# Climate Change – What we know and what not

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EPS-SIF International School on Energy, July 2021

(Note: due to unclear copyright situations, some of the figures have been removed from the original presentation, but references are given)

# Content



- Basics
  - What is climate?
  - Atmospheric energy balance
- The current state of climate research
  - Observations
  - Causes of climate change
  - Models
  - Projections

*„Climate is what you expect,*
*weather is what you get.“*

(Robert A. Heinlein, 1907-1988, amerikanischer Schriftsteller)

# Alexander von Humboldt: Climate

*"The word climate, however, denotes first and foremost a specific property of the atmosphere, but this property depends on the perpetual interactions of a fully and deeply moving, of currents of contrasting temperatures furrowed sea surface with the heat-radiating dry Earth, which is manifoldly structured, elevated, coloured, naked, or covered with woods and herbs."*

*A. v. Humboldt, "Kosmos – Entwurf einer physischen Weltbeschreibung ", 1845-1862, translated by H. Schmidt*

(Picture of A. v. Humboldt)

# Climate as a probability distribution

(time series and pdf of some climate variable)

# The atmospheric energy budget

(Fig. 7 from Kiehl and Trenberth: Earth's annual global mean energy budget, Bulletin of the American Meteorological Society, 1997)

# The IPCC


IPCC: Intergovernmental Panel on Climate Change

Established in 1988 by WMO und UNEP

Organized in 3 working groups:

- WG I assesses the physical scientific basis of the climate system and climate change.
- WG II assesses the vulnerability of socio-economic and natural systems to climate change.
- WG III assesses options for mitigating climate change.

About every 6 or 7 years reports of the working groups are published. Hundereds of scientists are involced in this exercise. The „Fifth Assessement Report“ (AR5) was published in 2013/14. The publication series of AR6 reports will start on August, 9, 2021 with WG1.

