Global warming - physicist's perspective
02 – measurements and modelling

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NAUKA O KLIMACIE
DLA SCEPTYCZNYCH

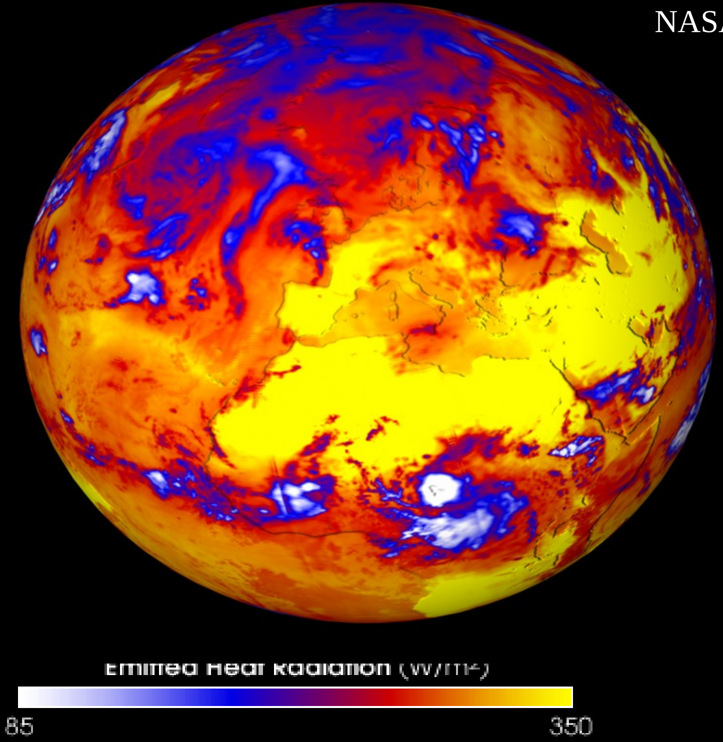
UNIVERSITY
OF WARSAW

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 = ¼ of Solar constant
   $1/4*1362W/m^2 \approx 341W/m^2$.

2. Earth's surface albedo, mean ≈0.3, highly variable,
   from 0.9 (fresh snow) to 0.07 (clean ocean).

3. Geothermal energy flux $\approx 0.092W/m^2$.

4. Heat flux from fossil fuel combustion $\approx 0.026W/m^2$.

BASIC PROPERTIES OF THE CLIMATE SYSTEM

1. Air: surface pressure ≈1000hPa (10m of water), c_p=1004J/kg*K.
2. Water: global average depth ≈ 3000m, c_w=4192J/kg*K.
3. Ground – only a shallow layer responding to radiative fluxes.
4. Greenhouse gases: H_2O, CO_2, CH_4, 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, CO2 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.

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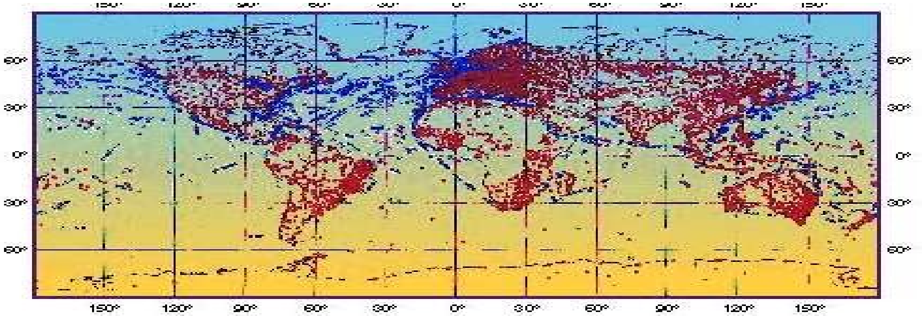
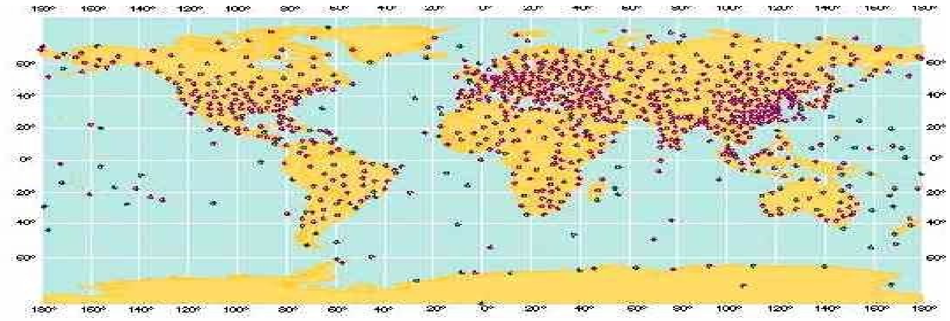
http://www.wmo.int/pages/themes/climate/climate_observation_networks_systems.php

World Meteorological Organization
Weather • Climate • Water

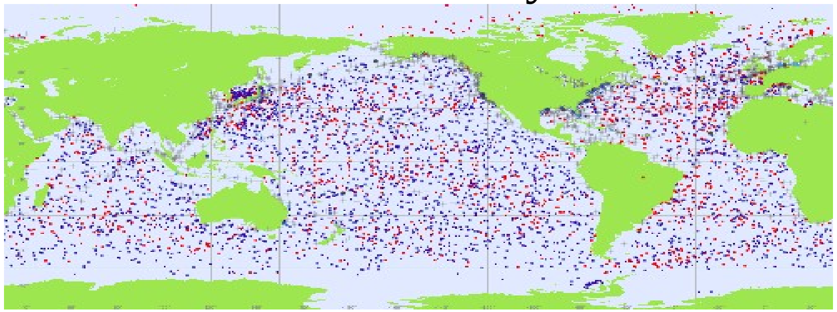
Atmosphere: Over 11,000 weather stations, as well as satellites, ships and aircraft take measurements.
1040 of stations are selected to provide high quality climate data.
There are special networks at national (e.g. Reference Climate Stations), regional (e.g. Regional Basic Climatological Network) and global scales. (e.g. the Global Climate Observing System - GCOS - Surface Network, GSN).



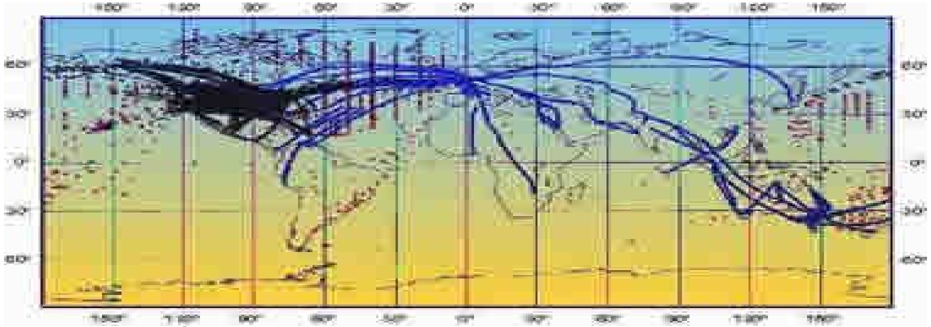
Weather stations and buoys



Upper air soundings



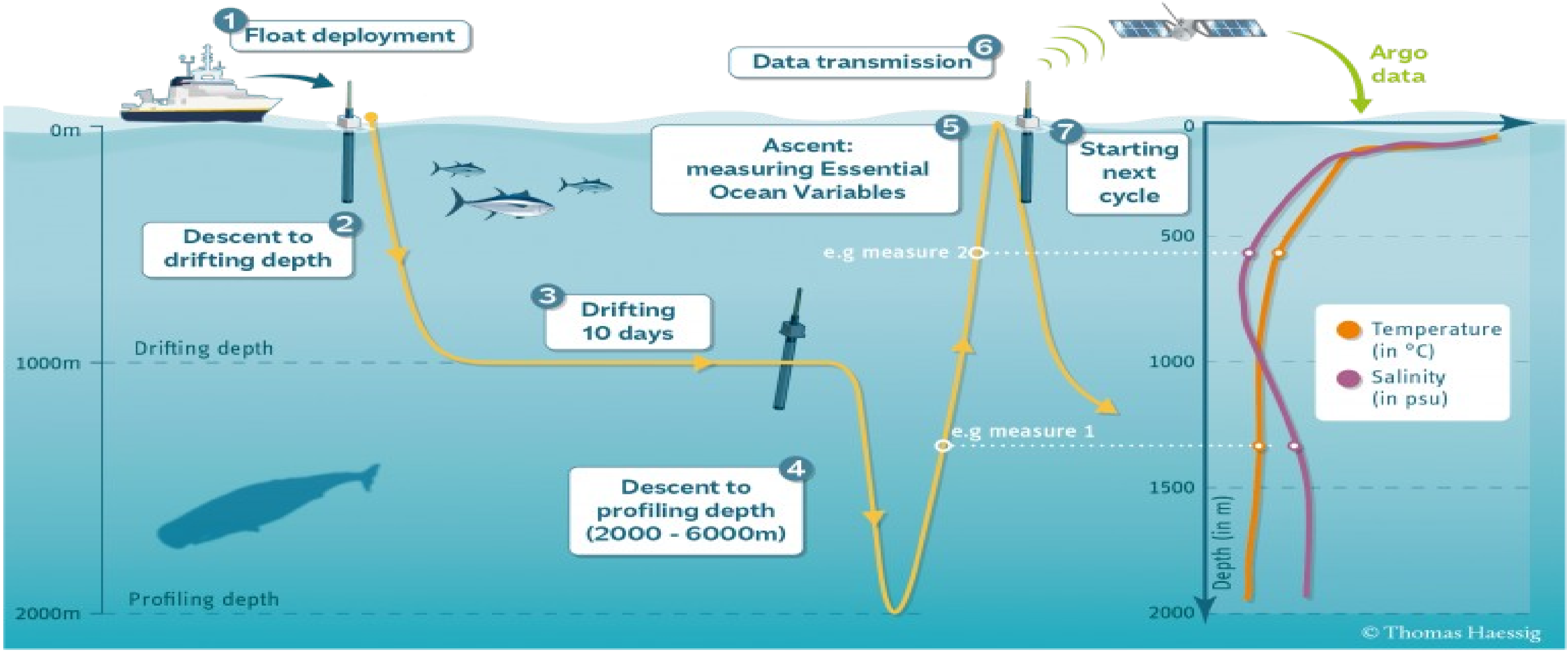
Voluntary ship observations



Aircraft based observations

OCEAN:

