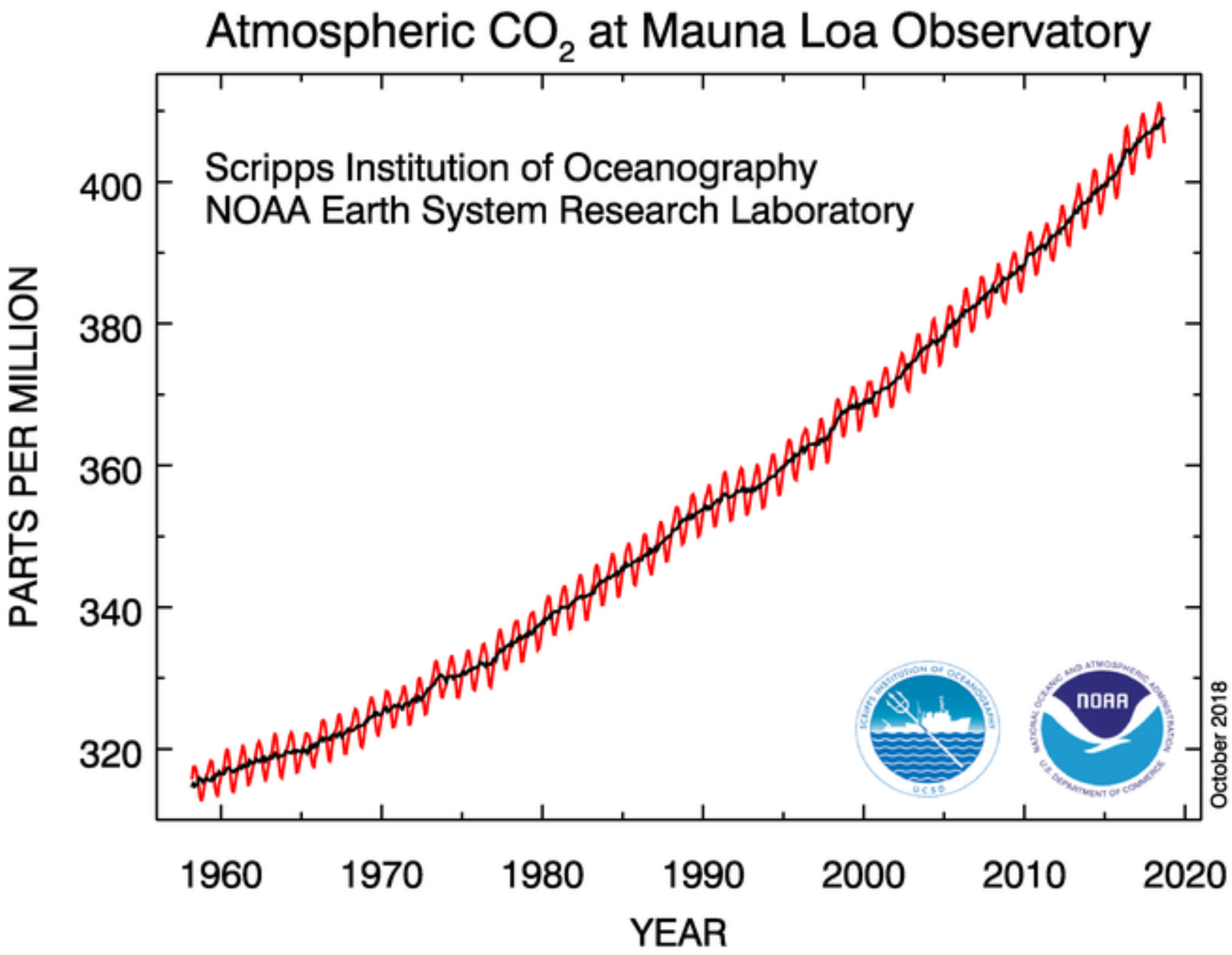
Experimental Evidences and Future Projections of Greenhouse Warming