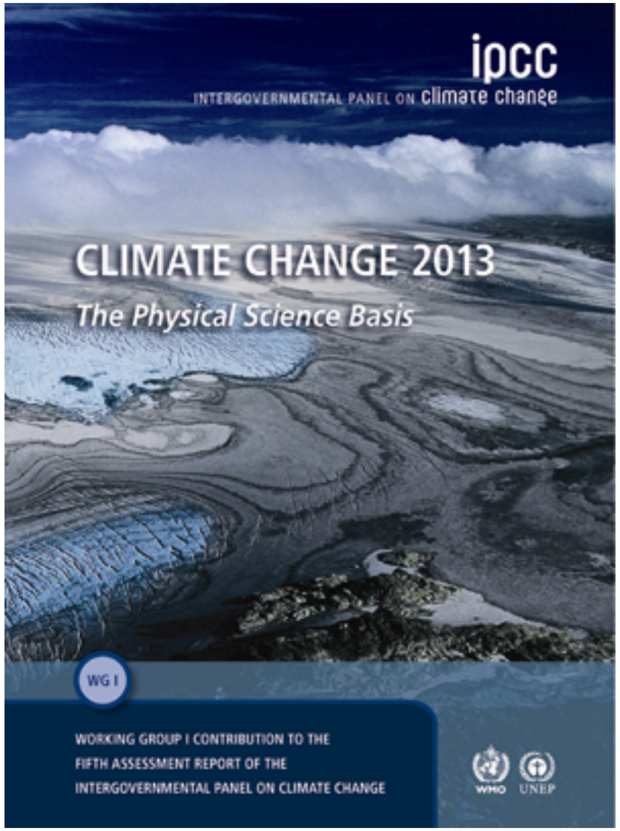
Downloads: www.ipcc.ch

# The current state of climate research



WORKING GROUP I CONTRIBUTION TO THE IPCC AR5
CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS

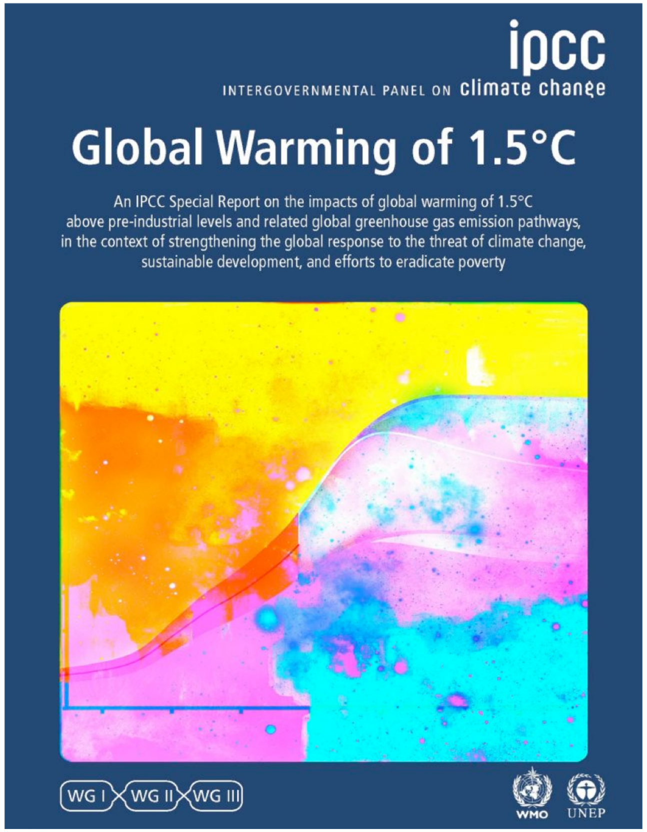
(http://www.ipcc.ch)



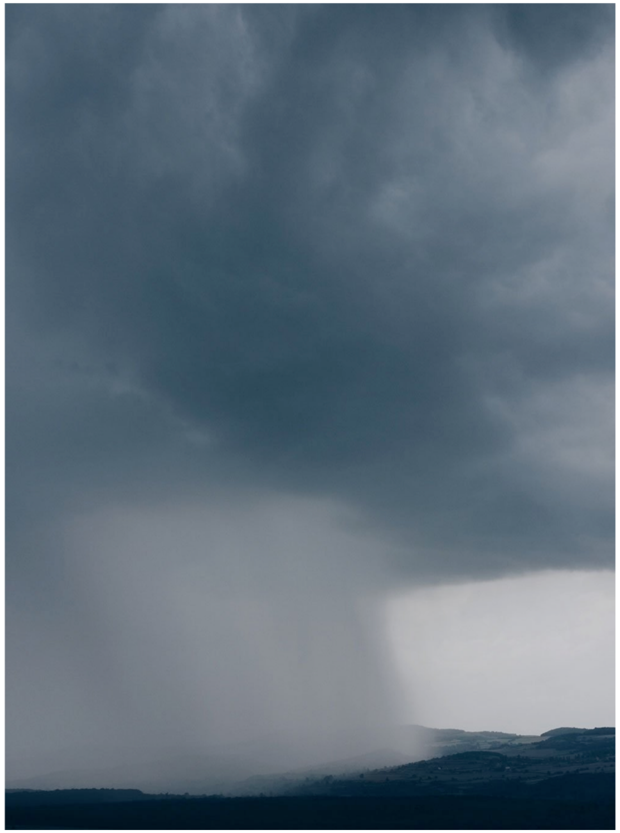

IPCC Special Report on Global Warming of 1.5 °C

(published in 2018)