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

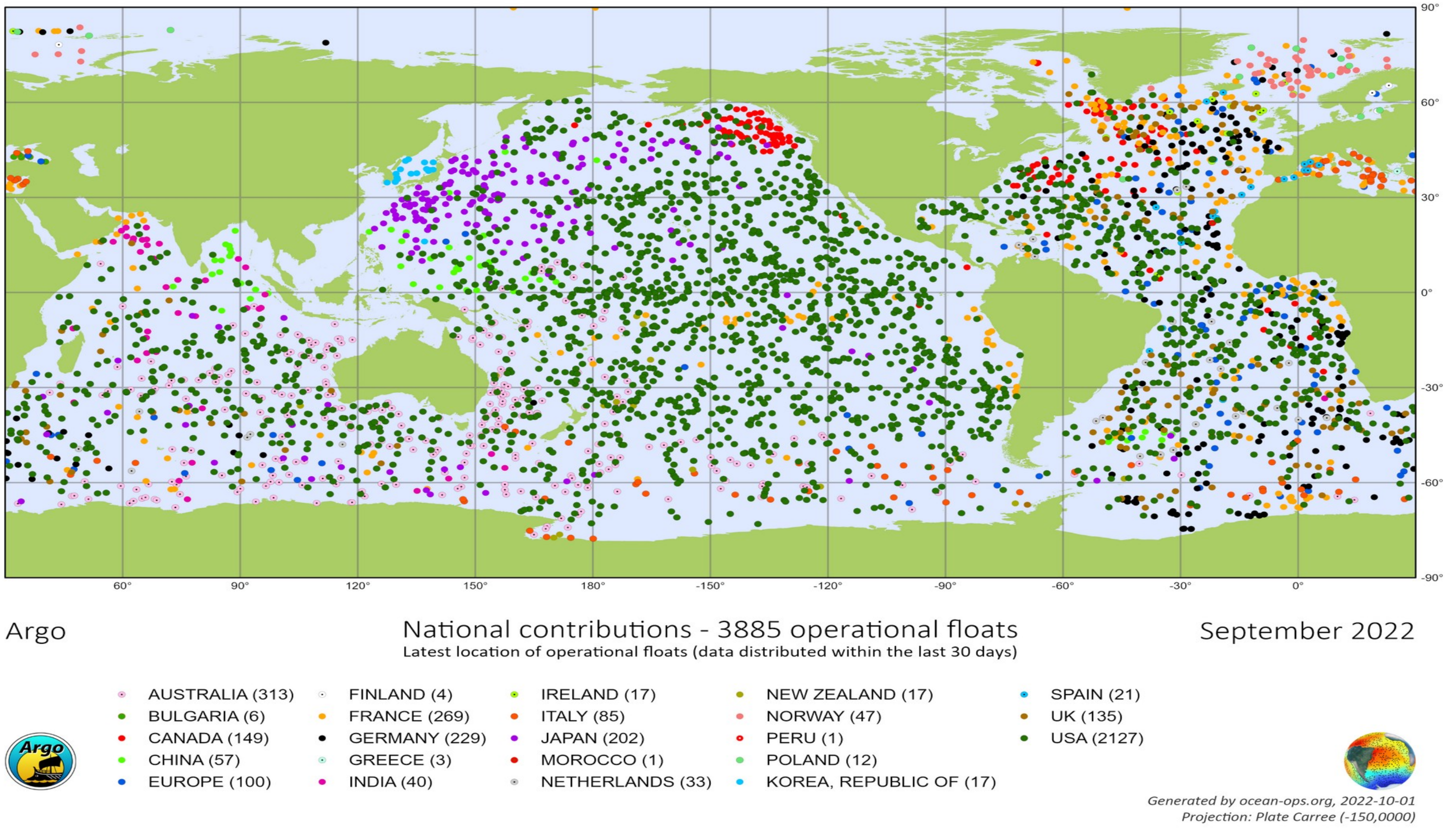


http://www.argo.ucsd.edu/

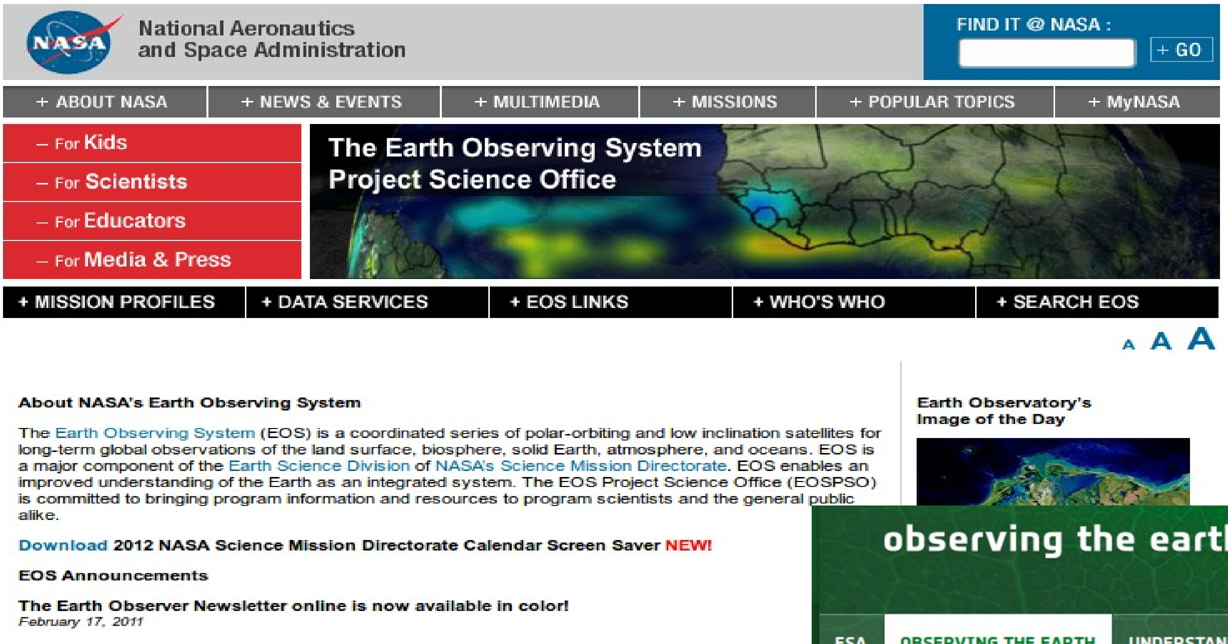
OCEAN:

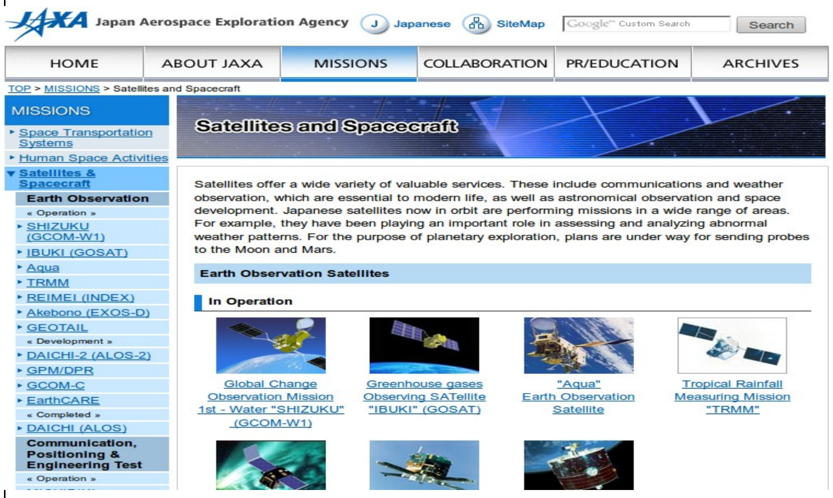
ARGO project: temperature and salinity profiling, deep sea currents.

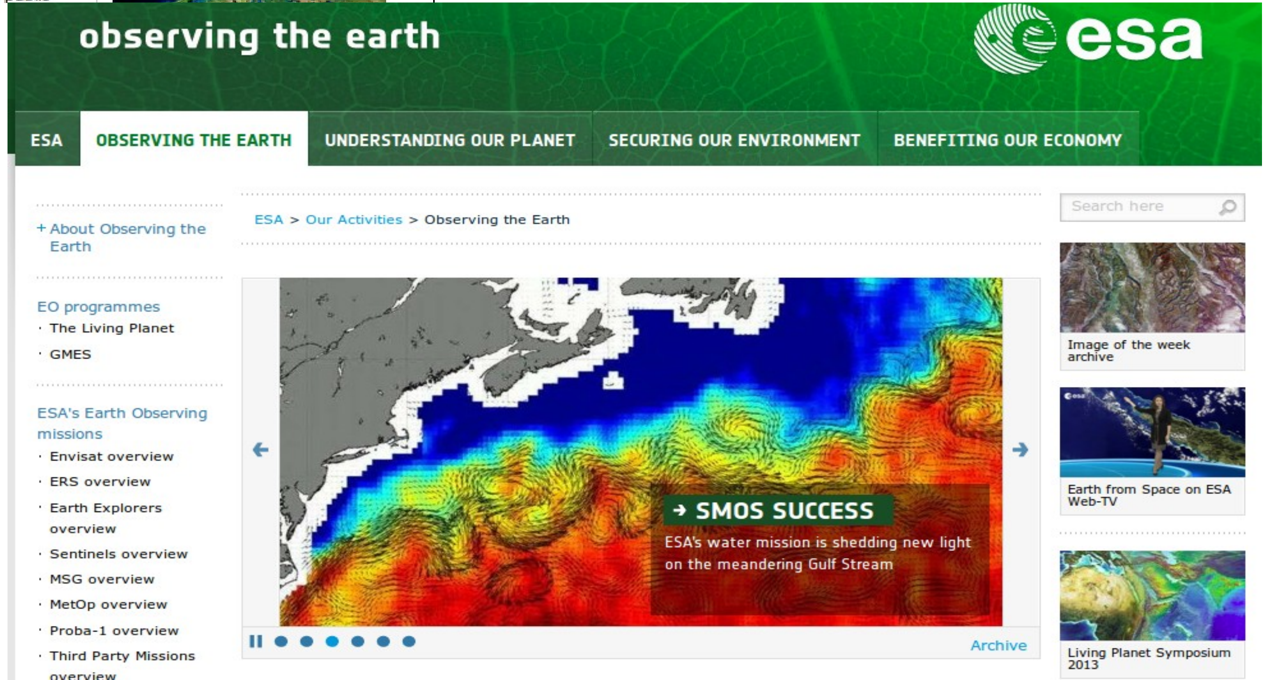
Thousands of automatic profilers provide actual data from the world ocean.