Buildup of Greenhouse Gases

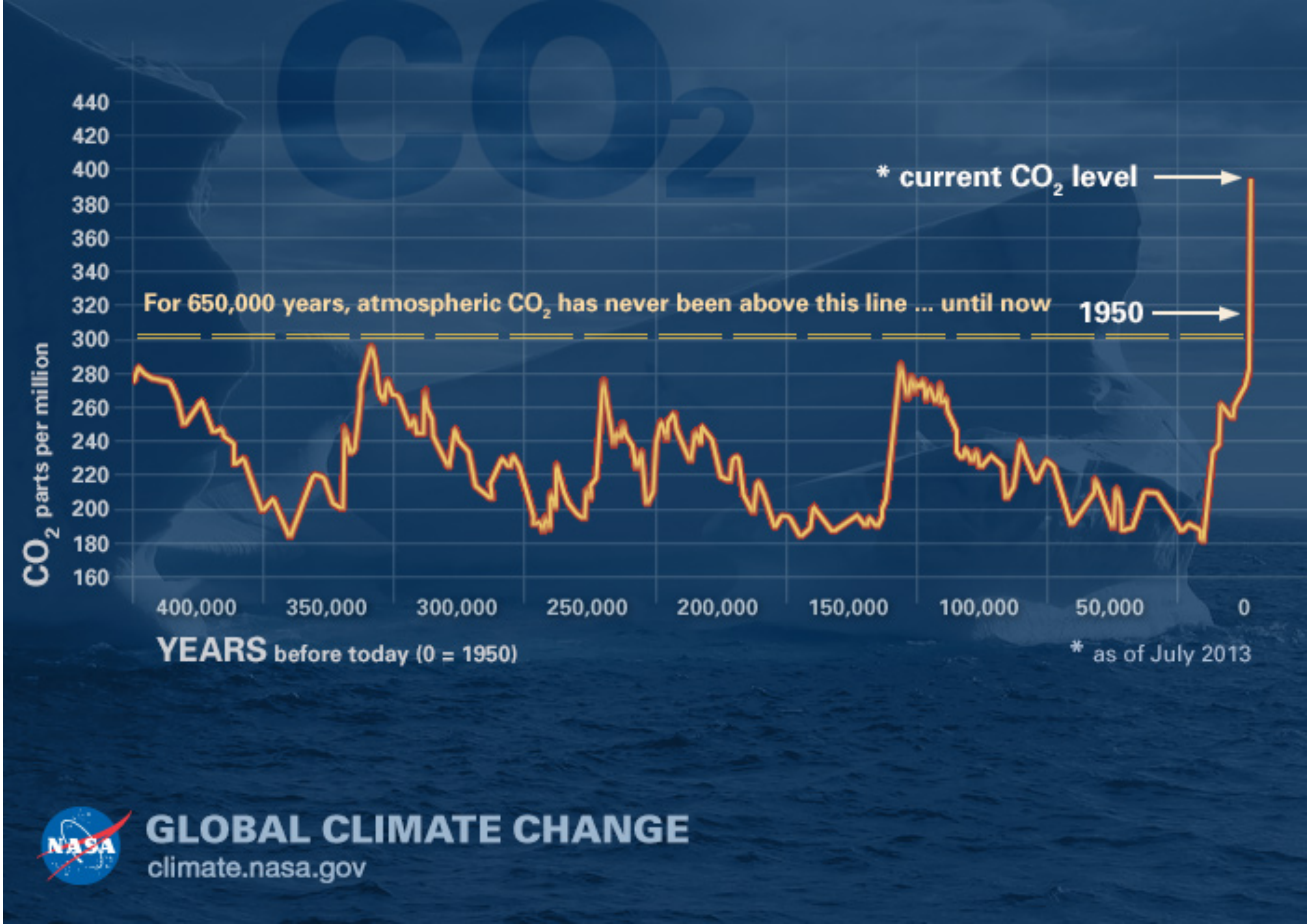
- CO_2 trend from experimental data: 1.3 ppmv/year (1958-2000) to 2ppmv/year recently



400 ppmv
(2018)
Antropocene !

Buildup of Greenhouse Gases

- Trend due to fossil fuel burning:
  - Analysis of gas bubbles trapped in ice cores extracted from the Greenland and Antarctic ice sheets indicates that atmospheric CO_2 started to increase around the time of the industrial revolution and it has roughly tracked the rate of growth of fossil fuel consumption since that time


CO2
* current CO2 level
1950
For 650,000 years, atmospheric CO2 has never been above this line ... until now
CO2 parts per million
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
YEARS before today (0 = 1950)
* as of July 2013
GLOBAL CLIMATE CHANGE
climate.nasa.gov

Buildup of Greenhouse Gases

- Trend due to fossil fuel burning:
  - Analysis of gas bubbles trapped in ice cores extracted from the Greenland and Antarctic ice sheets indicates that atmospheric CO_2 started to increase around the time of the industrial revolution and it has roughly tracked the rate of growth of fossil fuel consumption since that time
  - Atmospheric CO_2 concentrations are higher by several ppmv in the northern hemisphere, where most of the strongest carbon sources are located
  - Global decrease of atmospheric Oxygen (3 ppm/year) consistent with the hypothesis that the CO_2 being added to the atmosphere is a product of combustion, and ratio of C radioactive isotopes

Buildup of Greenhouse Gases

- We should also consider that:
  - On average, the atmosphere is taking up only about 50% of the carbon that is being released (present and future situation depends on Oceanic PH, which in turns depend on the amount of CO_2 absorbed).
  - Interaction with terrestrial biosphere (forest fires and forest clearings)
  - Total amount of CO_2 available: CO_2 emissions will eventually decline, if for no other reason than fossil fuel reservoirs will become depleted. The relaxation of atmospheric CO_2 concentrations back toward preindustrial levels depends on the uptake of carbon by the larger reservoirs in the Earth system, which takes place on a timescale much longer than that of the human induced buildup of CO_2 (e.g. timescale of a century for deep ocean)

Buildup of Greenhouse Gases

- Other GHGs besides CO_2:
  - CO_2 is not the only greenhouse gas whose atmospheric concentrations has been increasing during the industrial era: CH_4, N_2O, CFCs (now leveling off) and HFCs (replacement for CFCs in order to protect O_3 layer). Also, stratospheric O_3 has declined (CFCs induced- Ozone Hole effect) but tropospheric O_3 has increased due to increasing of urban air pollution
  - The impact, on a per molecule basis, of the increment of these other gases might be stronger than CO_2 due to the zone of the spectrum considered: we need to define a <u>Greenhouse Warming Potential (GWP)</u>

The **Global Warming Potential (GWP)** provides a simple measure of the radiative effects of emissions of various greenhouse gases, integrated over a specified time horizon, relative to an equal mass of CO_2 emissions.

