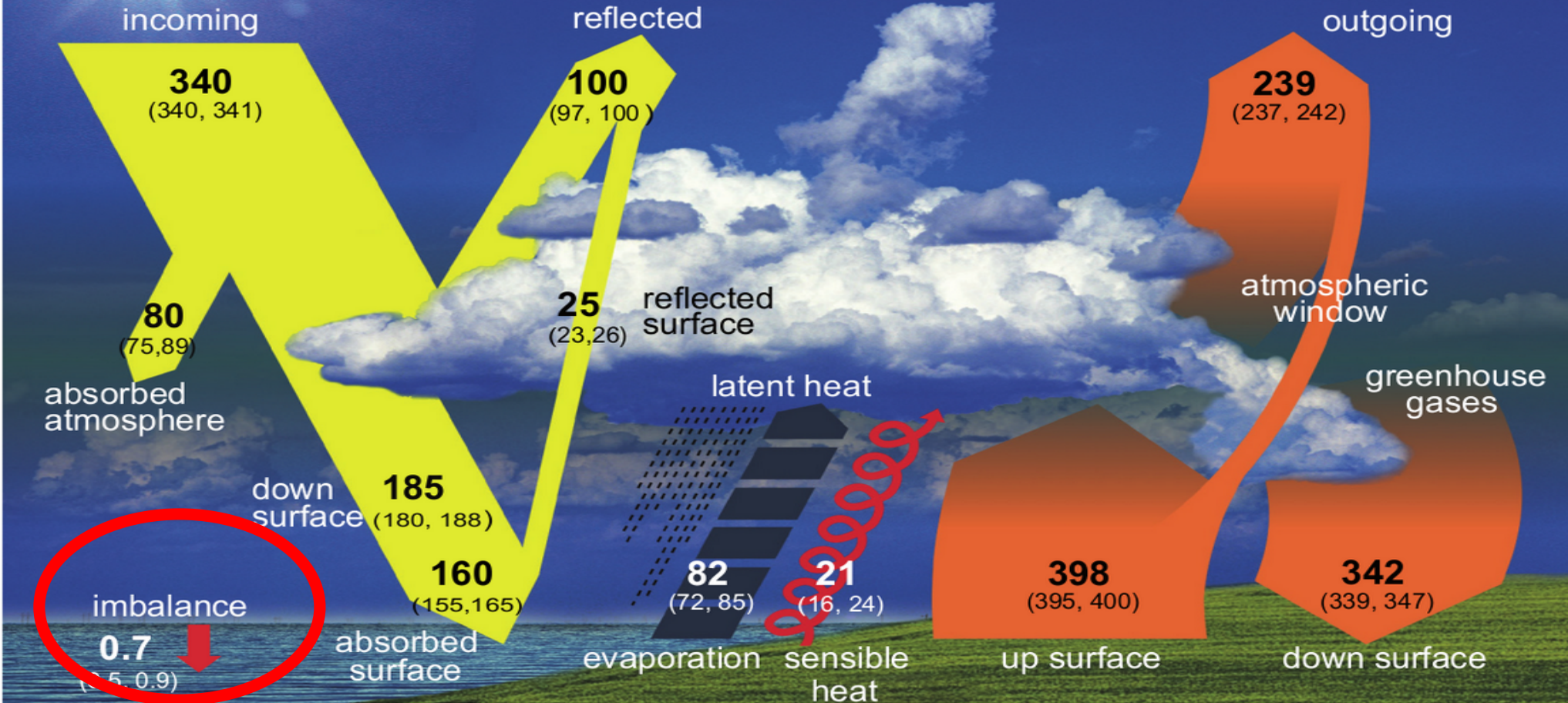


Units  $\text{Wm}^{-2}$

# All sky

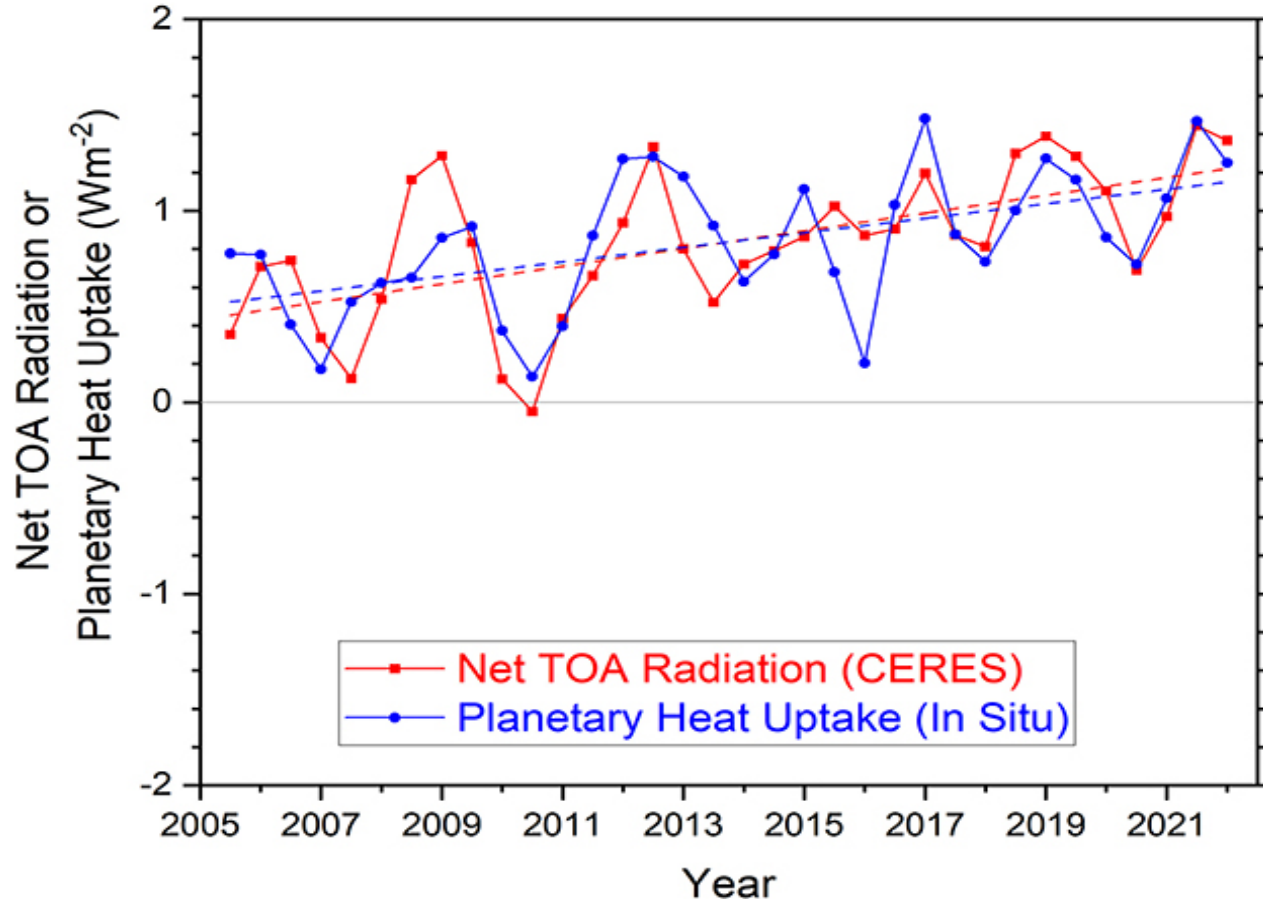
## Solar

## Thermal outgoing



Energy balance of climate system. Units:  $\text{W/m}^2$ . <https://www.ipcc.ch/report/ar6/wg1/>