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



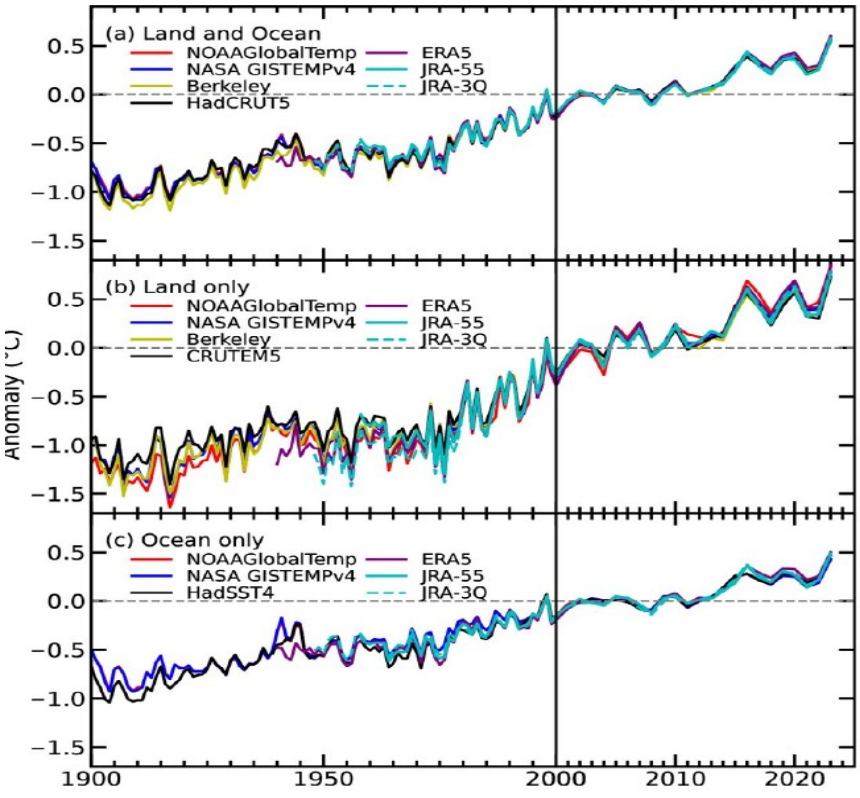




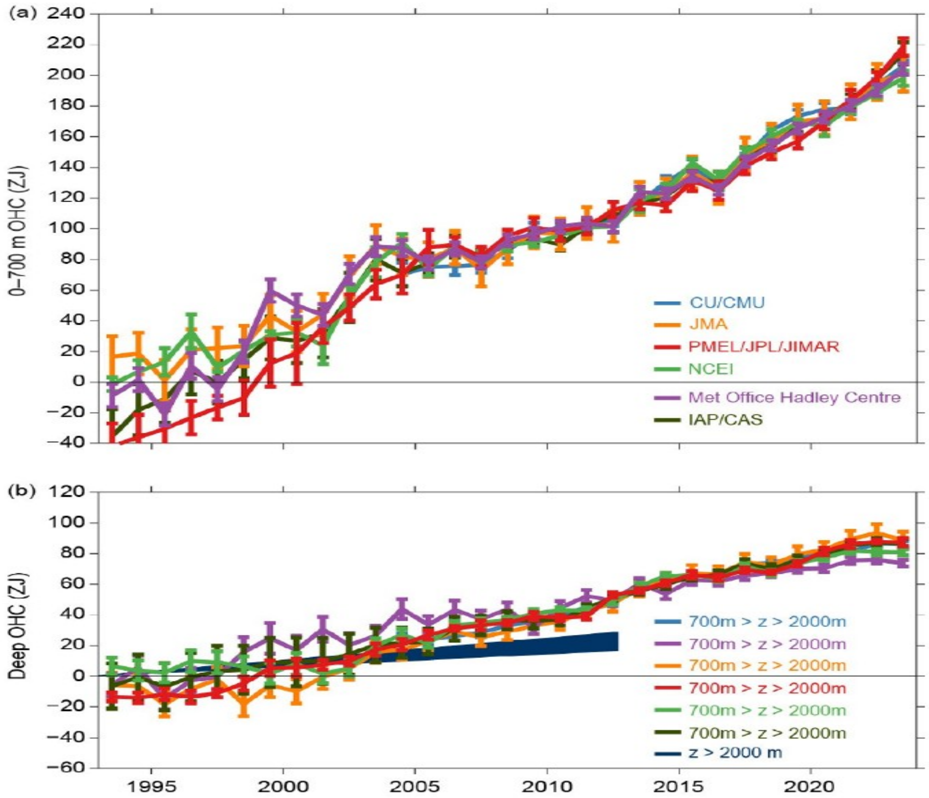
Satellite systems of NASA, ESA, JAXA and others.

Observations - summary

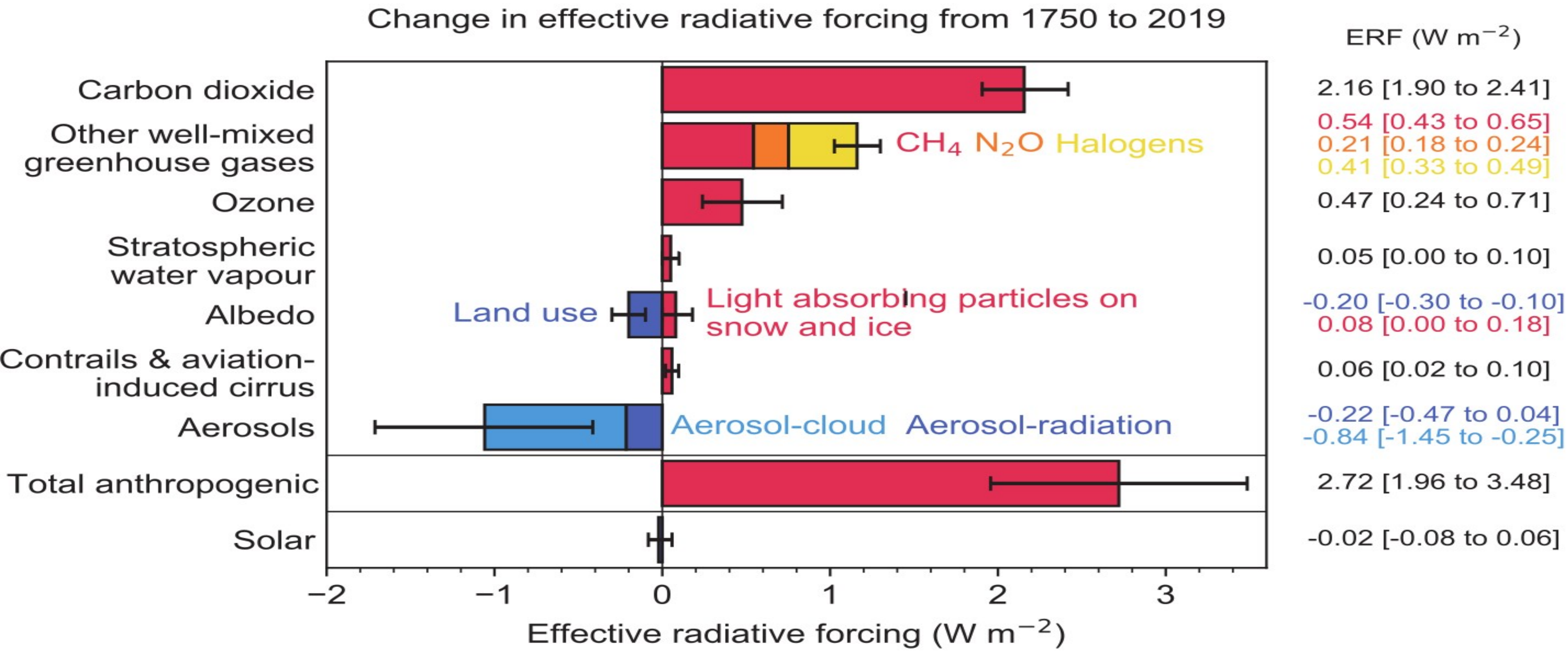
Temperature anomaly



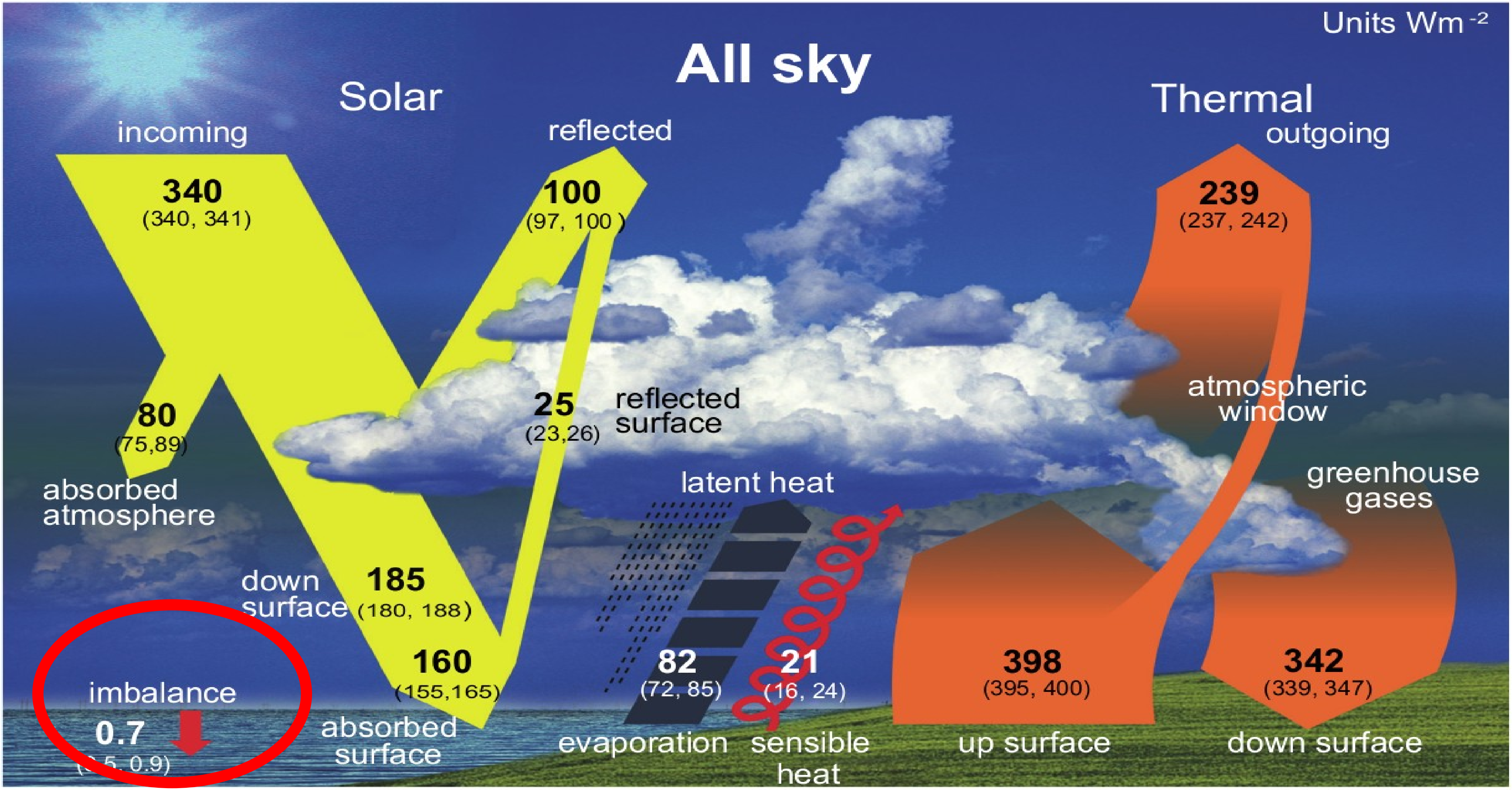
OHC change



https://www.ametsoc.org/index.cfm/ams/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/