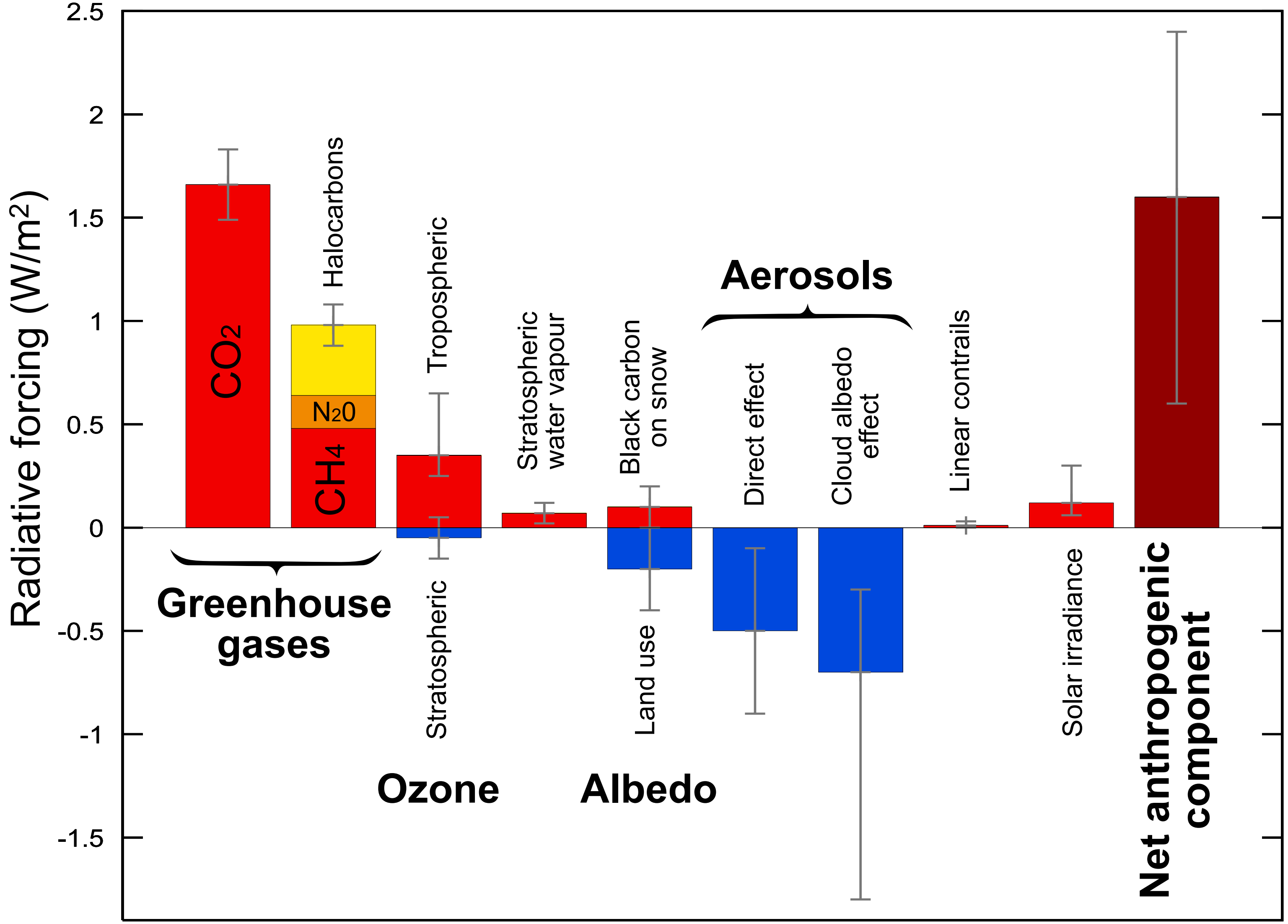
$$GWP_i = \frac{\int_{TR}^{TH} a_i C_i(t)\,dt}{\int_{TR}^{TH} a_{CO_2} C_{CO_2}(t)\,dt}$$

$\mathbf{a_i}$ is the instantaneous radiative forcing due to the release of a unit mass of trace gas, i, into the atmosphere, at time **TR**,

$\mathbf{C_i}$ is the amount of that unit mass remaining in the atmosphere at time, t, after its release and **TH** is TR plus the time horizon over which the calculation is performed