# Energy imbalance increases ...



Schmidt GA, et al., 2023, CERESMIP: a climate modeling protocol to investigate recent trends in the Earth's Energy Imbalance. *Front. Clim.* 5:1202161.  
<https://doi.org/10.3389/fclim.2023.1202161>

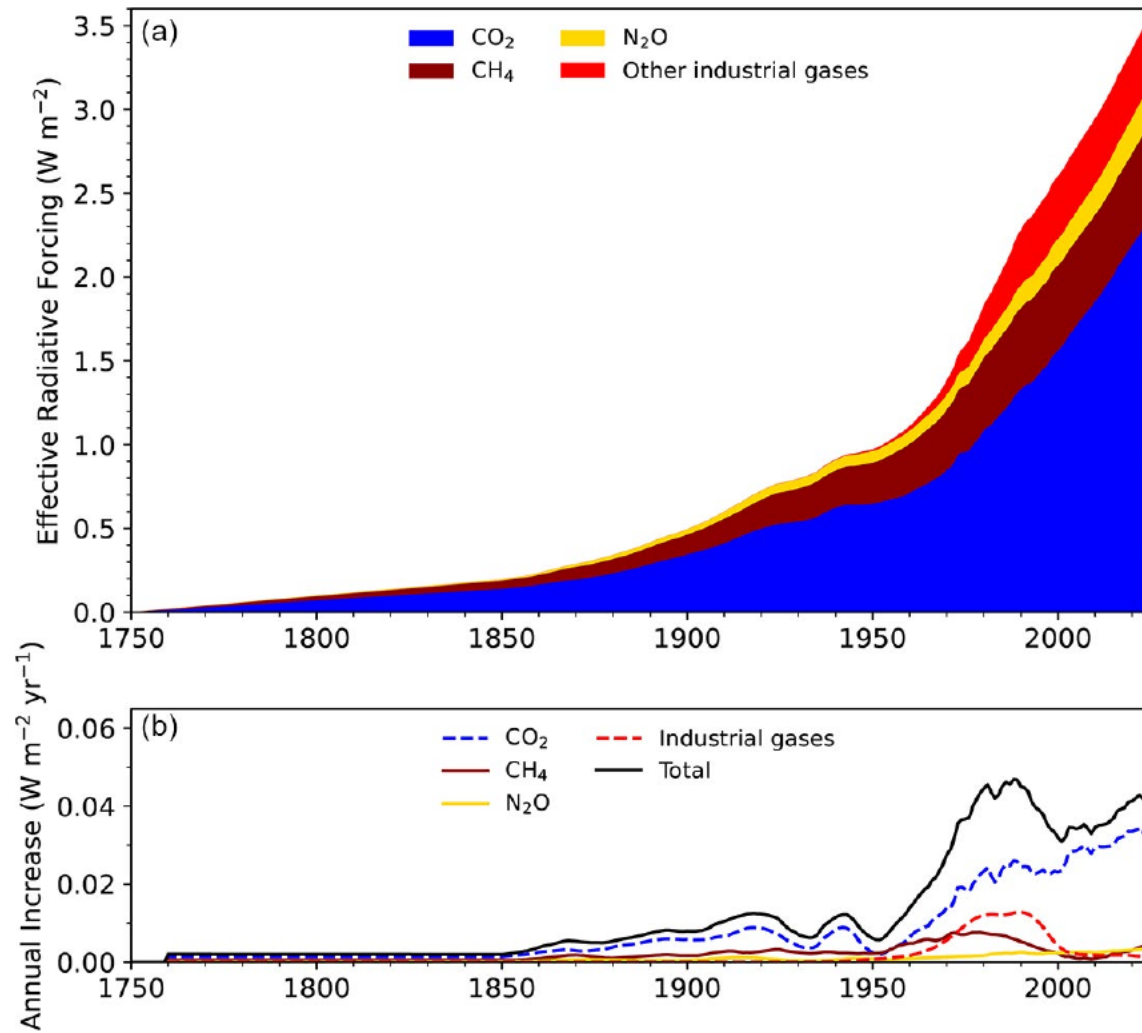


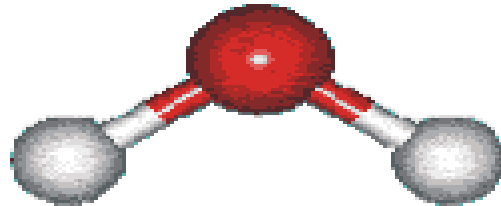
Fig. 2.65. (a) Effective radiative forcing ( $\text{W m}^{-2}$ ) due to long-lived greenhouse gases (LLGHGs; see Table 2.11 for details on industrial gases). (b) Annual increase in effective radiative forcing ( $\text{W m}^{-2} \text{ yr}^{-1}$ ) smoothed by a 10-year running average.