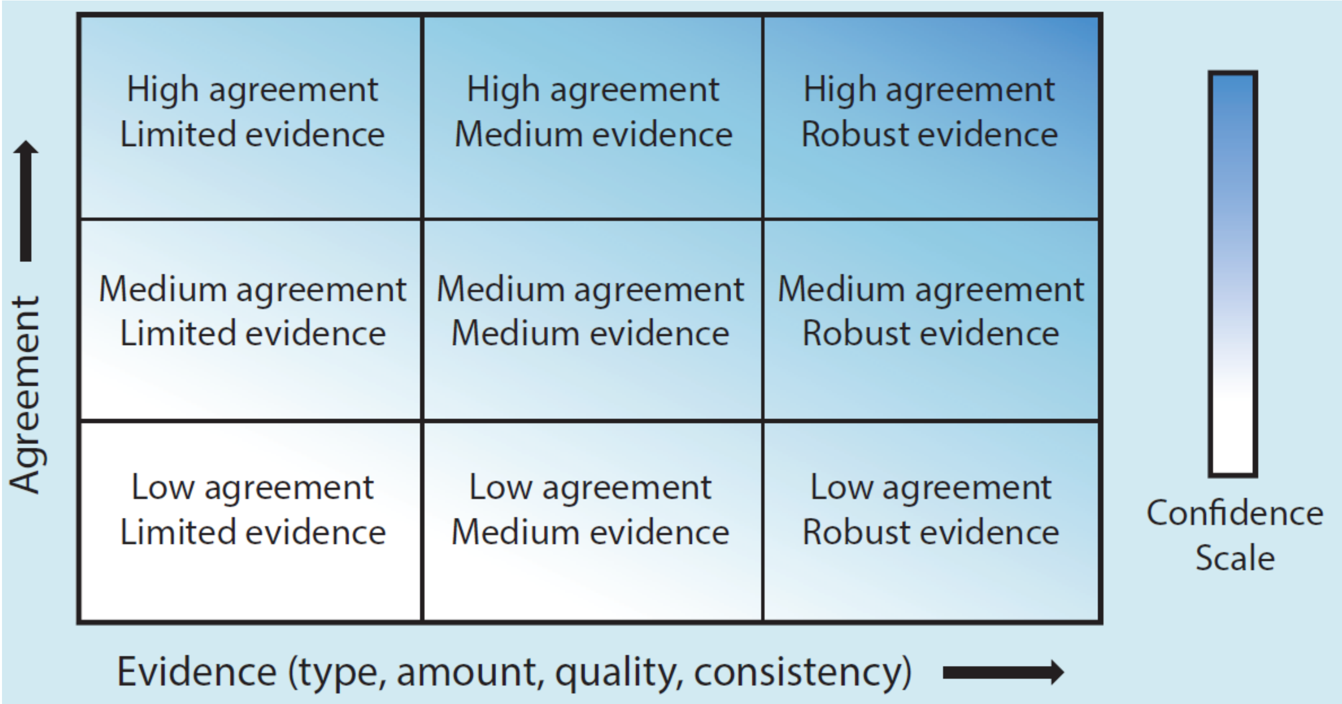
(http://www.ipcc.ch)




WORKING GROUP I CONTRIBUTION TO THE IPCC AR6
(expected to be published August, 9, 2021)



# Uncertainties – The language of the IPCC




The following terms have been used to indicate the assessed likelihood, and typeset in italics:

| **Term*** | **Likelihood of the outcome** |
|---|---|
| *Virtually certain* | 99–100% probability |
| *Very likely* | 90–100% probability |
| *Likely* | 66–100% probability |
| *About as likely as not* | 33–66% probability |
| *Unlikely* | 0–33% probability |
| *Very unlikely* | 0–10% probability |
| *Exceptionally unlikely* | 0–1% probability |

* Additional terms (*extremely likely*: 95–100% probability, *more likely than not*: >50–100% probability, and *extremely unlikely*: 0–5% probability) may also be used when appropriate.

(IPCC AR5, WG1, TS, 2013)