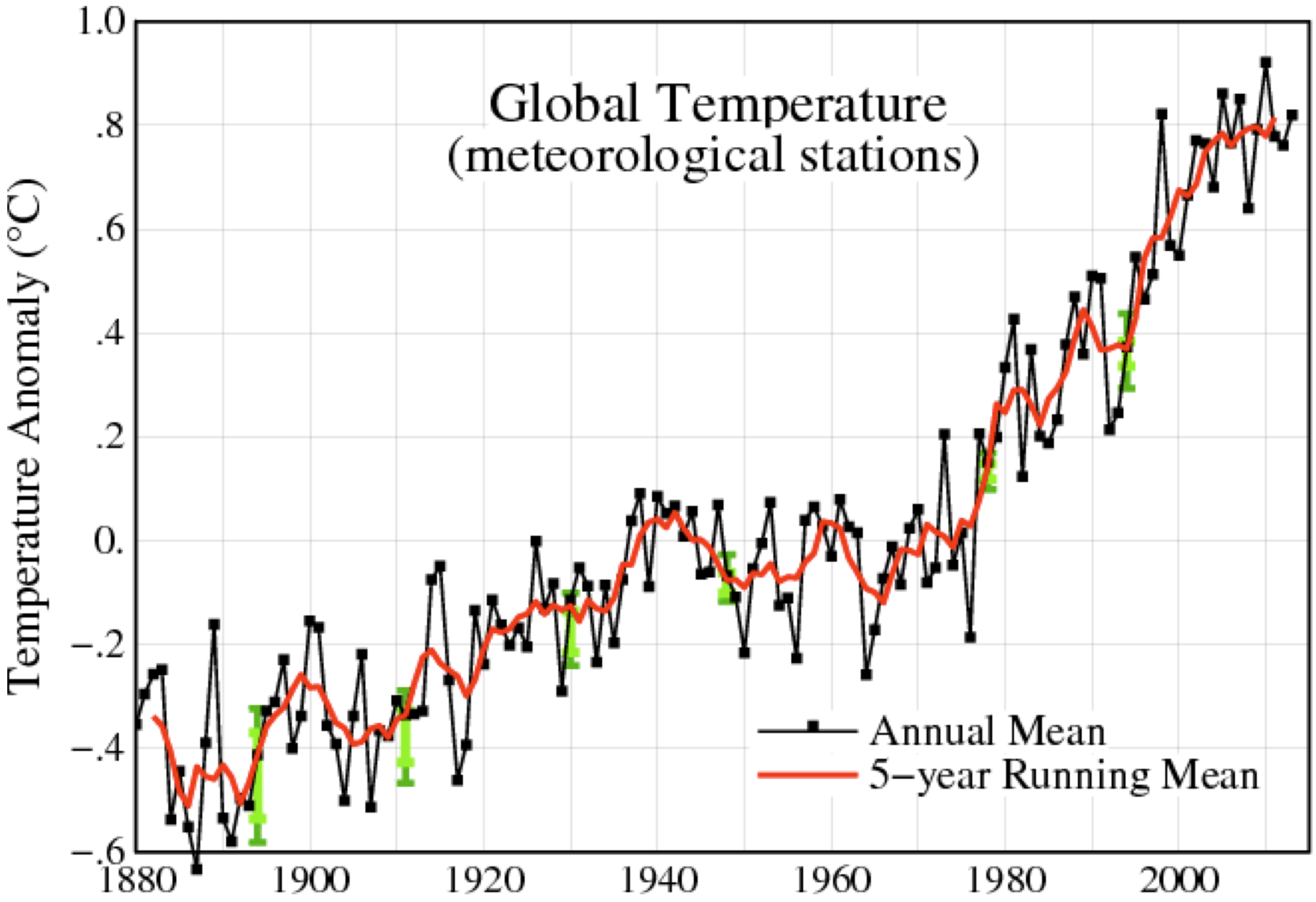
% DF	Gas name	Chemical formula	Lifetime (years)	Global warming potential (GWP) for given time horizon		
				20-yr	100-yr	500-yr
65	Carbon dioxide	CO_2	30-95	1	1	1
17	Methane	CH_4	12	72	25	7.6
6	Nitrous oxide	N_2O	114	289	298	153
12	CFC-12	CCl_2F_2	100	11 000	10 900	5 200
	HCFC-22	$CHClF_2$	12	5 160	1 810	549