# Why particles with 3 or more atoms absorb long-wave (low energy) radiation?



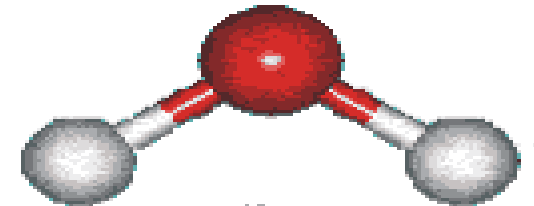
$\nu_1$

symmetric stretch



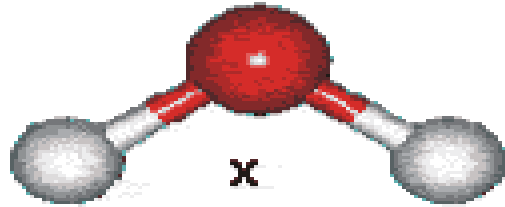
$\nu_3$

asymmetric stretch

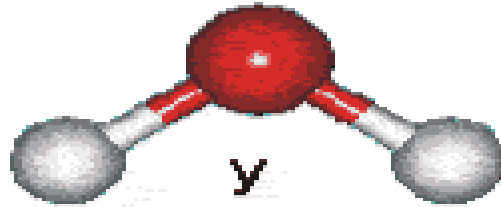


$\nu_2$

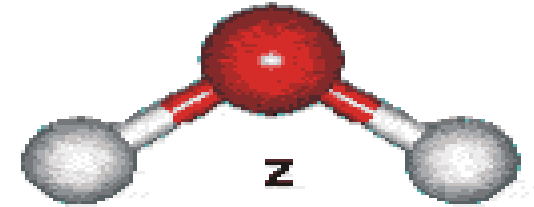
bend



x



y

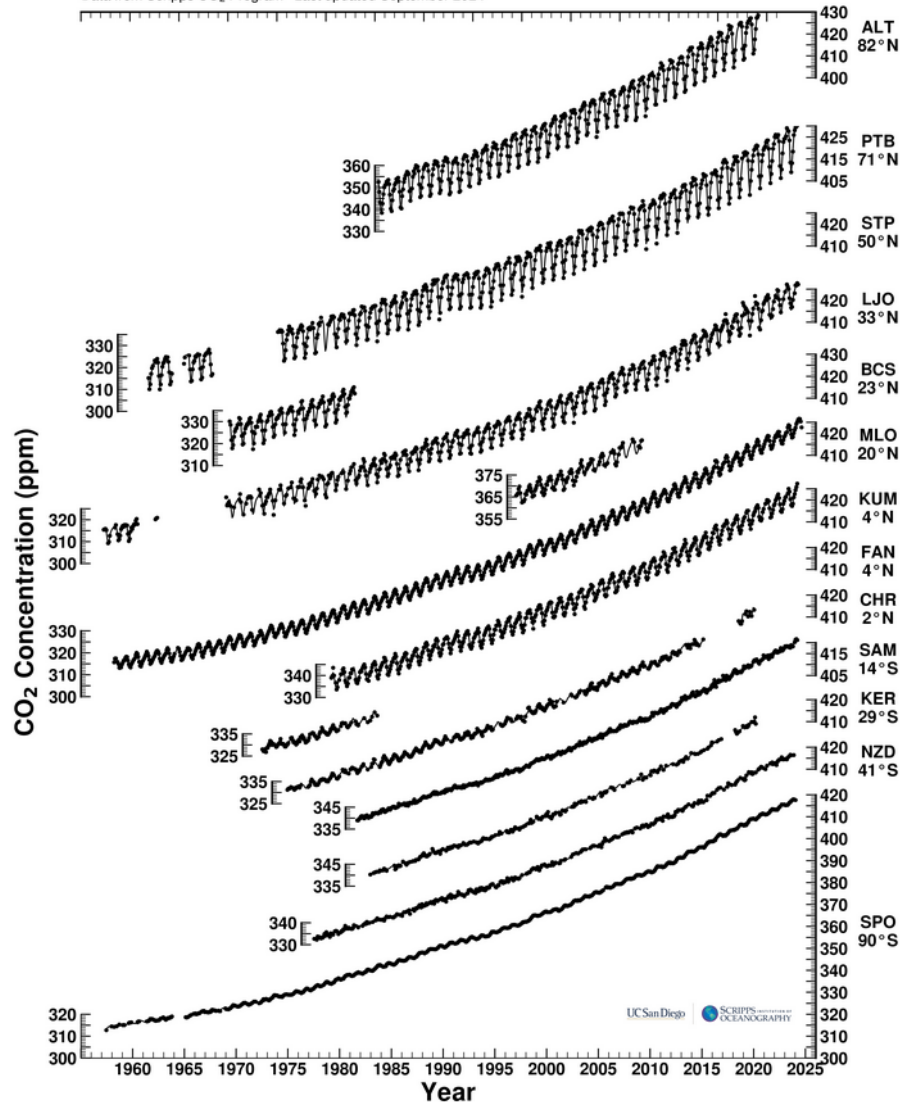


z

librations

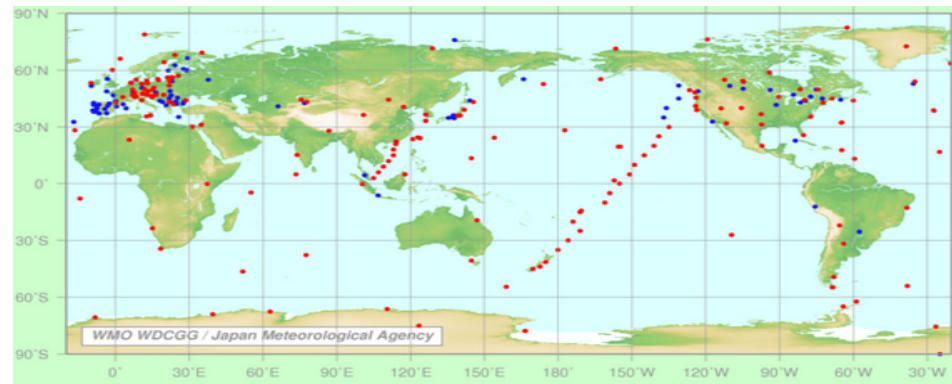
# Global Stations Carbon Dioxide Concentration Trends

Data from Scripps CO<sub>2</sub> Program Last updated September 2024



Regular observations of CO<sub>2</sub> and the other atmospheric gases are reported to WMO World Data Centre for Greenhouse Gases (WDCGG)

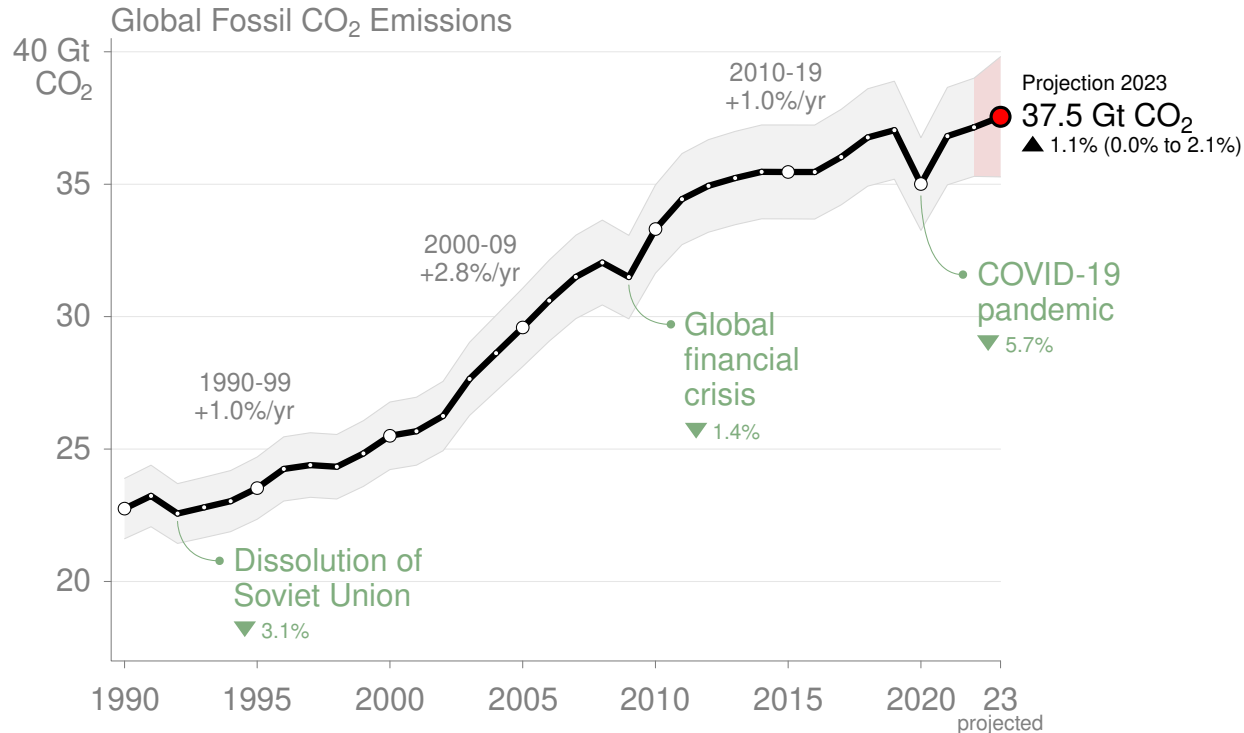
<http://ds.data.jma.go.jp/gmd/wdcgg/>





# Global Fossil CO<sub>2</sub> Emissions

Global fossil CO<sub>2</sub> emissions: 37.1 ± 2 GtCO<sub>2</sub> in 2022, 63% over 1990  
 Projection for 2023: 37.5 ± 2 GtCO<sub>2</sub>, 1.1% [0.0% to +2.1%] higher than 2022