# Observed climate change

# Global mean surface temperatures 1880-2020

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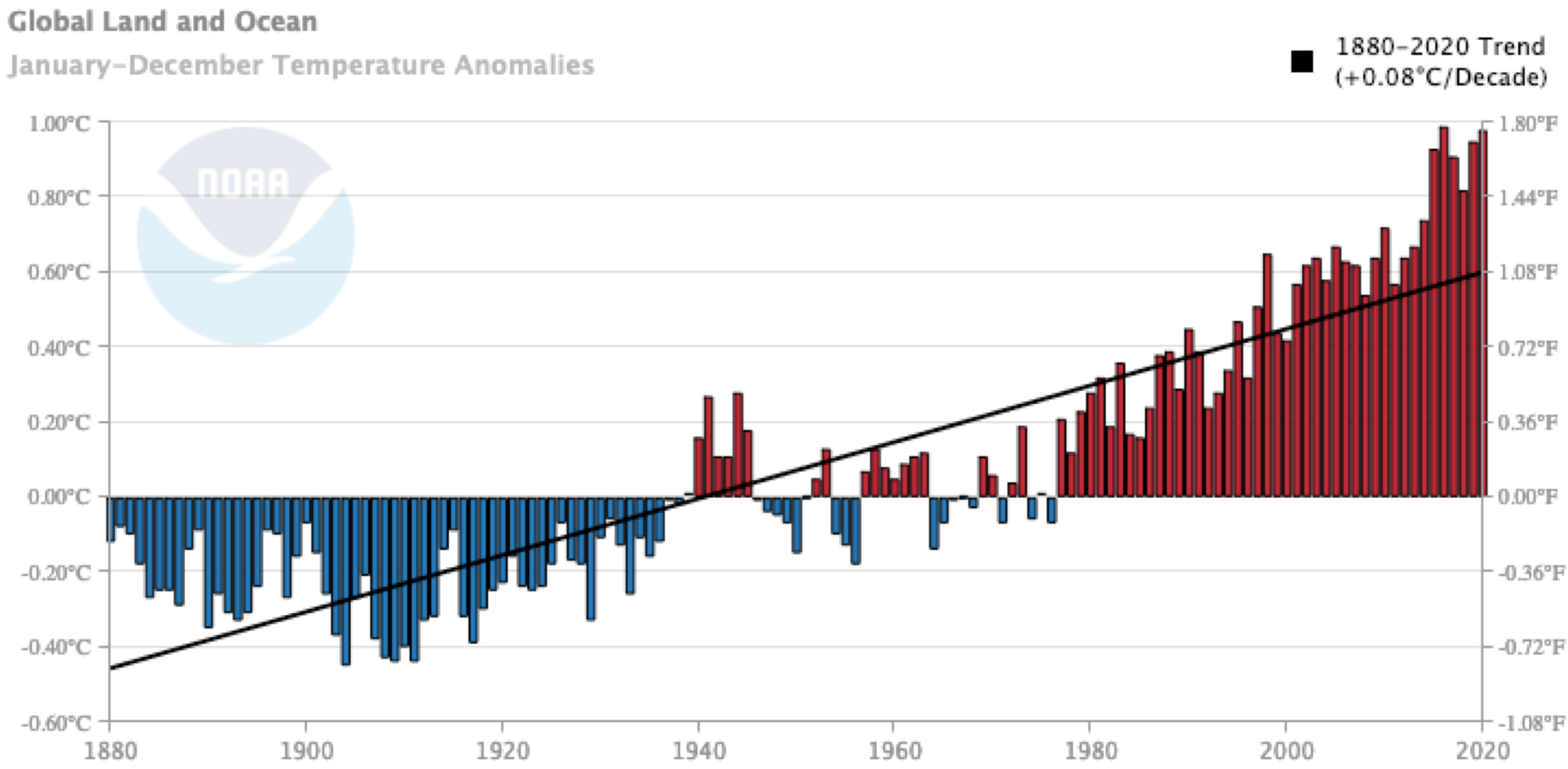
für Meteorologie




*(NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published July 2021, retrieved on July 18, 2021 from* [https://www.ncdc.noaa.gov/cag/](https://www.ncdc.noaa.gov/cag/)*)*