Radiative forcing components

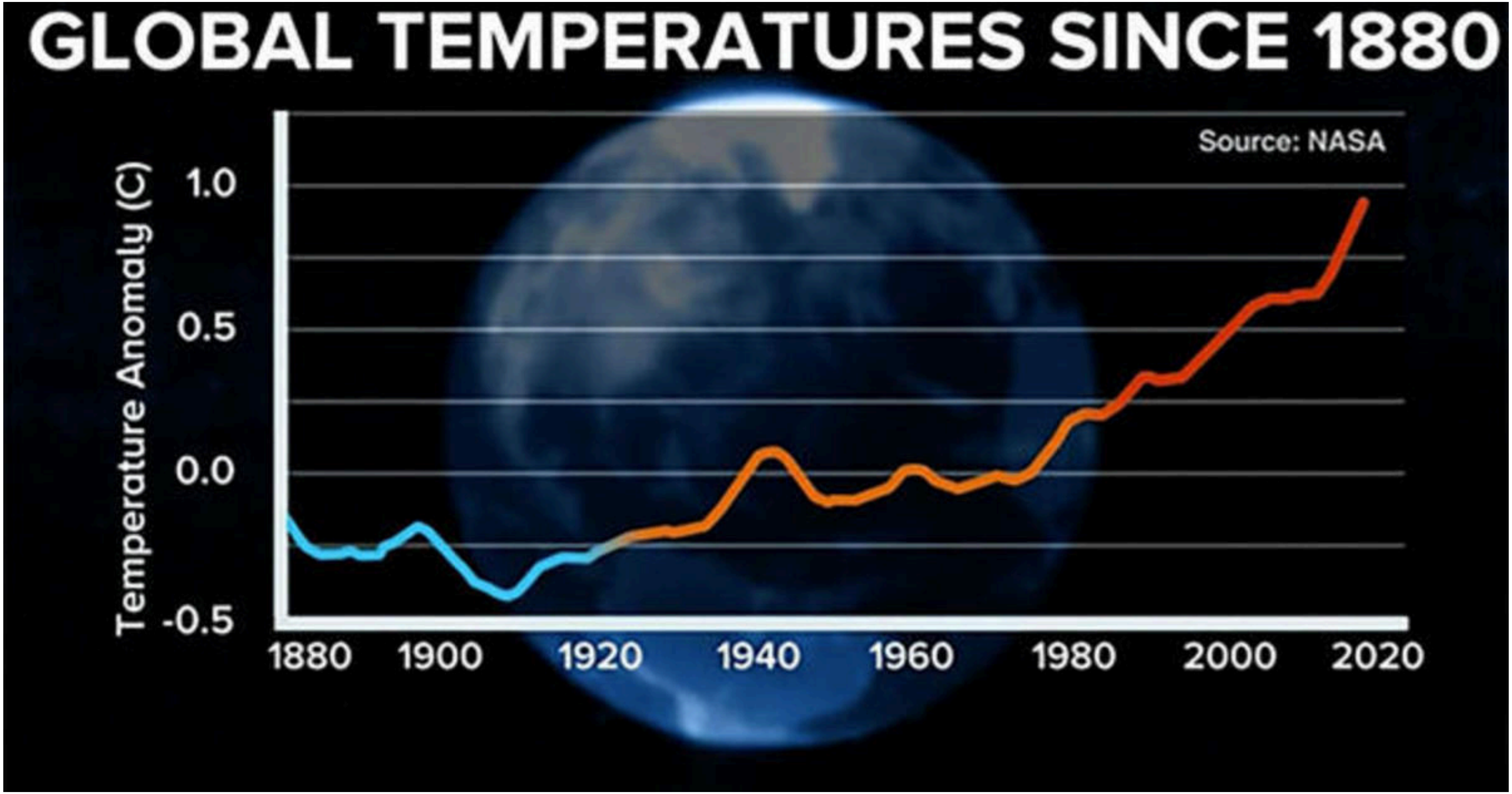


Anthropogenic (Human-Induced) Greenhouse Warming

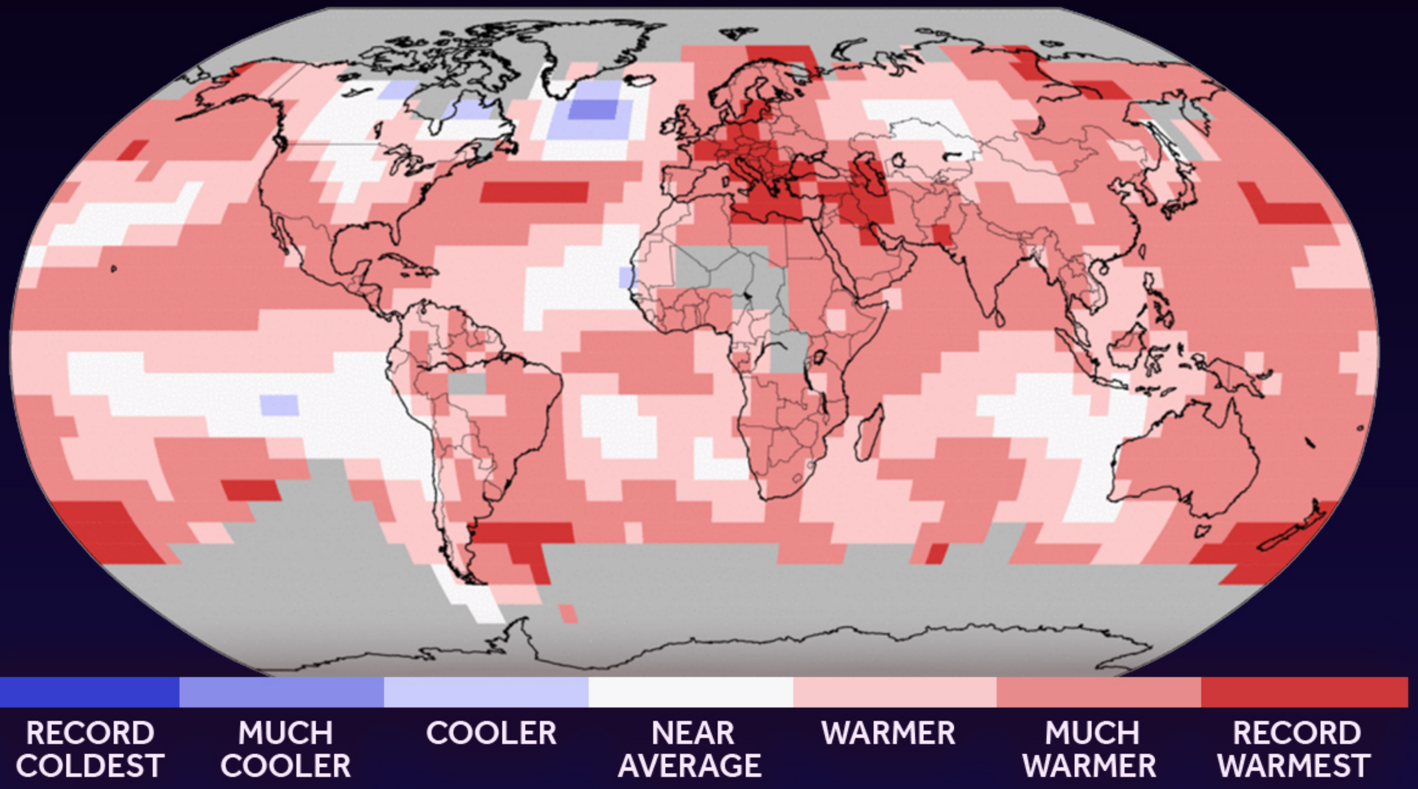
- **Experimental evidences**: warming is reflected in records of many **variables**: surface air temperature over both land and ocean, the retreat of mountain glaciers and the extension of arctic ice, the rise in global sea level and Ph of the ocean