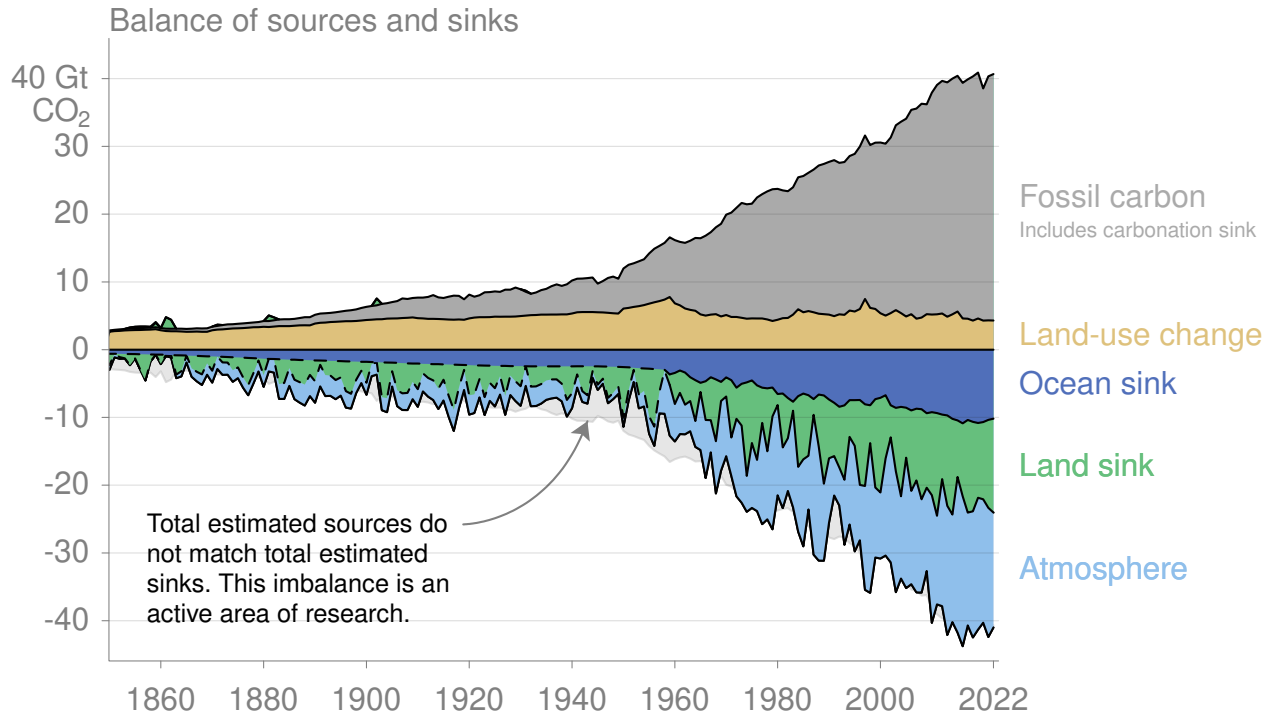
Uncertainty is ±5% for one standard deviation (IPCC “likely” range)

When including cement carbonation, the 2022 and 2023 estimates amount to 36.4 ± 2 GtCO<sub>2</sub> and 36.8 ± 2 GtCO<sub>2</sub> respectively

The 2023 projection is based on preliminary data and modelling.  
 Source: [Friedlingstein et al 2023](#); [Global Carbon Project 2023](#)

# Global carbon budget

Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean  
 The “imbalance” between total emissions and total sinks is an active area of research



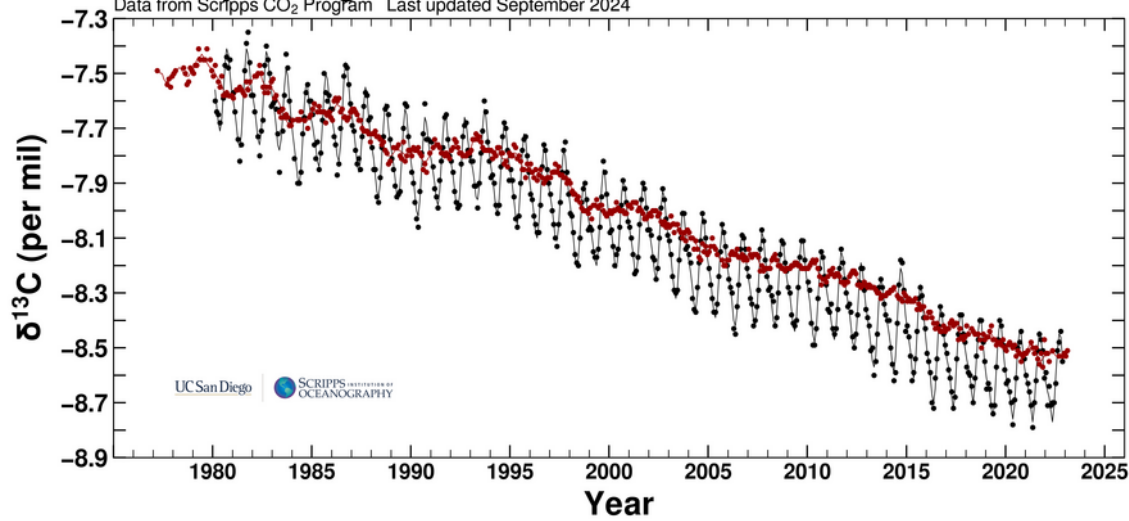
© Global Carbon Project

Source: [Friedlingstein et al 2023](#); [Global Carbon Project 2023](#)

## Mauna Loa Observatory, Hawaii and South Pole, Antarctica

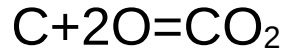
### Monthly Average $\delta^{13}\text{C}$ Trends

Data from Scripps CO<sub>2</sub> Program Last updated September 2024



Carbon stable isotopes concentration ratio  $^{13}\text{C}/^{12}\text{C}$  allows to determine the role of fossil fuel combustion in CO<sub>2</sub> concentration increase in the atmosphere and in the ocean.

Another signature of fossil fuel combustion

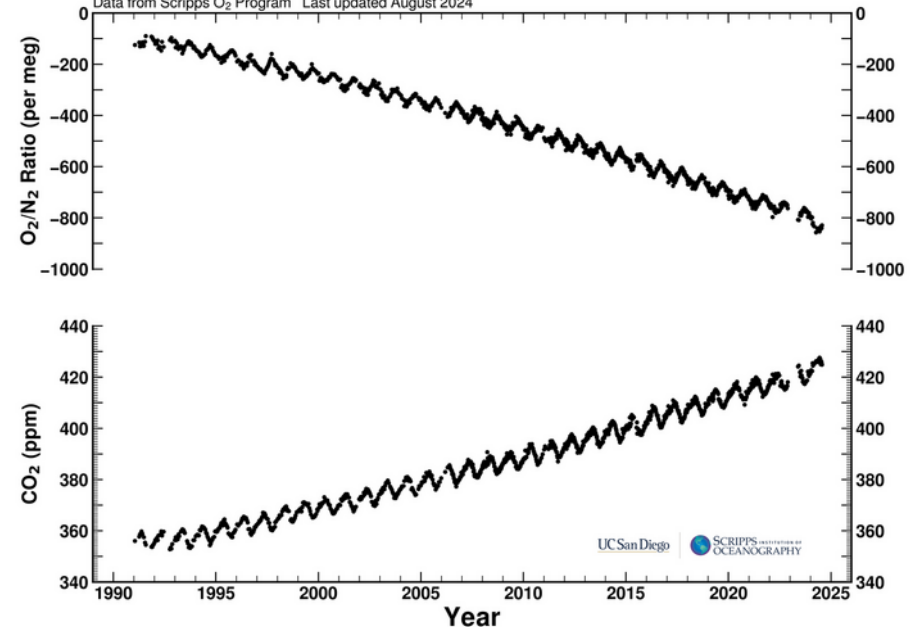


is the ratio of  $\text{O}_2/\text{N}_2$  in air.