# Warming over oceans and land

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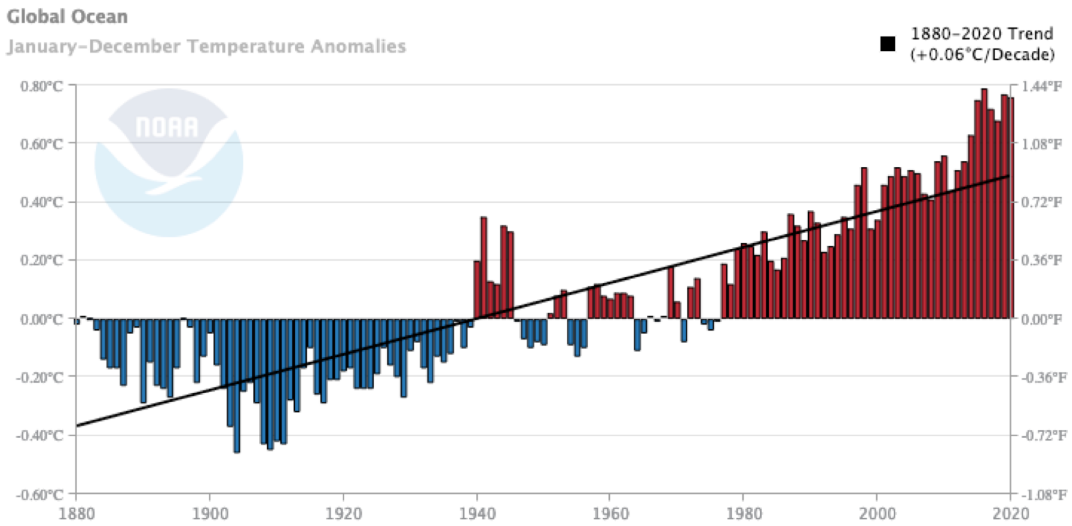
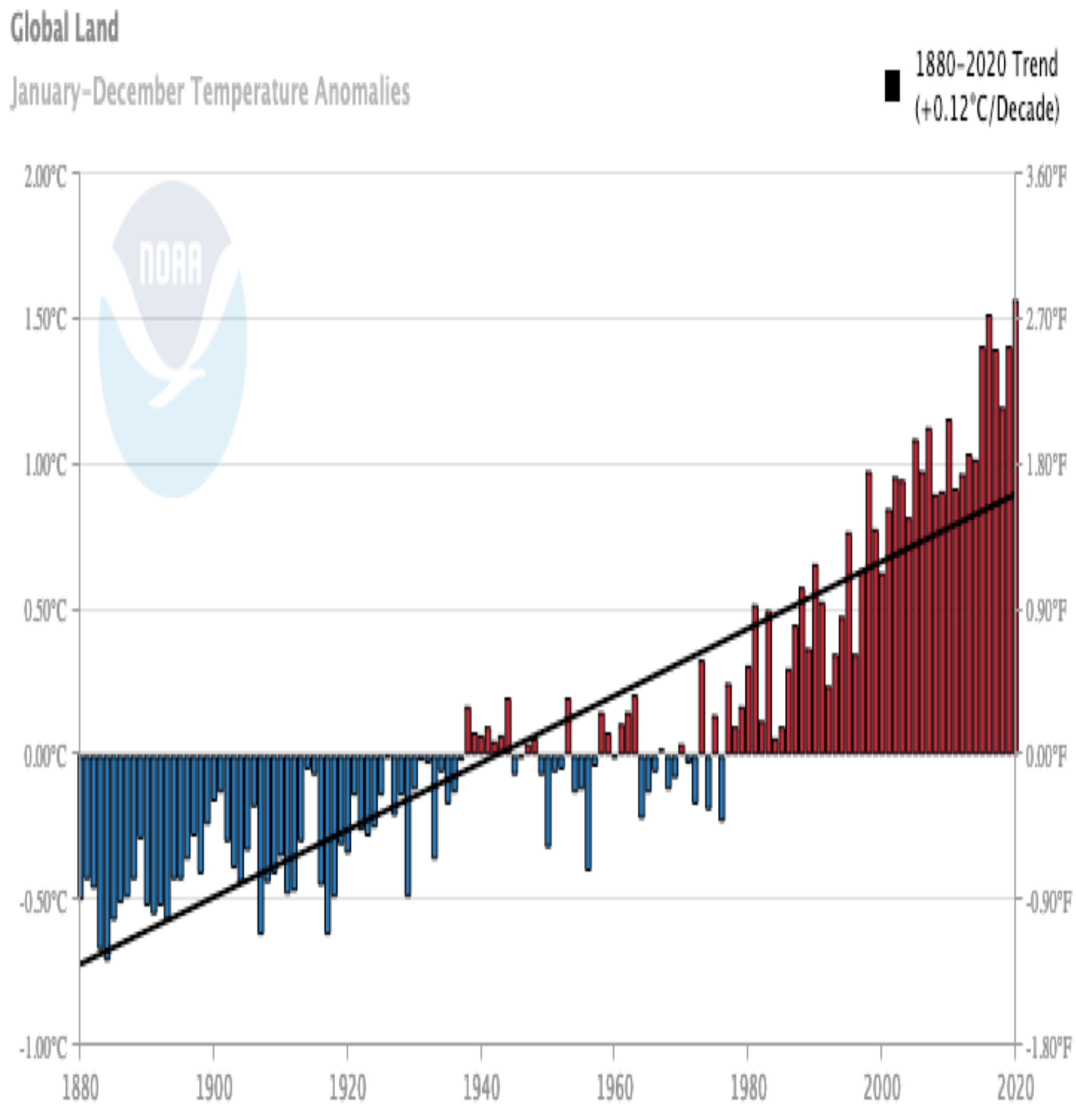
für Meteorologie