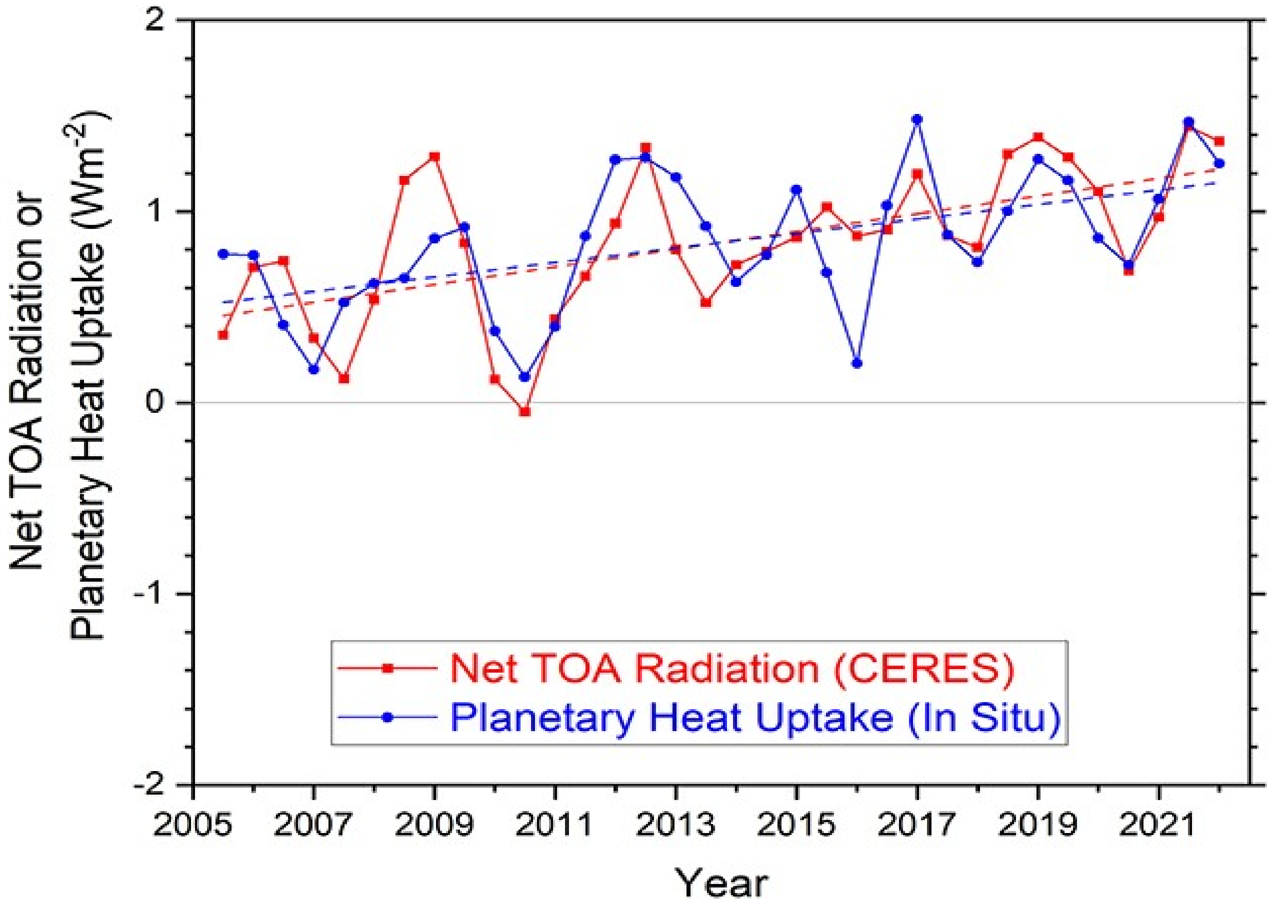


https://www.ipcc.ch/report/ar6/wg1/



Energy balance of climate system. Units: 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

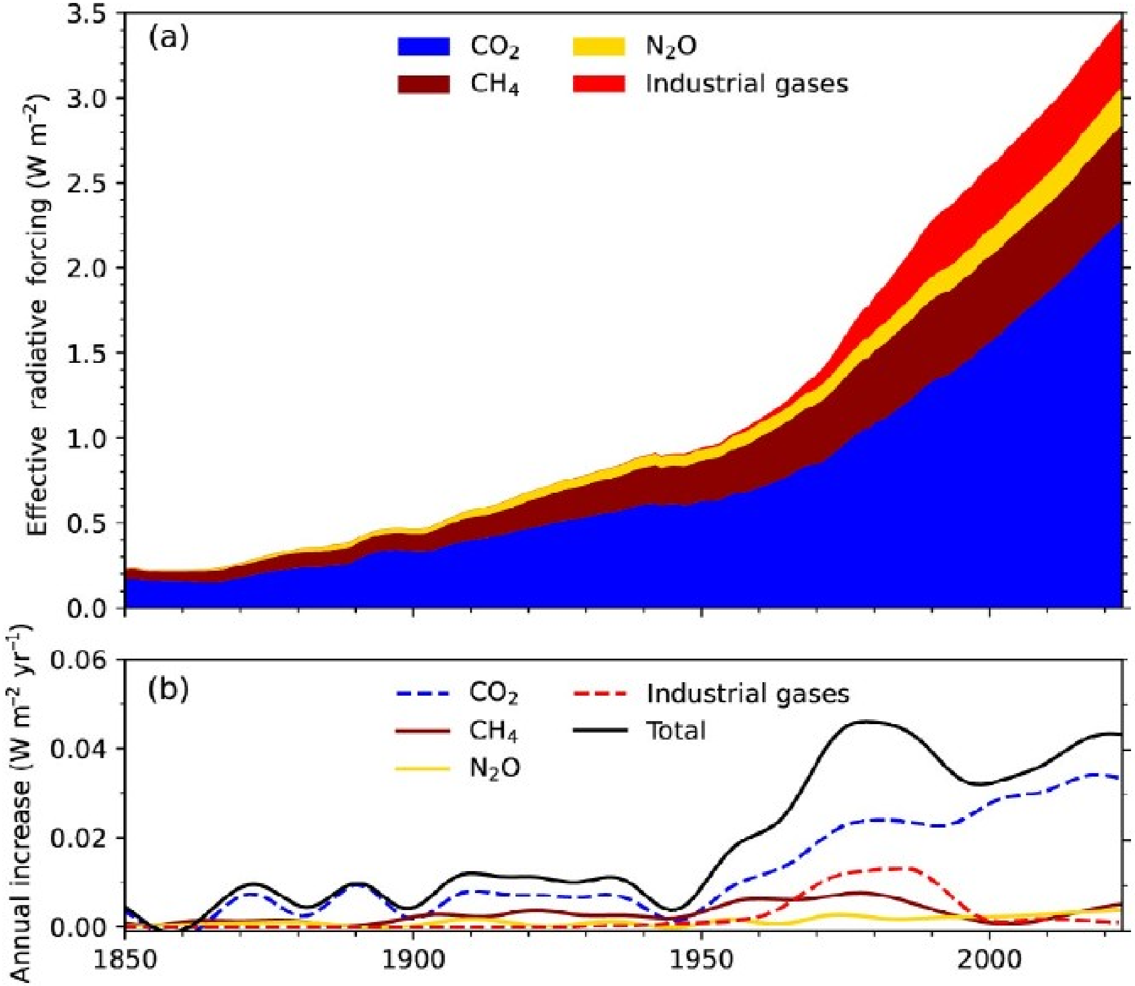
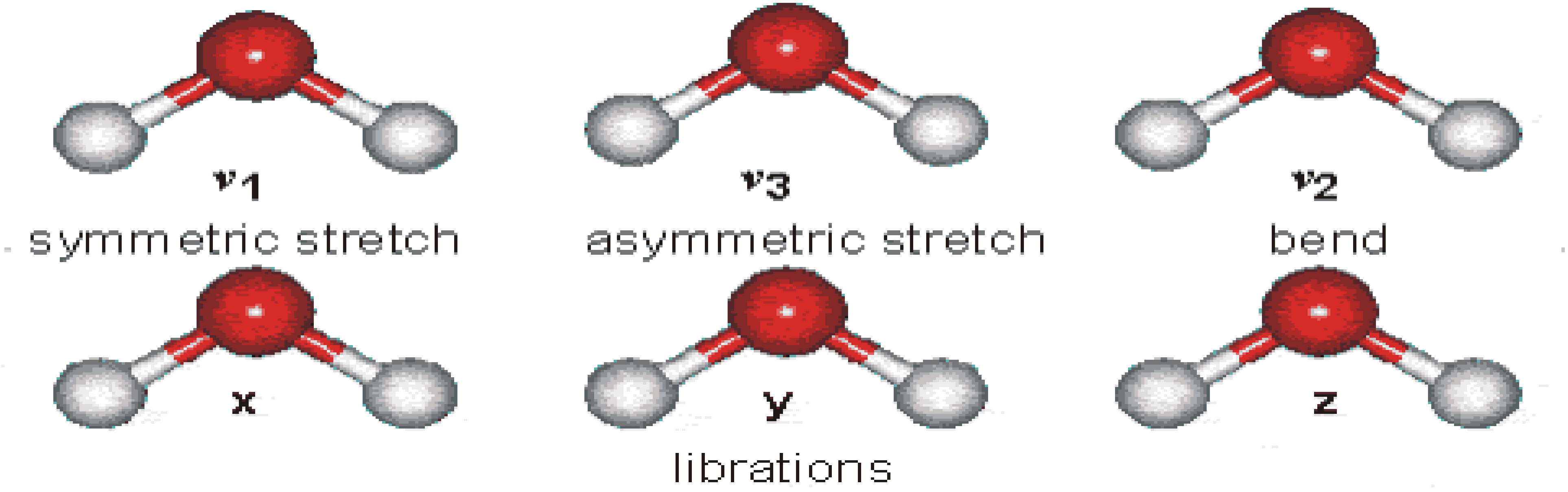
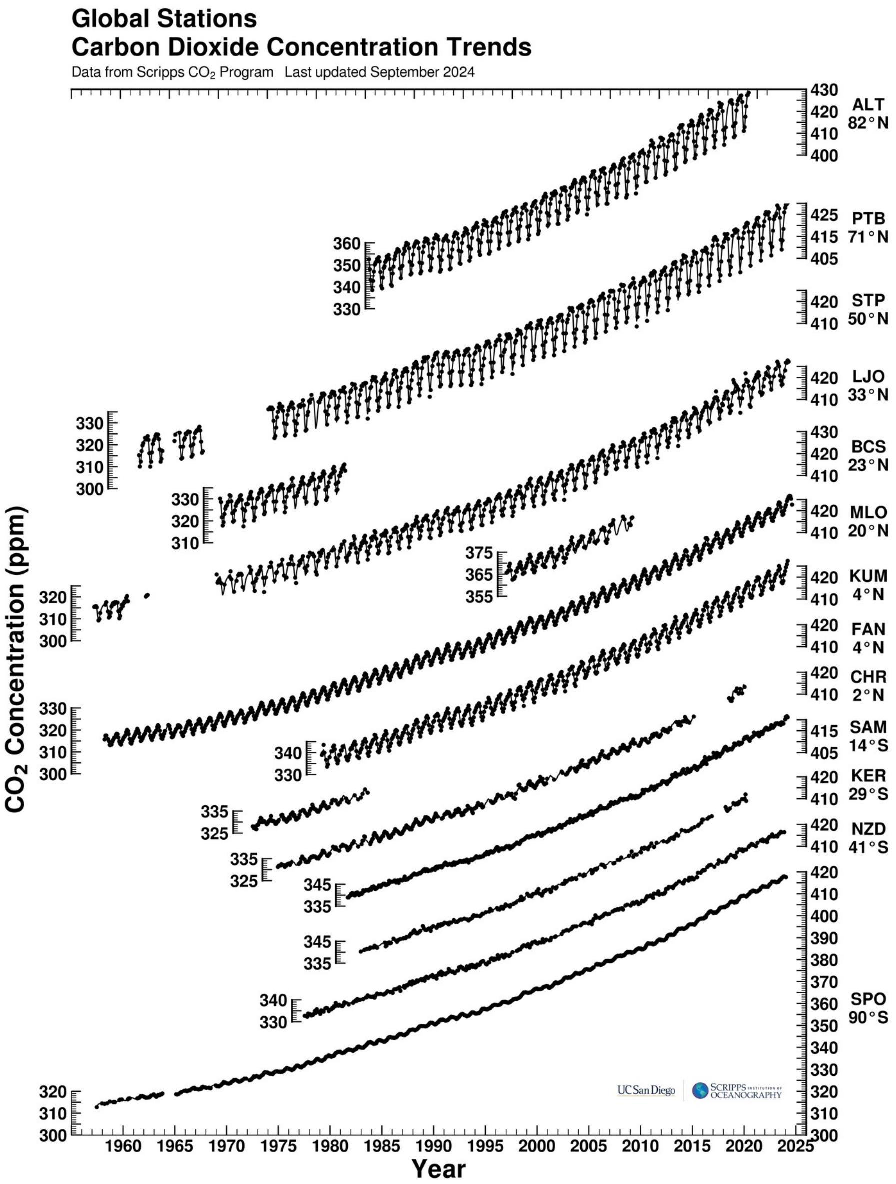