## Mauna Loa Observatory, Hawaii

### $\text{O}_2/\text{N}_2$ Ratio and CO<sub>2</sub> Trends

Data from Scripps O<sub>2</sub> Program Last updated August 2024

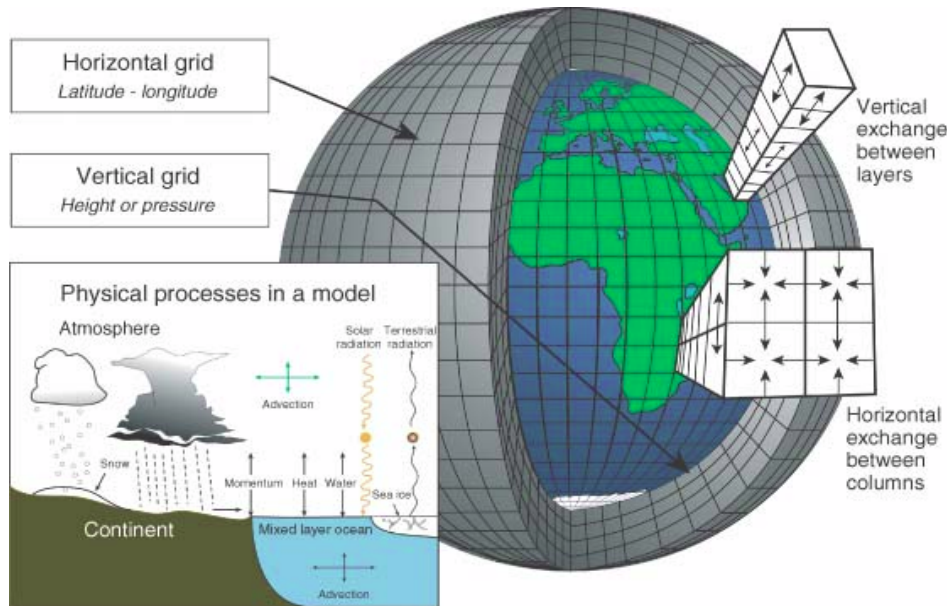




# Outline:

1. Physical properties and principles of climate system
2. Contemporary climate
3. Climate modeling

# Climate modeling: a virtual planet



geophysical fluid dynamics  
thermodynamics  
radiative transfer  
chemistry equations  
boundary conditions

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model equations

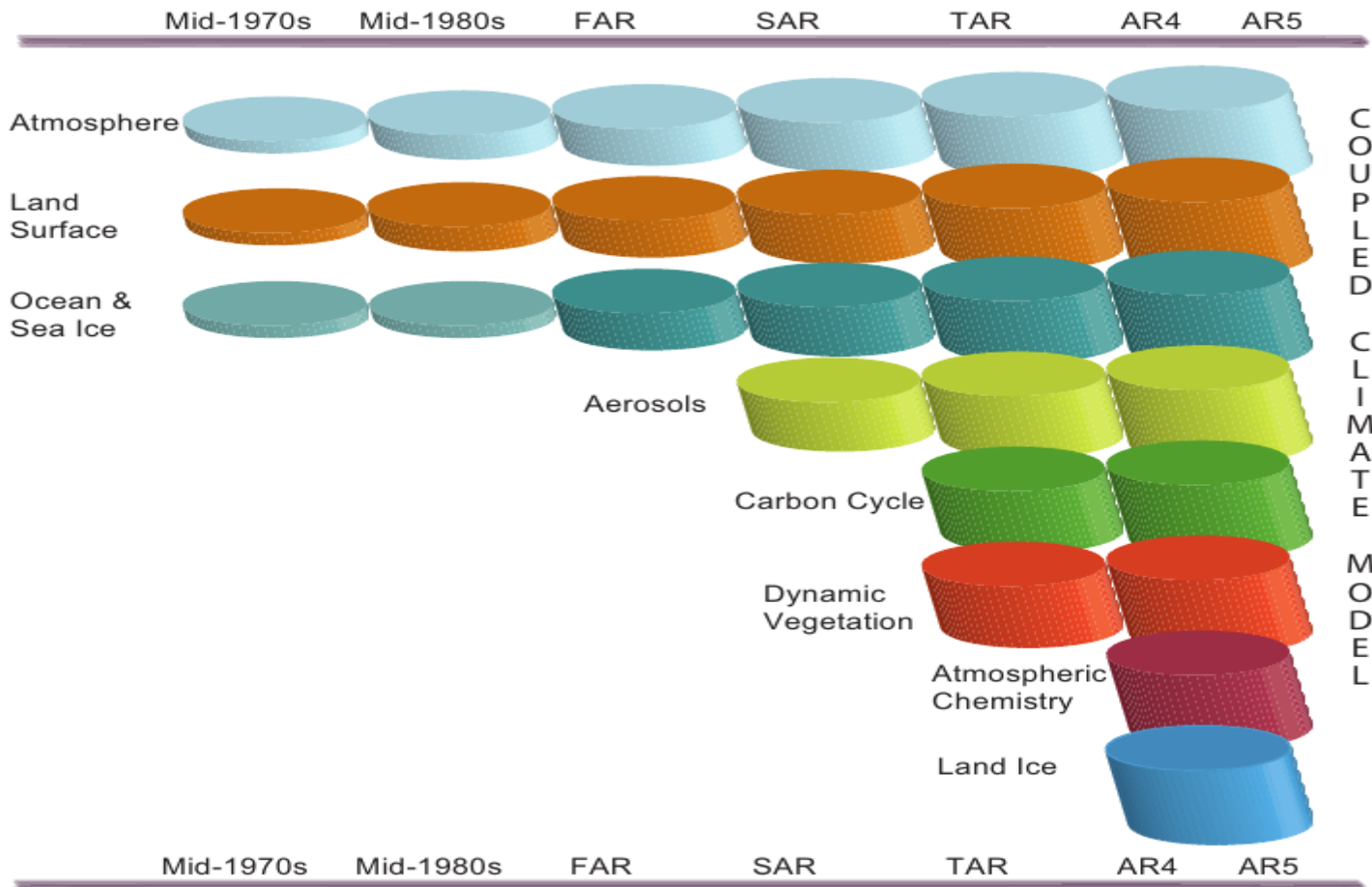


- \* numerical code
- \* data and initial conditions
- \* supercomputing facility



virtual reality allowing for simulating climate

# The development of climate models over the last 35 years



# Predictability of weather and climate

Edward N. Lorenz (1917-2008):

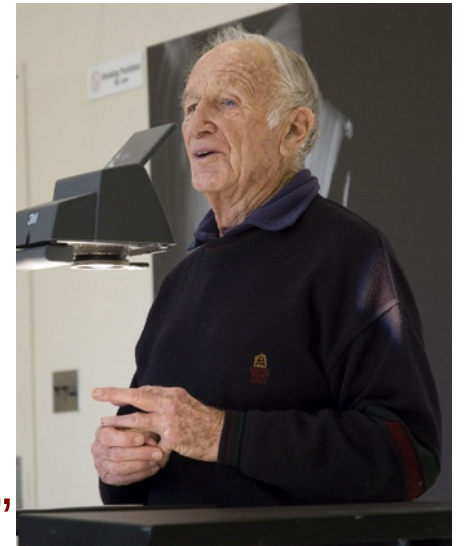
Selected papers:

„Deterministic nonperiodic flow”, 1963  
(sensitivity of solutions to initial conditions: “butterfly effect”  
attractor)