Source: NASA Goddard Space Flight Center http://data.giss.nasa.gov/gistemp/graphs_v3/


GLOBAL TEMPERATURES SINCE 1880
Source: NASA
Temperature Anomaly (C)
1.0
0.5
0.0
-0.5
1880
1900
1920
1940
1960
1980
2000
2020

2018 GLOBAL TEMPERATURE
4TH HOTTEST YEAR ON RECORD



Source: NOAA/NCEI Climate at a Glance
Data as of 2/6/2019

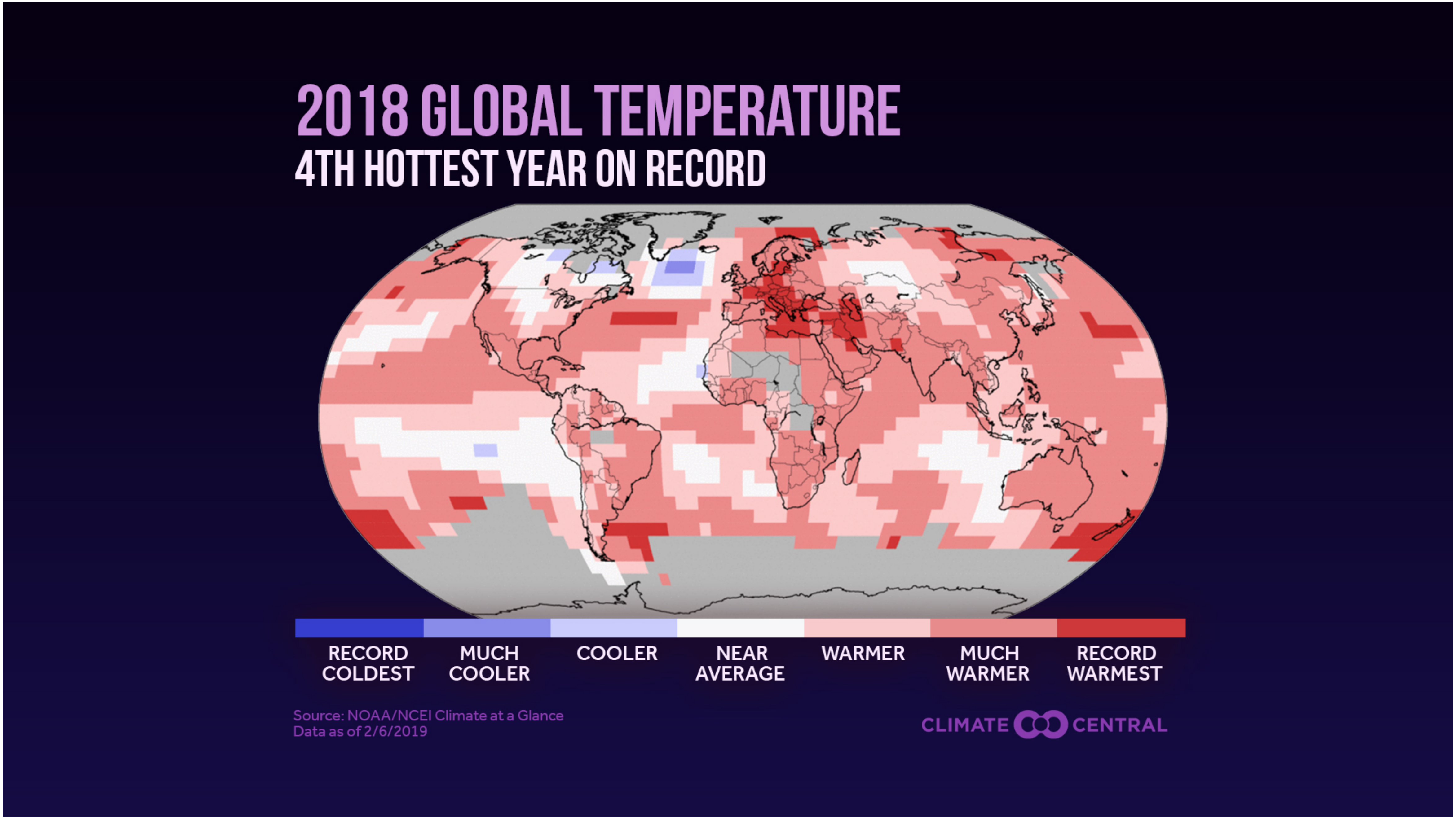
CLIMATE CENTRAL

Anthropogenic (Human-Induced) Greenhouse Warming

- Experimental evidences: warming is reflected in records of many **variables**: surface air temperature over both land and ocean, the retreat of mountain glaciers and the extension of arctic ice, the rise in global sea level and Ph of the ocean, and in a variety