Fig. 2.60. (a) Effective radiative forcing (W m^{-2}) due to long-lived greenhouse gases (LLGHGs; see Table 2.10 for details on industrial gases). (b) Annual increase in direct radiative forcing (W m^{-2}).

https://www.ametsoc.org/index.cfm/ams/publications/bulletin-of-the-american-meteorological-society-bams/state-of-the-climate/

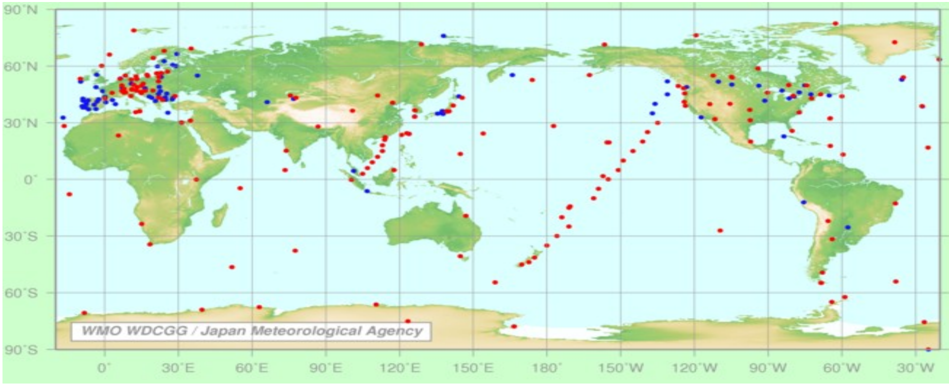
Why particles with 3 or more atoms absorb long-wave (low energy) radiation?





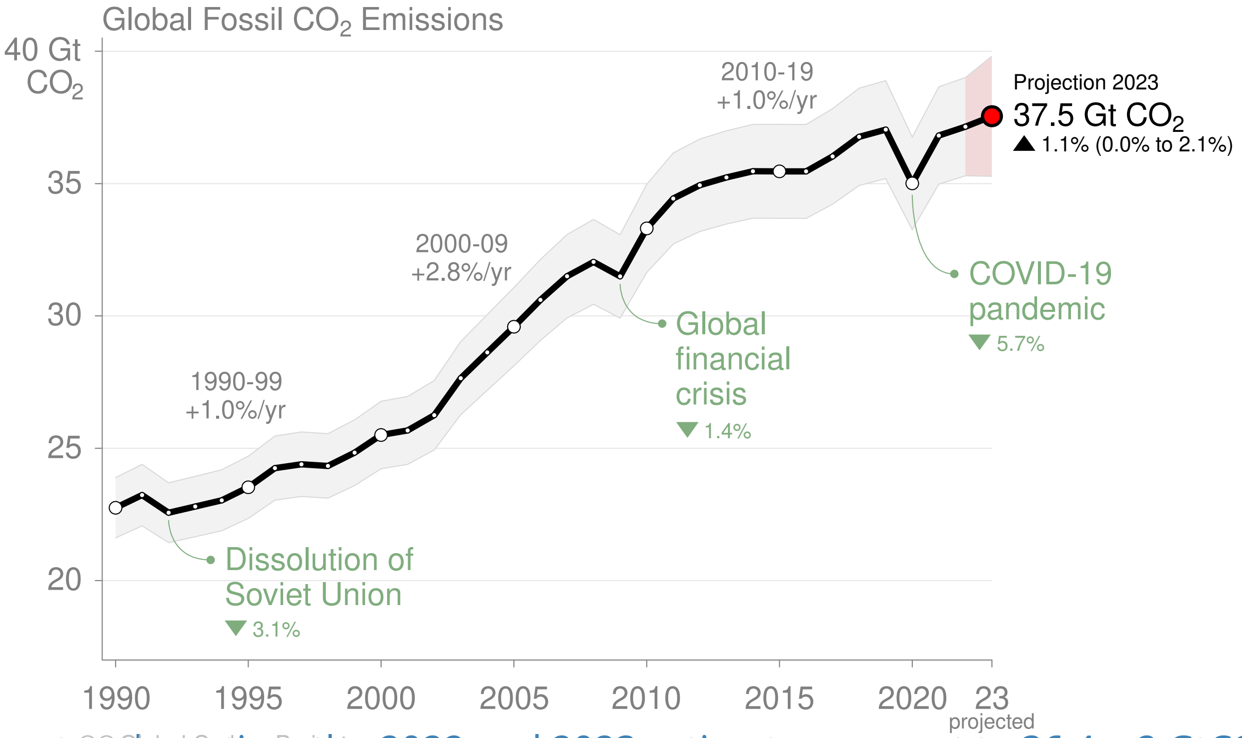
Regular observations of CO_2 and the other atmospheric gases are reported to WMO World Data Centre for Greenhouse Gases (WDCGG)

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



Global Fossil CO_2 Emissions

Global fossil CO_2 emissions: 37.1 ± 2 $GtCO_2$ in 2022, 63% over 1990
Projection for 2023: 37.5 ± 2 $GtCO_2$, 1.1% [0.0% to +2.1%] higher than 2022



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

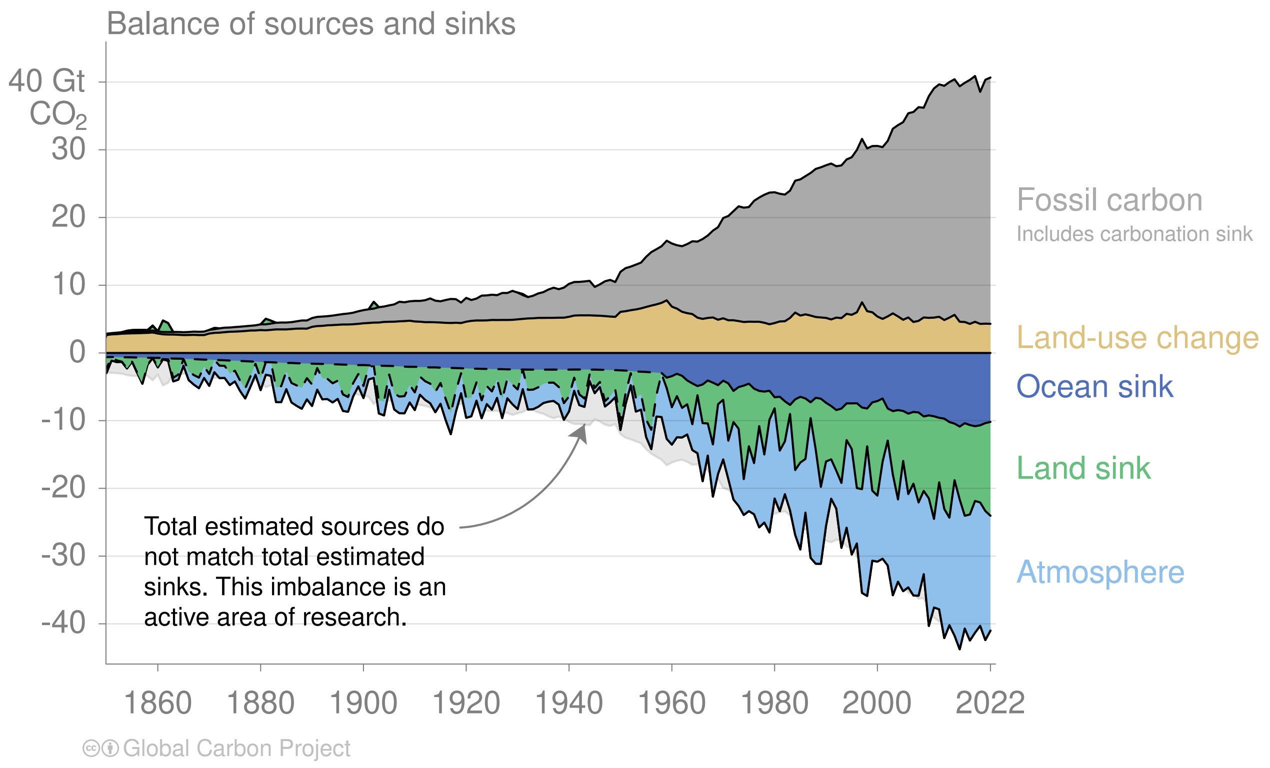
When including cement carbonation, the 2022 and 2023 estimates amount to 36.4 ± 2 $GtCO_2$ and 36.8 ± 2 $GtCO_2$ respectively

The 2023 projection is based on preliminary data and modelling.