(*NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published July 2021, retrieved on July 18, 2021 from https://www.ncdc.noaa.gov/cag/*)

# Why warming over land is larger than over oceans?

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(Fig. 7 from Kiehl and Trenberth: Earth's annual global mean energy budget, Bulletin of the American Meteorological Society, 1997)

Increased downward infrared radiation at the surface has to be compensated by surface warming which leads to increased longwave emission of the surface and increased latent and sensible heat transfer. However, evaporation is limited over dry surfaces.

# Global temperature increase, 1850-2020, max-min range ≈ 1.5℃

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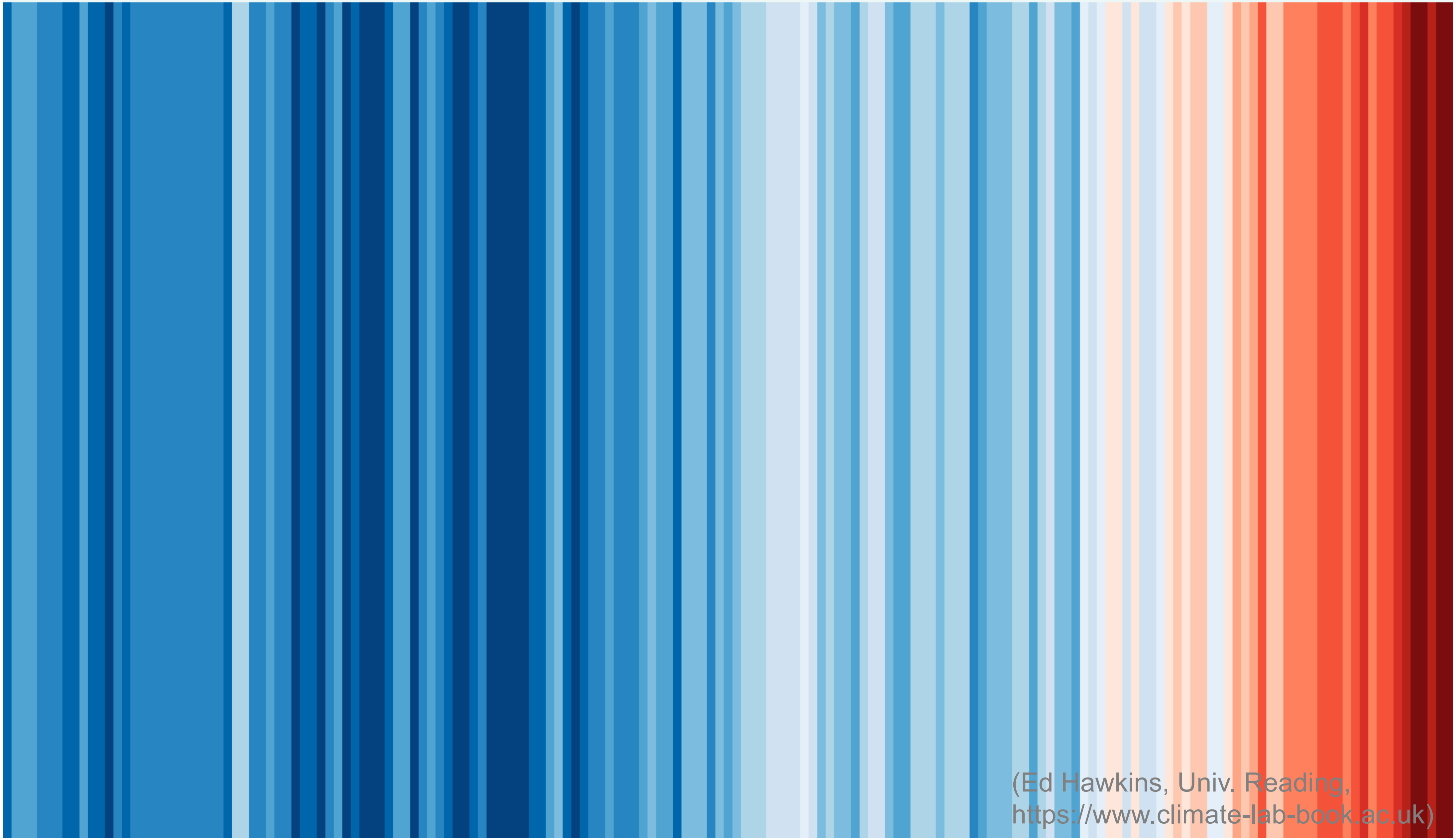
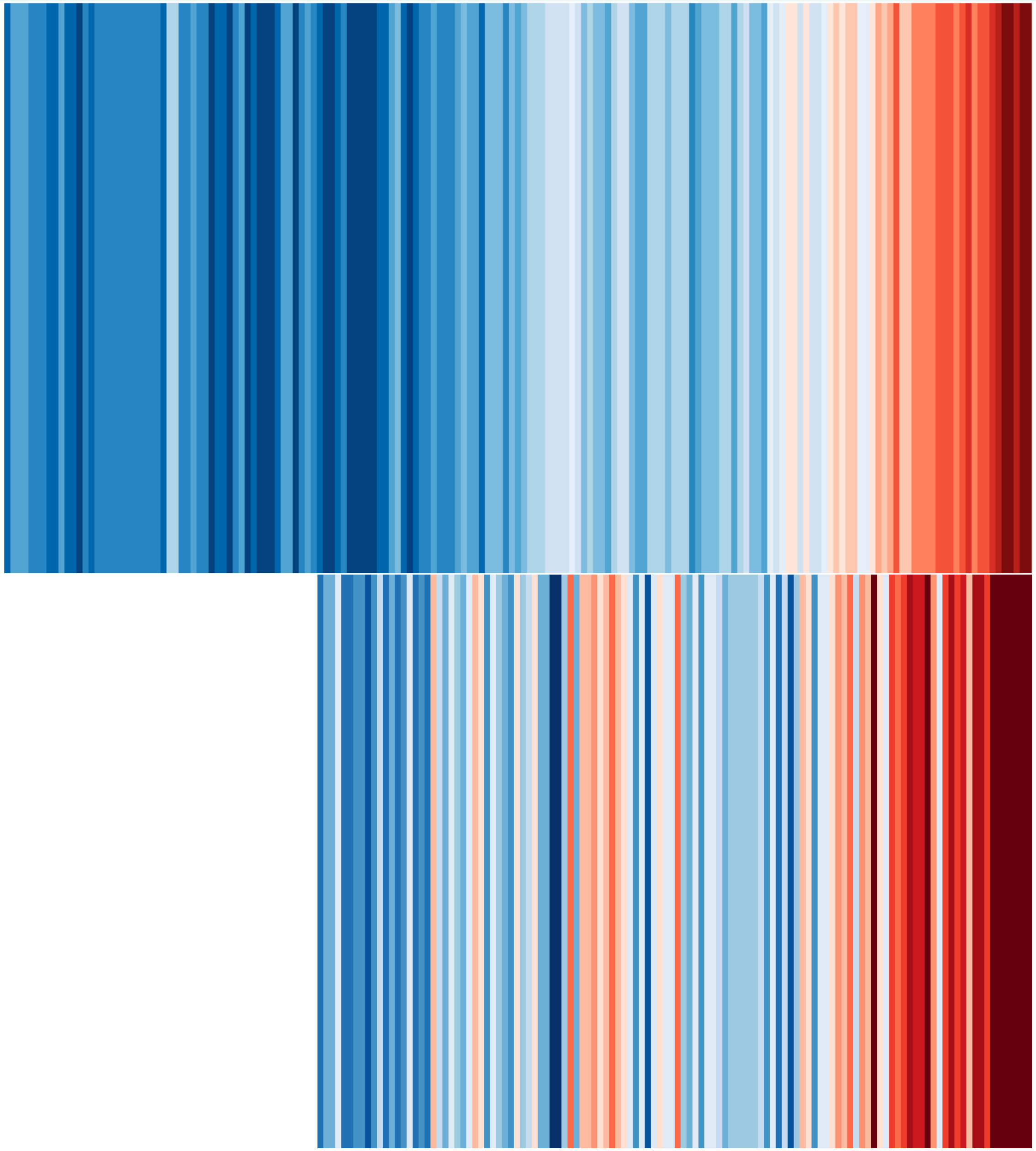