of other **indicators** such as melt and freeze dates on lakes and rivers, blooming dates of flowering plants, timing of bird migrations, and the poleward extent of plant, insect, and animal species.
- All considered, based on previous available data, the rate of warming observed during the 20th century and up to present days <u>appears to be unprecedented in the past millennium</u>.

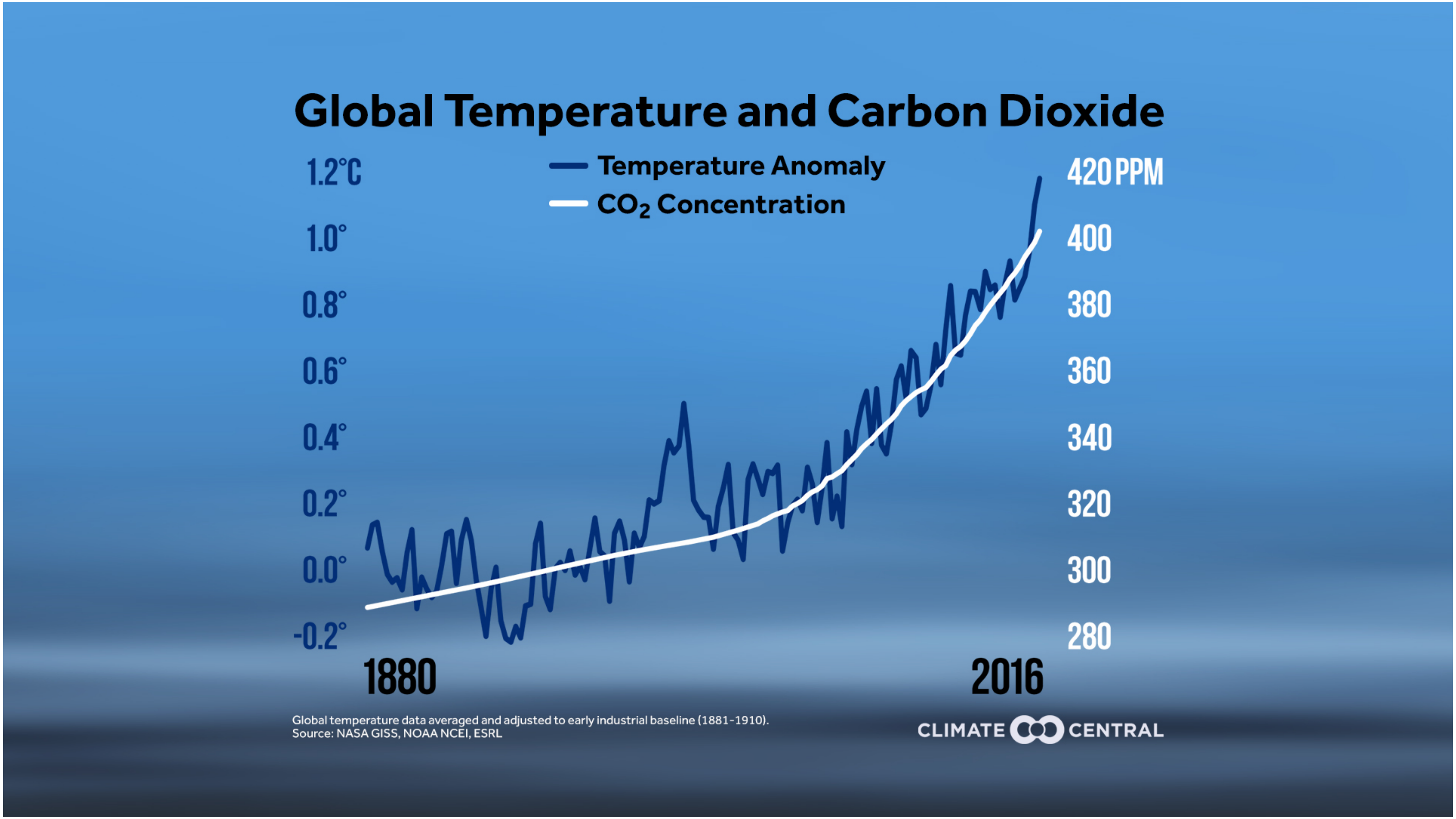
Anthropogenic (Human-Induced) Greenhouse Warming

- The observed warming has been not uniform either in space or in time. I.E.: Arctic has warmed at different rates in time and Antarctic peninsula has warmed way more then the interion of the Antarctic continent.