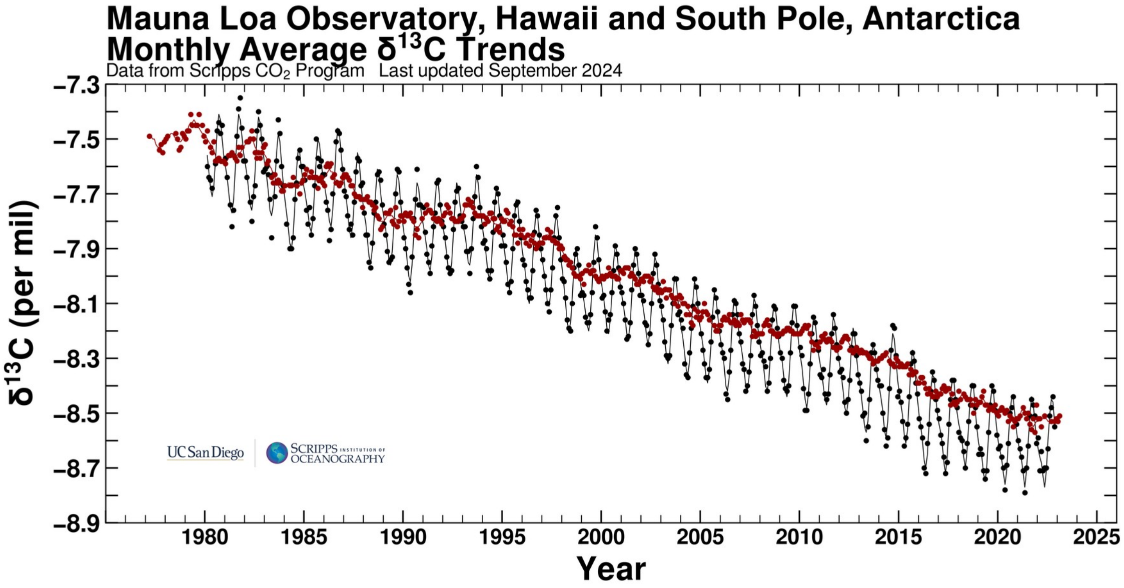
Source: [Friedlingstein et al 2023](); [Global Carbon Project 2023]()

Global carbon budget

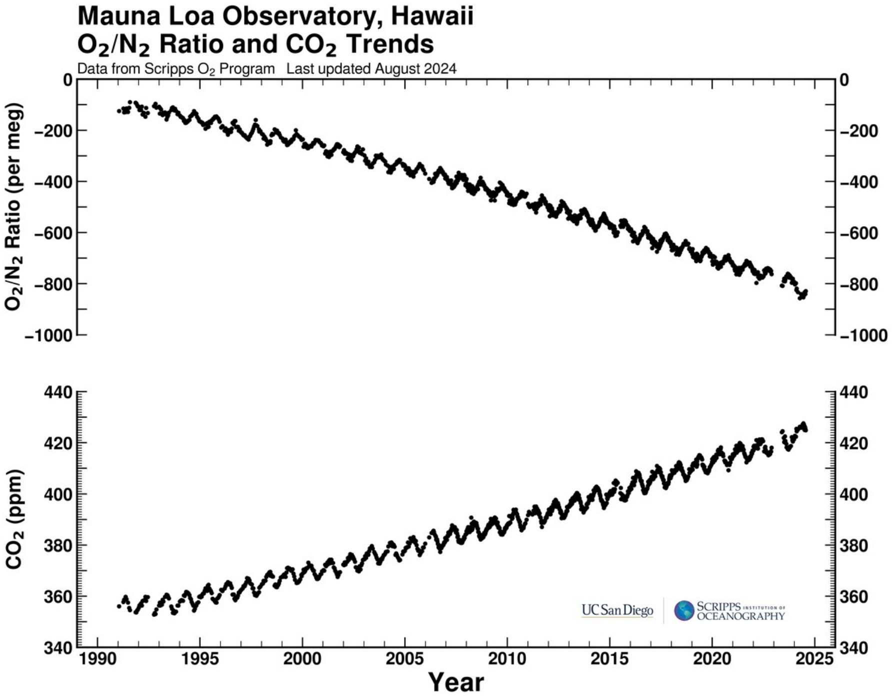
Carbon emissions are partitioned among the atmosphere and carbon sinks on land and in the ocean
The "imbalance" between total emissions and total sinks is an active area of research



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



Carbon stable isotopes concentration ratio $^{13}C/^{12}C$ allows to determine the role of fossil fuel combustion in CO_2 concentration increase in the atmosphere and in the ocean.



Another signature of fossil fuel combustion

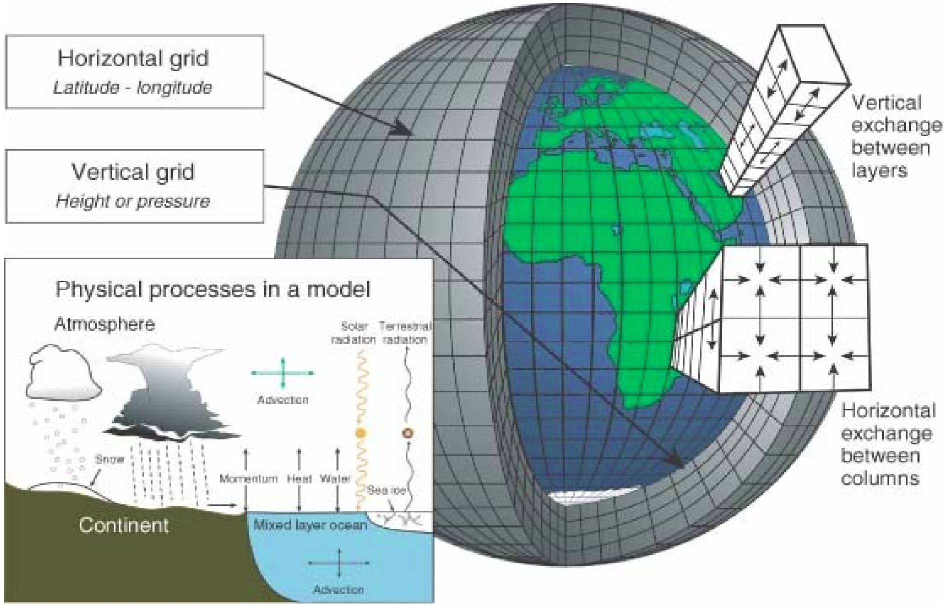
$$C+2O=CO_2$$

is the ratio of O_2/N_2 in air.

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

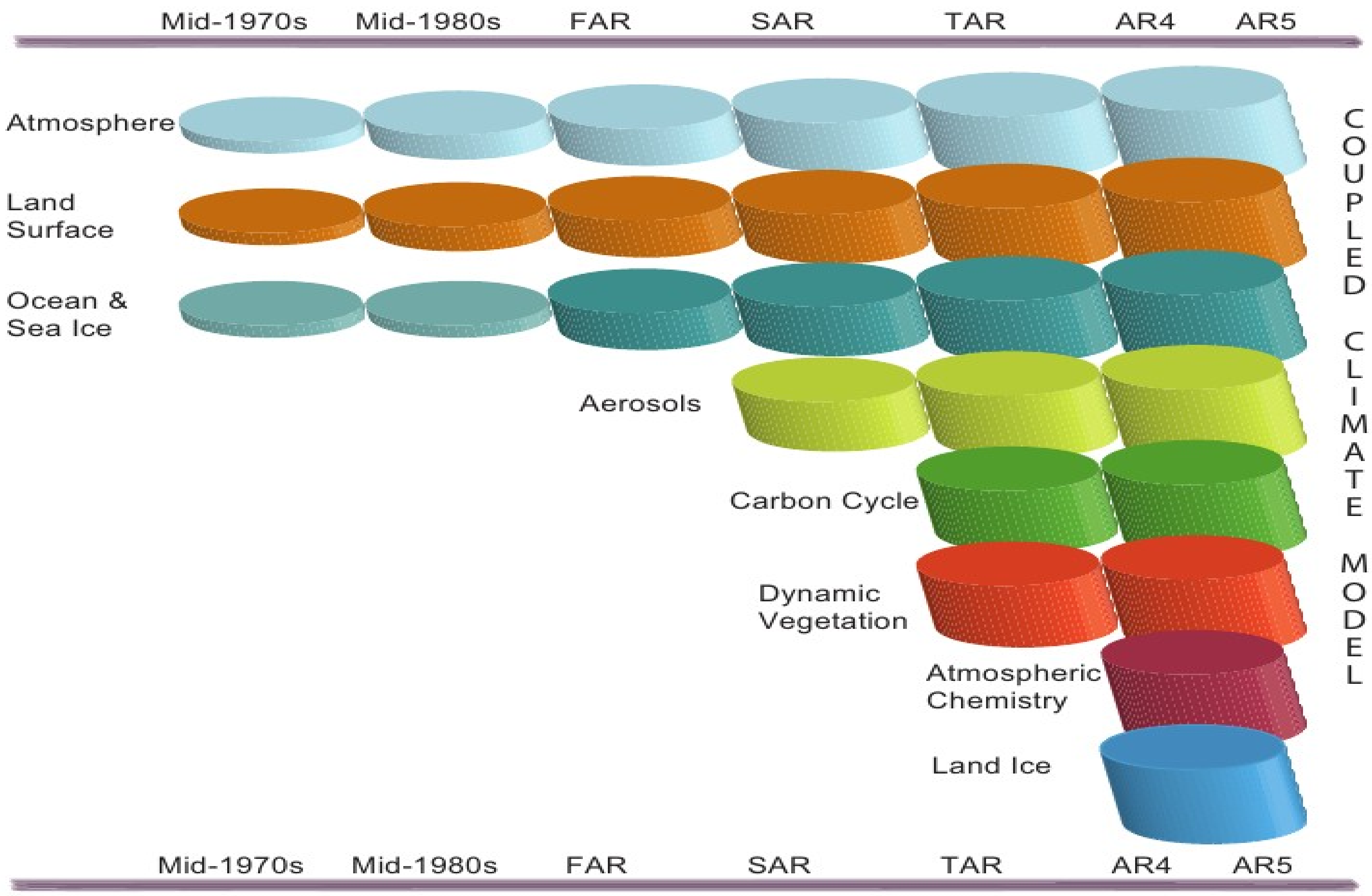
↓

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

↓

virtual reality allowing for simulating climate

The development of climate models over the last 35 years

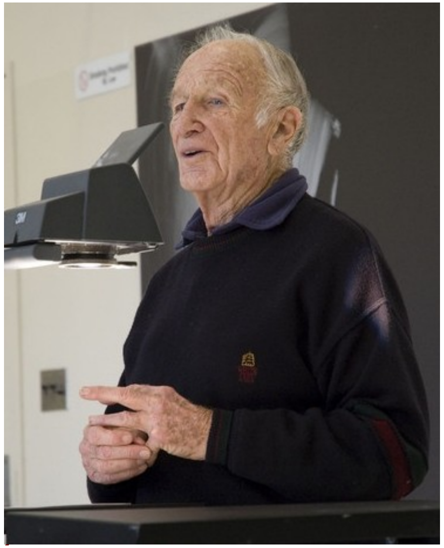


Predictability of weather and climate

Edward N. Lorenz (1917-2008):

Selected papers:

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

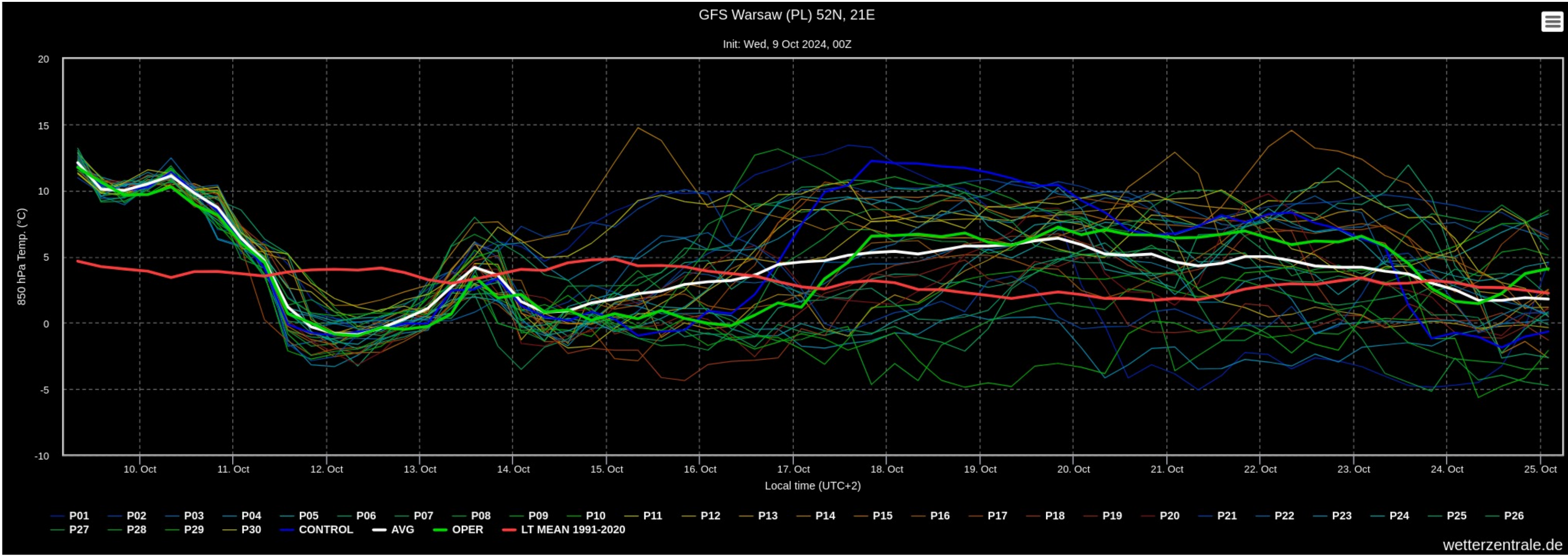


„The problem of deducing the climate from the governing equations”, 1964
(long term predictability – obcertainties in the governing equations)

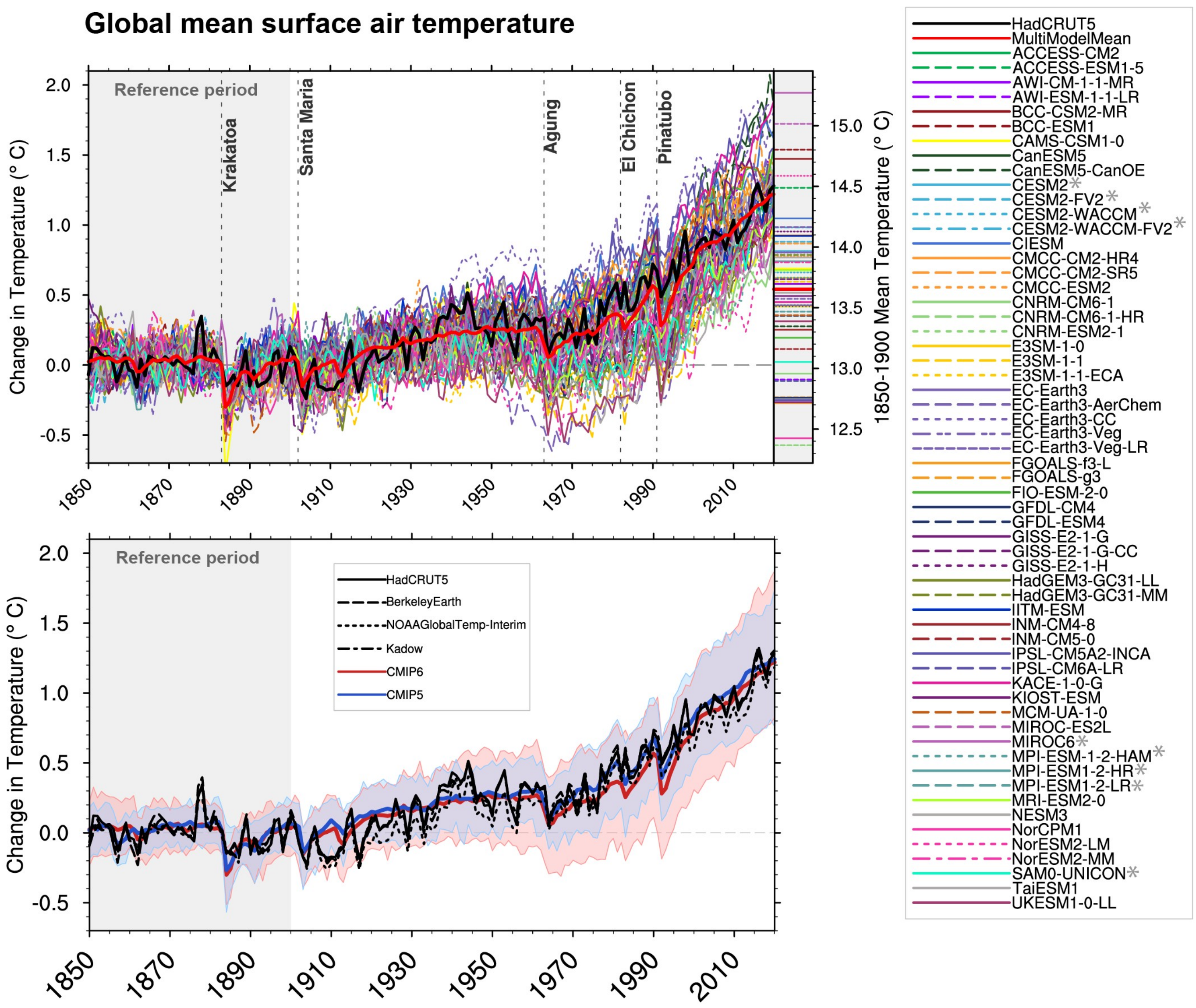
„Climatic change as a mathematical problem”, 1970
(unpredictable weather does not mean that climate is not predictable)

„Predictability – a problem partly solved”, 2006

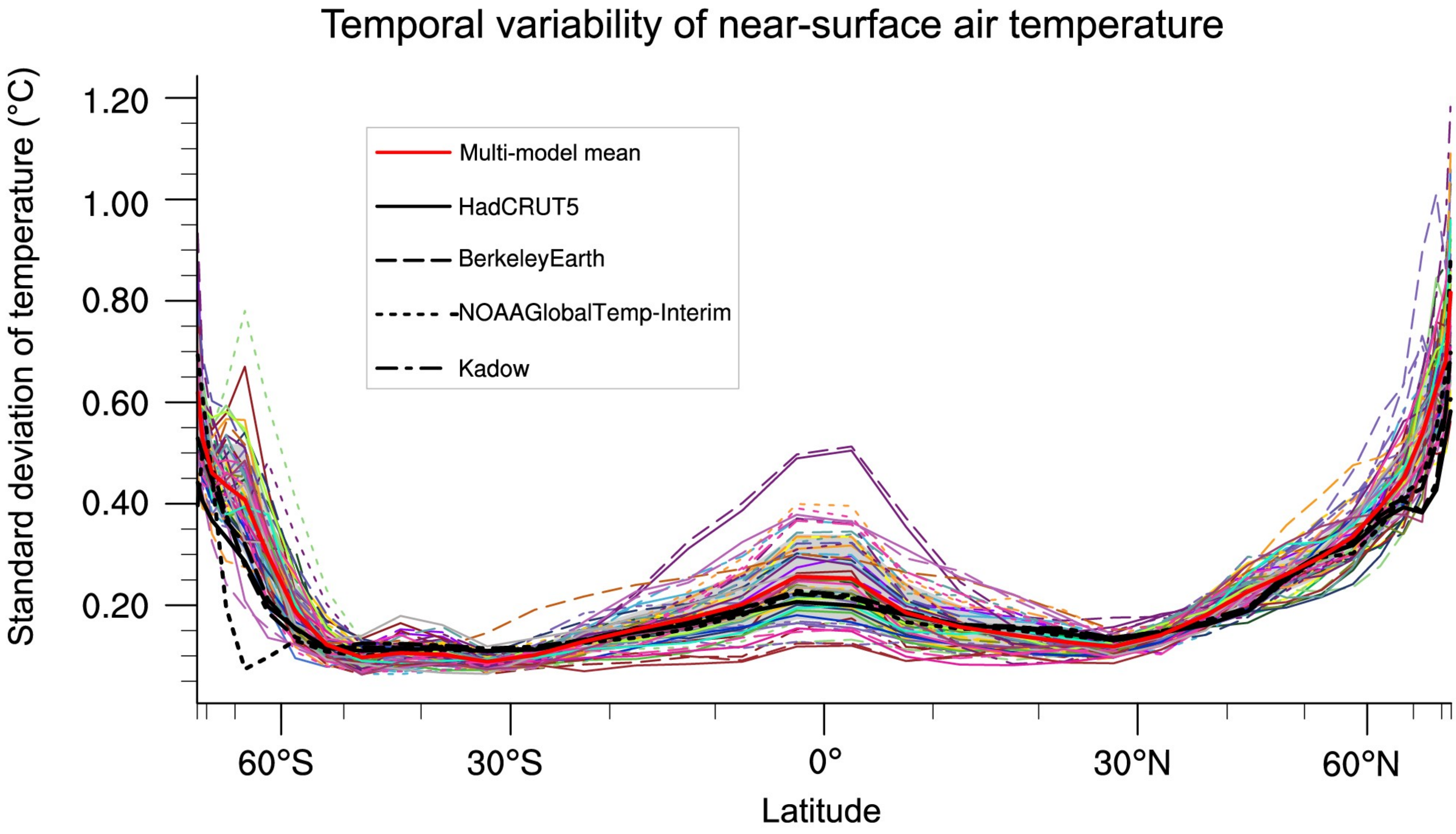
Predictability of weather and climate – illustration:



http://www.wetterzentrale.de/topkarten

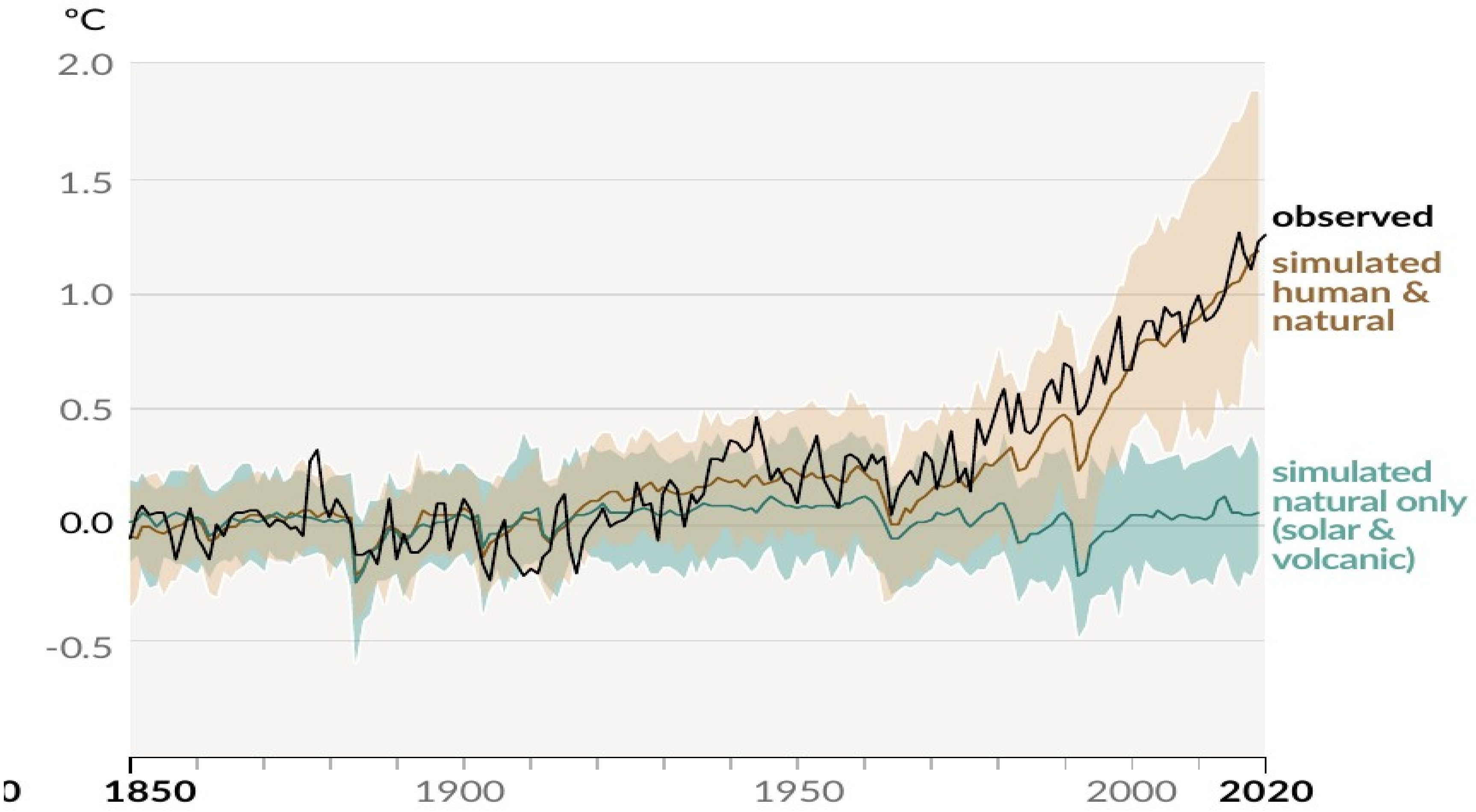


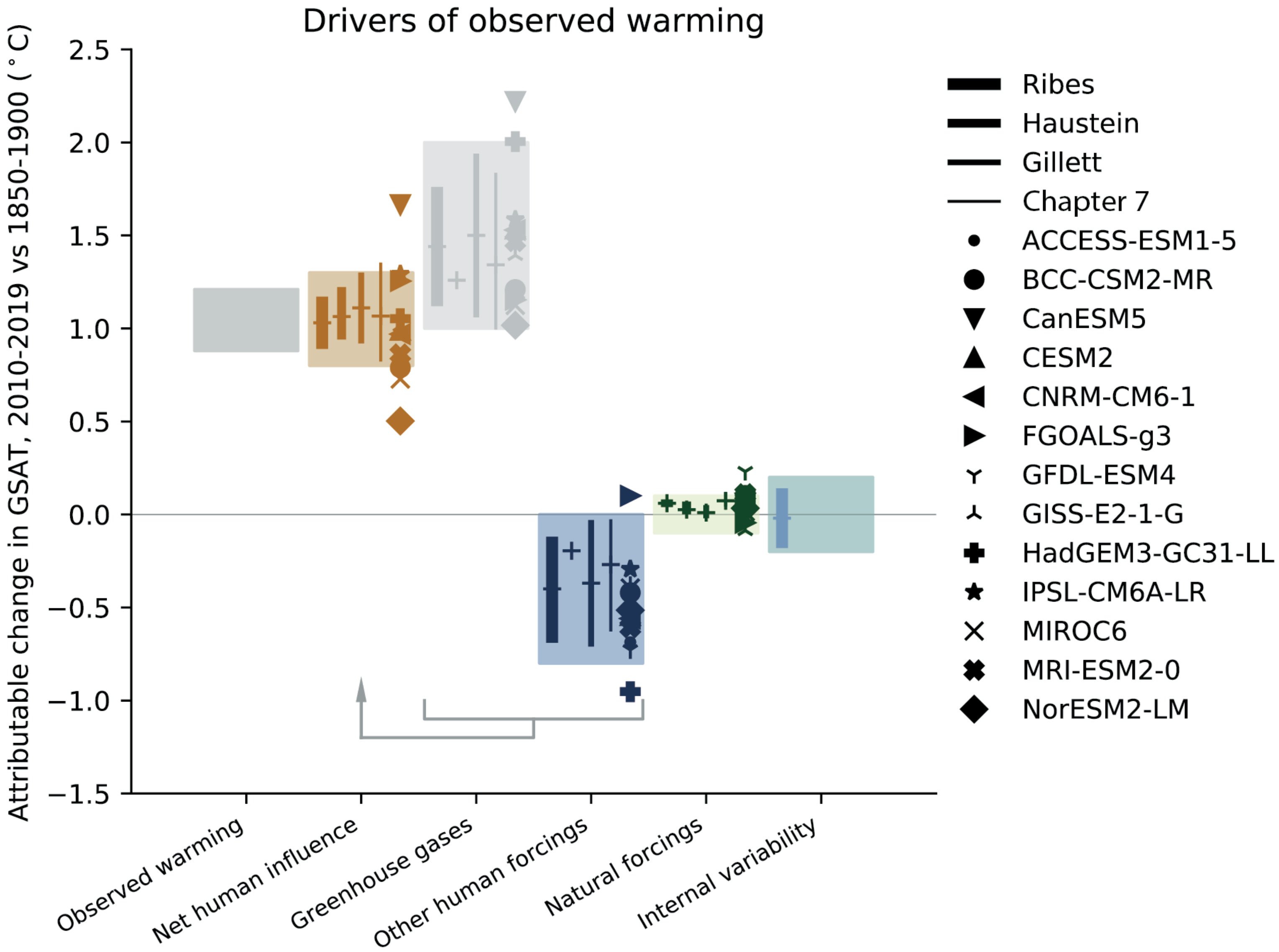
Global mean surface air temperature
Reference period
Krakatoa
Santa Maria
Agung
El Chichon
Pinatubo
Change in Temperature (° C)
1850-1900 Mean Temperature (° C)
HadCRUT5
MultiModelMean
ACCESS-CM2
ACCESS-ESM1-5
AWI-CM-1-1-MR
AWI-ESM-1-1-LR
BCC-CSM2-MR
BCC-ESM1
CAMS-CSM1-0
CanESM5
CanESM5-CanOE
CESM2*
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-f3-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
IITM-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
Reference period
HadCRUT5
BerkeleyEarth
NOAAGlobalTemp-Interim
Kadow
CMIP6
CMIP5
Change in Temperature (° C)

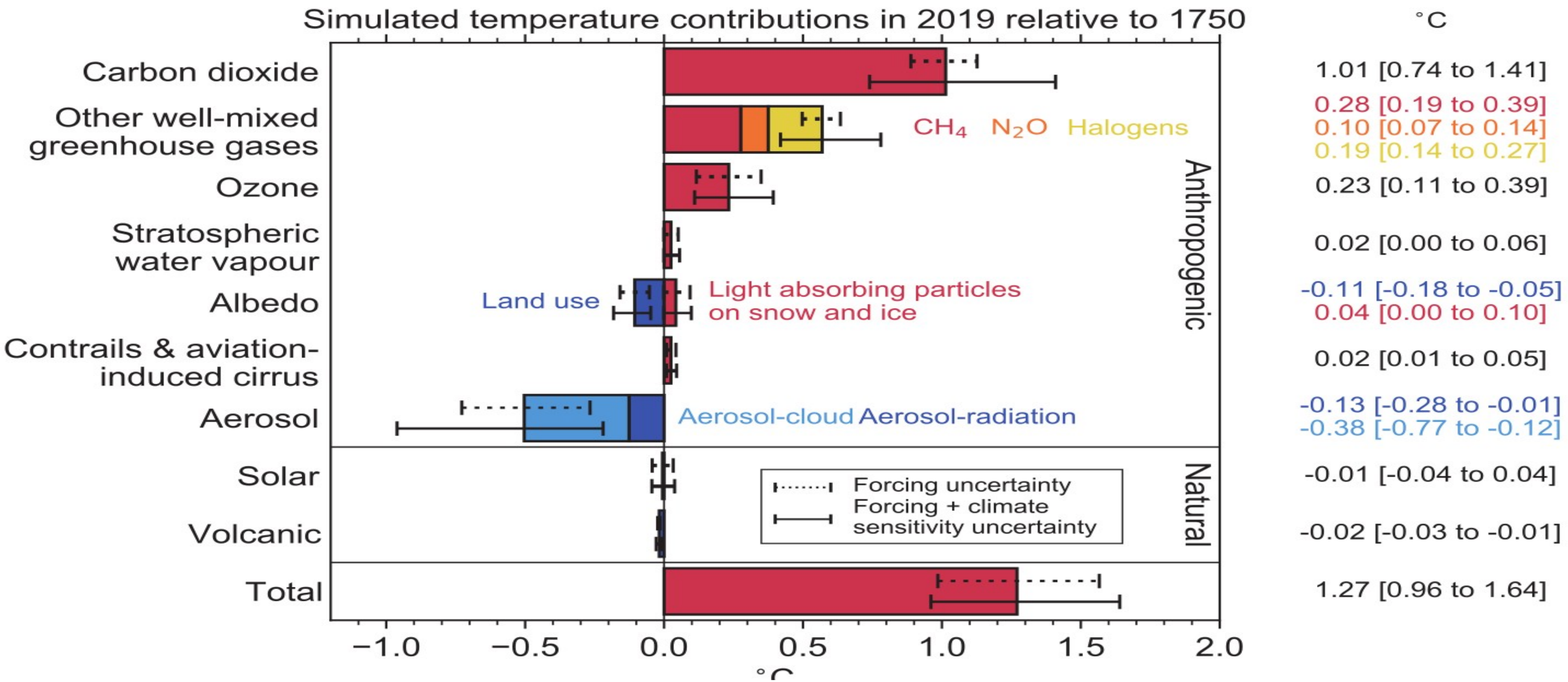


Temporal variability of near-surface air temperature
Standard deviation of temperature (°C)
1.20
1.00
0.80
0.60
0.40
0.20
Multi-model mean
HadCRUT5
BerkeleyEarth
NOAAGlobalTemp-Interim
Kadow
60°S
30°S
0°
30°N
60°N
Latitude

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
Attributable change in GSAT, 2010-2019 vs 1850-1900 (°C)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
Observed warming
Net human influence
Greenhouse gases
Other human forcings
Natural forcings
Internal variability
Ribes
Haustein
Gillett
Chapter 7
ACCESS-ESM1-5
BCC-CSM2-MR
CanESM5
CESM2
CNRM-CM6-1
FGOALS-g3
GFDL-ESM4
GISS-E2-1-G
HadGEM3-GC31-LL
IPSL-CM6A-LR
MIROC6
MRI-ESM2-0
NorESM2-LM



https://www.ipcc.ch/report/ar6/wg1/

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.

Knutti, R., 2008: Should we believe model predictions of future climate change?doi: 10.1098/rsta.2008.0169