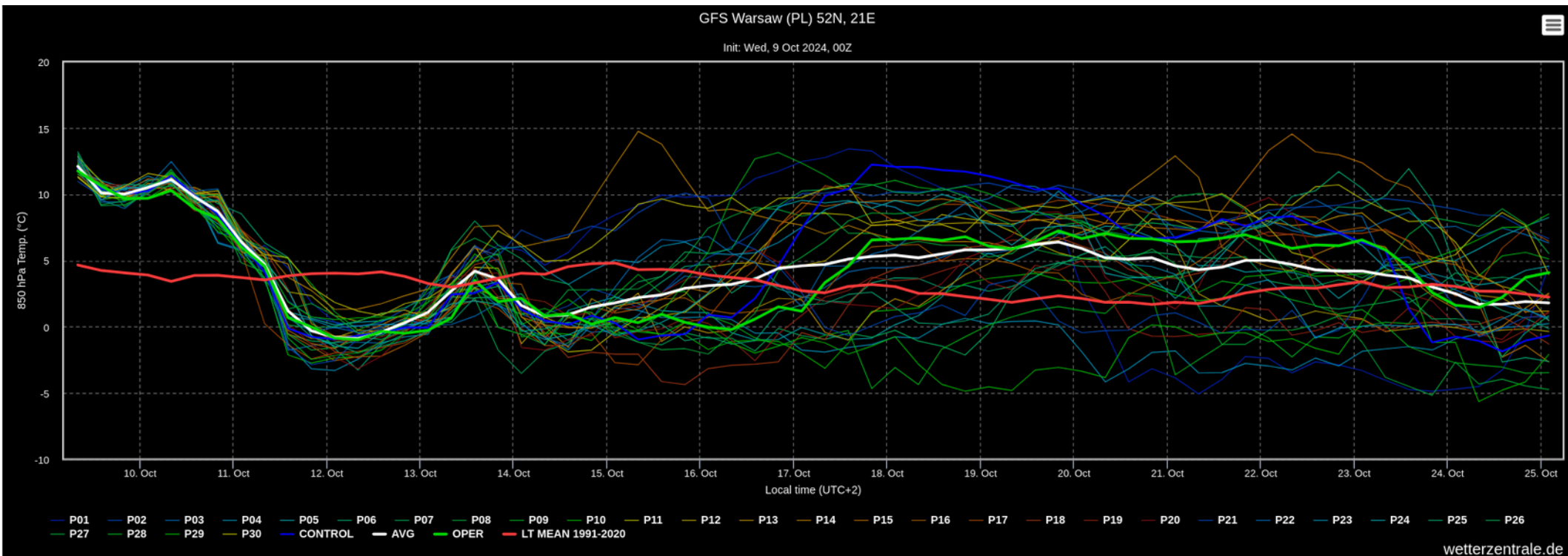
„The problem of deducing the climate from the governing equations”, 1964  
(long term predictability – uncertainties in the governing equations)

„Climatic change as a mathematical problem”, 1970  
(unpredictable weather does not mean that climate is not predictable)

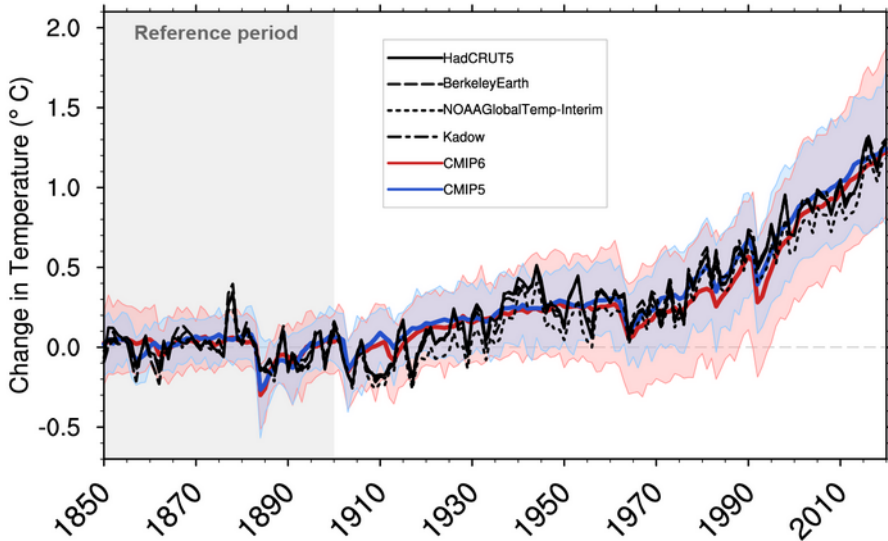
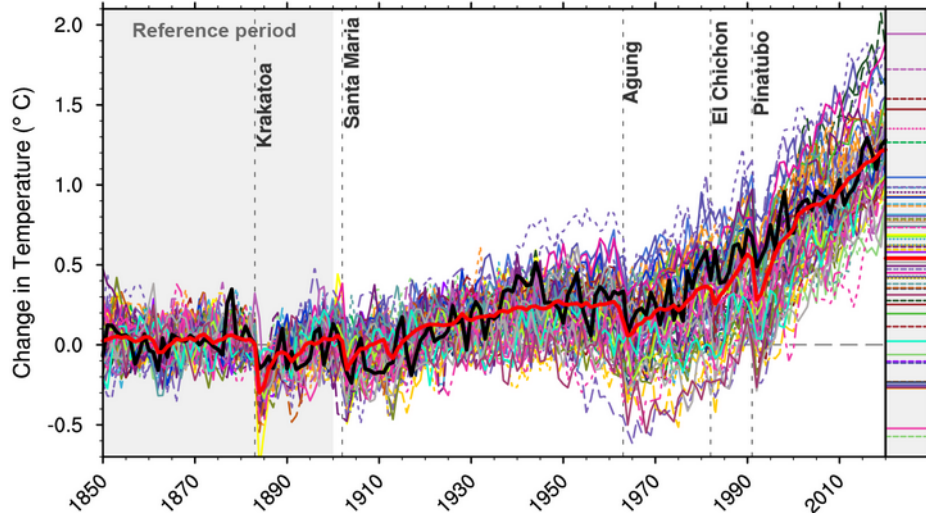
„Predictability – a problem partly solved”, 2006