2018 GLOBAL TEMPERATURE
4TH HOTTEST YEAR ON RECORD
RECORD COLDEST
MUCH COOLER
COOLER
NEAR AVERAGE
WARMER
MUCH WARMER
RECORD WARMEST
Source: NOAA/NCEI Climate at a Glance
Data as of 2/6/2019
CLIMATE CENTRAL

Anthropogenic (Human-Induced) Greenhouse Warming

- The observed warming has been not uniform either in space or in time. I.E.: Arctic has warmed at different rates in time and Antarctic peninsula has warmed way more then the interion of the Antarctic continent.
- Differentiating between human induced effect and natural variability of the Earth Climate System is the key of the analysis and is difficult from a modelling/data analysis point of view.
- Natural variability on decadal timescales has probably been responsible for some of the regional differences and the variation in time of the warming trends, but the warming of the last 30/40 years has been so pronounced and the cumulative warming since 1900 so large that the only plausible and widely supported explanation is that they are indications of a **response to the buildup of greenhouse gases**.


Global Temperature and Carbon Dioxide
Temperature Anomaly
CO₂ Concentration
1.2°C
1.0°
0.8°
0.6°
0.4°
0.2°
0.0°
-0.2°
420 PPM
400
380
360
340
320
300
280
1880
2016
Global temperature data averaged and adjusted to early industrial baseline (1881-1910).
Source: NASA GISS, NOAA NCEI, ESRL
CLIMATE CENTRAL

Anthropogenic (Human-Induced) Greenhouse Warming

- Projections of future Warming. Various approaches:
- Use present equilibrium state and past history of the Earth system to estimate the **(climate) sensitivity** of global mean surface air temperatures to changes in radiative forcing

Anthropogenic (Human-Induced) Greenhouse Warming

- Projections of future Warming. Various approaches:
- Use numerical models:
  - (A) either globally averaged, one-dimensional, radiative-convective equilibrium models with assumptions concerning water vapor, cloud and ice-albedo feedbacks -> (**EBMs** of various complexity)
  - (B) three-dimensional, coupled atmosphere-ocean-cryosphere-land surface models that explicitly compute water vapor concentrations, ocean temperatures and currents and include parameterizations of clouds, sea ice, snow cover, land vegetation, and soil wetness.

Advantages of 3D coupled model in GHG warming projections

- Test bed for improving our understanding of boundary layer, cloud, cryosphere, biospheric processes that have a bearing on climate sensitivity
- Various components of the atmosphere and the Earth system can interact in ways that cannot be investigated empirically or with the use of radiative-convective models. For example, they allow for the possibility of changes in the tropospheric temperature lapse rate, high or low cloud cover, and surface wind speed in different parts of the world, any of which might have implications for climate sensitivity.

Advantages of 3D coupled model in GHG warming projections

- more comprehensive predictions of how climate would change in response to a prescribed forcing, with regionally and seasonally specific (as opposed to globally and annually averaged) temperature projections, as well as estimates of patterns of changes in rainfall, snowfall, cloudiness, wind, and the statistics of severe weather events such as tropical cyclones.
- framework for investigating the impacts of climate change on the Earth system as a whole (e.g., sea level rise, changes in streamflow statistics for various watersheds, desertification of marginally arid regions, and changes in the range of various plant and animal species and diseases).

Simulations of GHG warming response varies from model to model but tends to be in the same overall range (similar to what calculated with of radiative/convective models) and shares a number of (physically reasonable) **common characteristics**:

- a polar amplification of the warming, particularly during winter and spring due, in large part, to the positive feedback from the cryosphere. This tendency is also clearly evident in historical temperature records from paleoclimate reconstructions
- a gradual buildup of the warming due to the large thermal inertia of the oceans

- a more rapid warming over the continents than over the oceans during the early stages of the warming.
- an increase in atmospheric precipitable water, leading to heavier precipitation events (particularly during winter over higher latitudes where the predicted warming is greatest).
- earlier spring snowmelt and enhanced evaporation rates, leading to drying of some continental regions during summer. In such regions, positive feedback from the biosphere amplifies the rise in daytime temperatures

- a rise in global sea level due to the thermal expansion of sea water as it warms (20–40 cm during the 21st century, compared to 15 cm during the 20th century). Present models are not capable of predicting the extent of the additional contribution dominated by the melting of the continental ice sheets and alpine glaciers.
- a reduced rate of formation of North Atlantic deep water in response to the freshening of the surface waters as precipitation increases and ice melts

Overall considerable uncertainty in cryosphere response to global warming (e.g. arctic ices coverage and rate/amount of melting) -→ implication on risk of "**Climate Surprises**"