# Predictability of weather and climate – illustration:



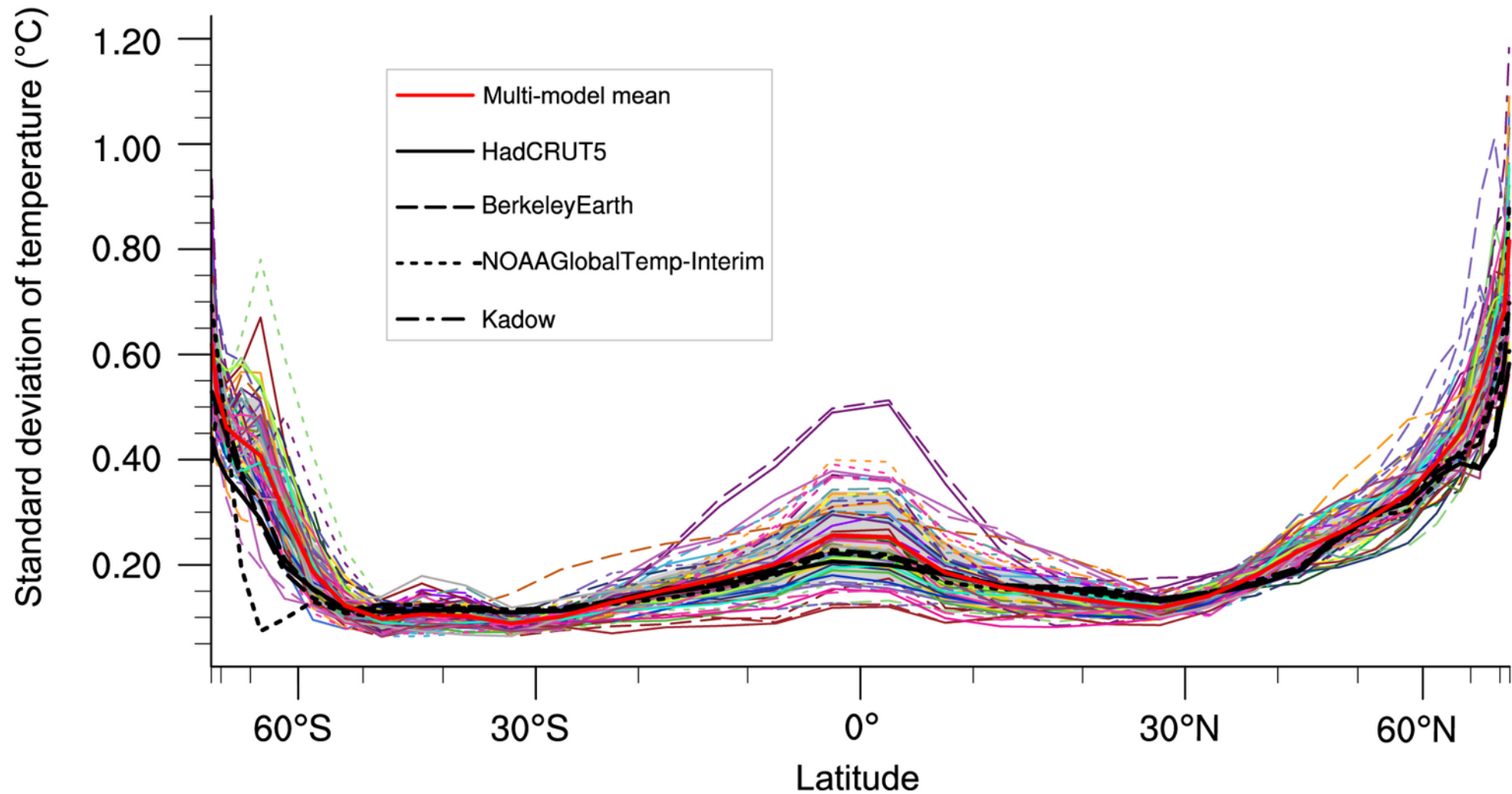
# Global mean surface air temperature



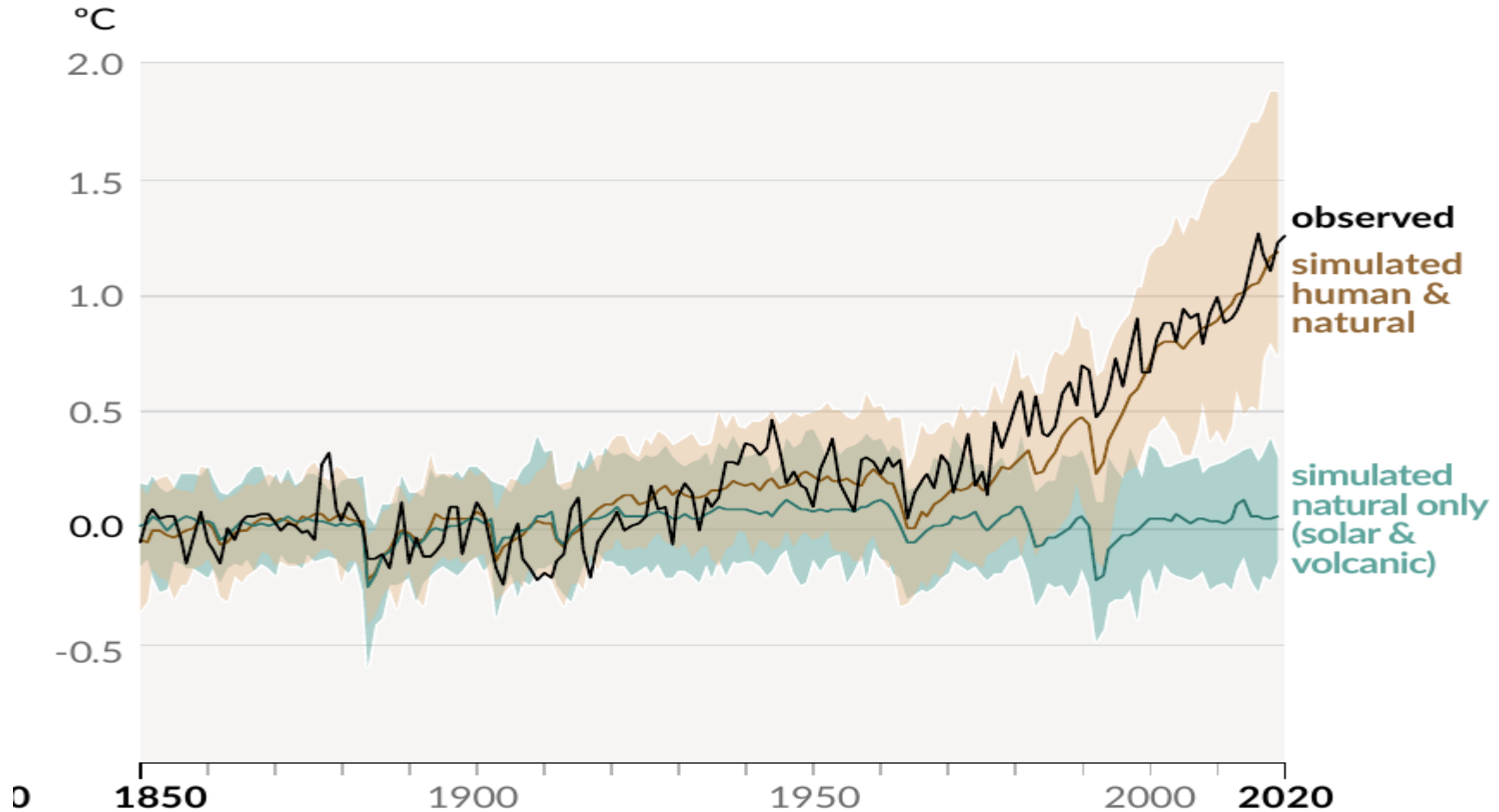
- HadCRUT5
- MultiModelMean
- ACCESS-CM2
- ACCESS-ESM1-5
- AWI-CM-1-1-MR
- AWI-ESM-1-1-LR
- BCC-CSM2-MR
- BCC-ESM1
- CAMS-CSM1-0
- CanESM5
- CanESM5-CanOE
- CESM2\*
- CESM2-FV2\*
- CESM2-WACCM\*
- CESM2-WACCM-FV2\*
- CIESM
- CMCC-CM2-HR4
- CMCC-CM2-SR5
- CMCC-ESM2
- CNRM-CM6-1
- CNRM-CM6-1-HR
- CNRM-ESM2-1
- E3SM-1-0
- E3SM-1-1
- E3SM-1-1-ECA
- EC-Earth3
- EC-Earth3-AerChem
- EC-Earth3-CC
- EC-Earth3-Veg
- EC-Earth3-Veg-LR
- FGOALS-r3-L
- FGOALS-g3
- FIO-ESM-2-0
- GFDL-CM4
- GFDL-ESM4
- GISS-E2-1-G
- GISS-E2-1-G-CC
- GISS-E2-1-H
- HadGEM3-GC31-LL
- HadGEM3-GC31-MM
- ITM-ESM
- INM-CM4-8
- INM-CM5-0
- IPSL-CM5A2-INCA
- IPSL-CM6A-LR
- KACE-1-0-G
- KIOST-ESM
- MCM-UA-1-0
- MIROC-ES2L
- MIROC6\*
- MPI-ESM-1-2-HAM\*
- MPI-ESM1-2-HR\*
- MPI-ESM1-2-LR\*
- MRI-ESM2-0
- NESM3
- NorCPM1
- NorESM2-LM
- NorESM2-MM
- SAM0-UNICON\*
- TaiESM1
- UKESM1-0-LL



# Temporal variability of near-surface air temperature

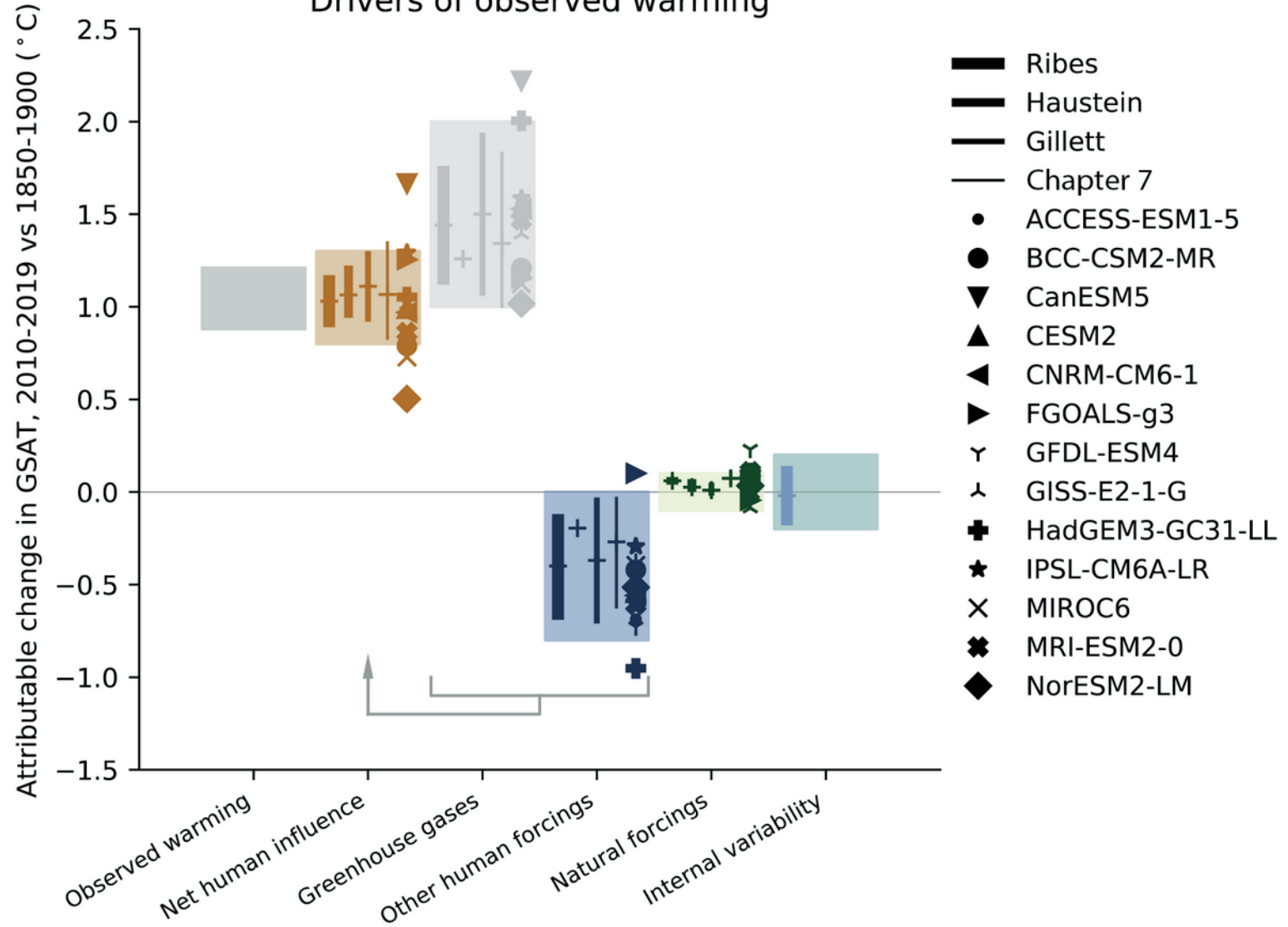


b) Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850-2020)

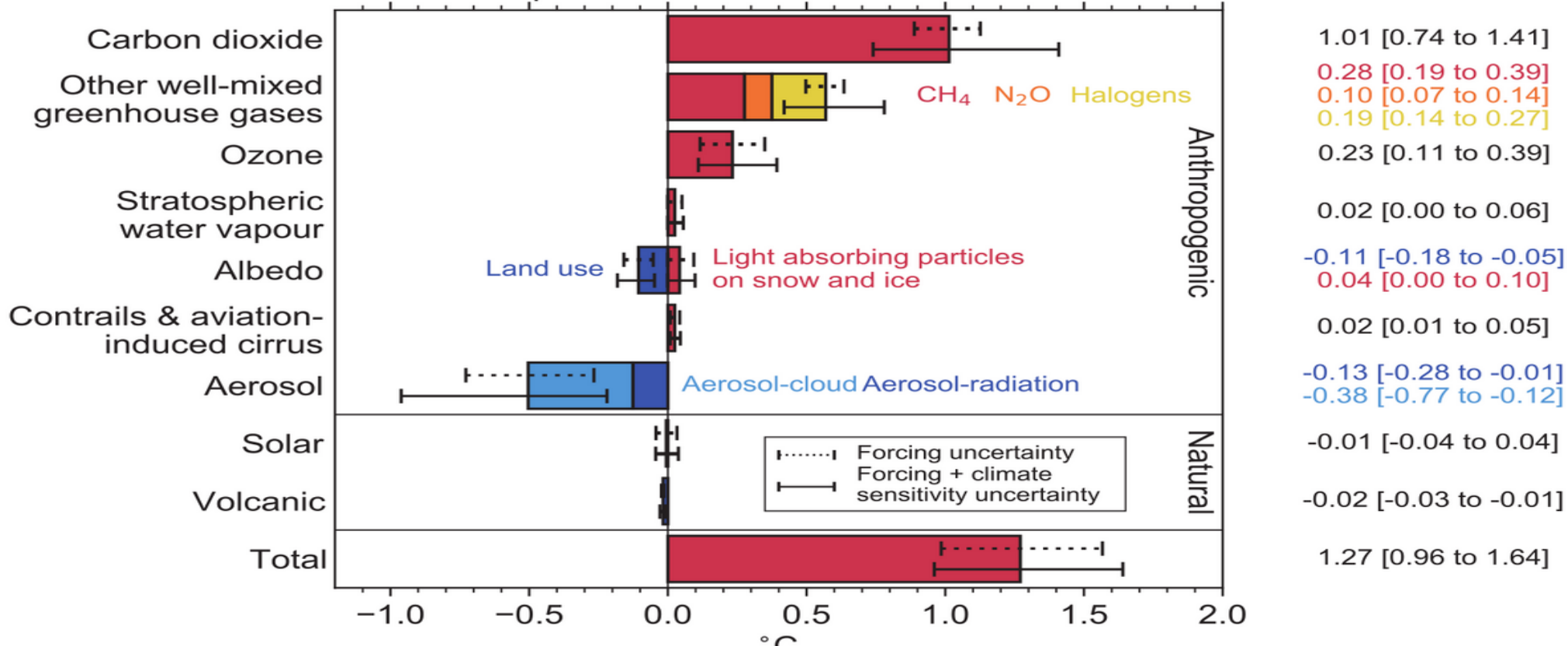




# Drivers of observed warming



Simulated temperature contributions in 2019 relative to 1750



Arguments, that climate model provide valuable information:

- 1) the models can reproduce the current climate;
- 2) the models can reproduce the recent observed trends as well as the more distant past;
- 3) the models are based on physical principles;
- 4) there is a hierarchy of the models from the simplest ones to most complicated, which allows for understanding and interpretation many of the results;
- 5) the value of simulations is increased where multiple models are available, since they indicate which changes are more certain than others.