# Temperature increase, global vs. Italy

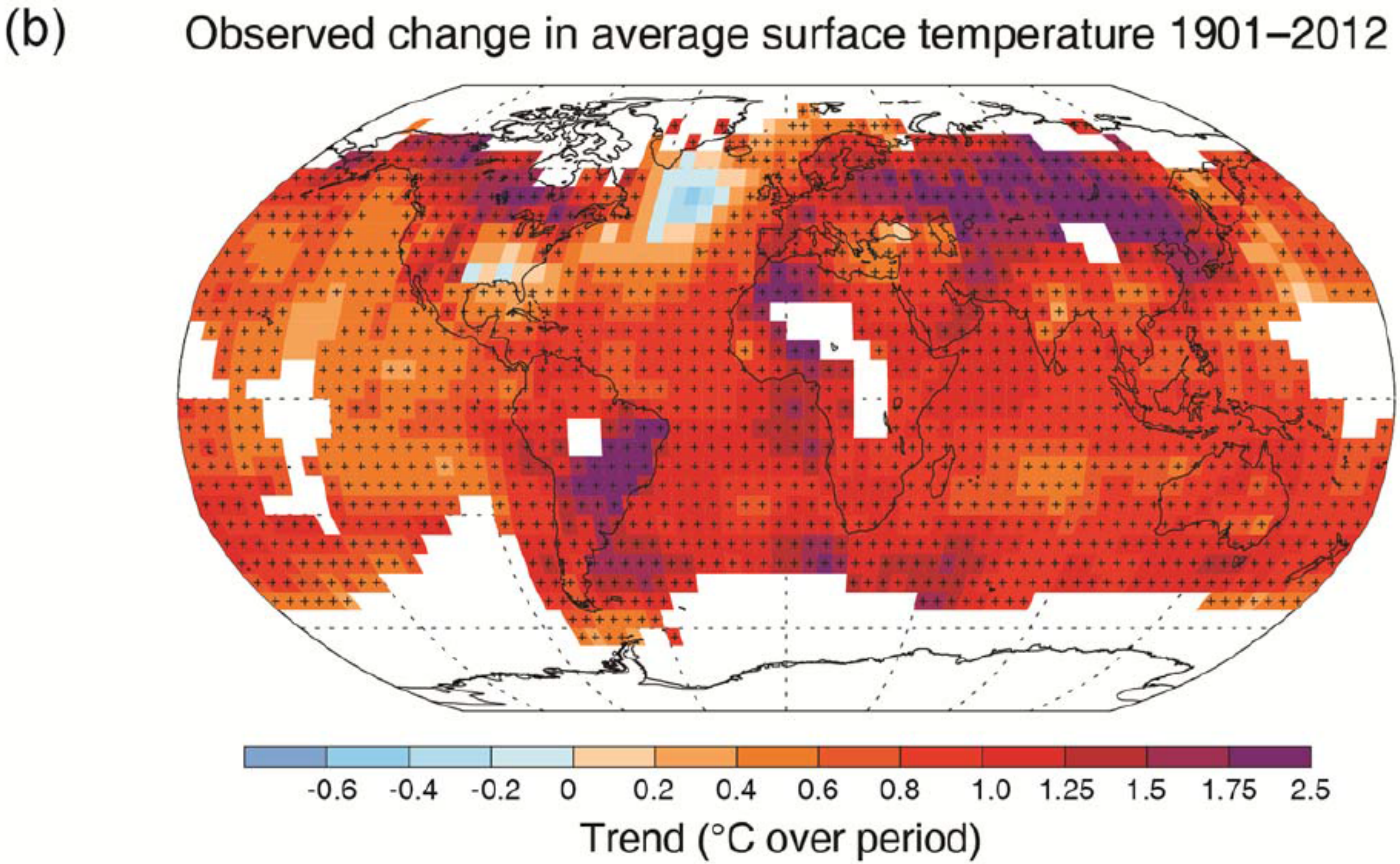


global, 1850-2020, max – min ≈ 1.5℃

Italy, 1901-2020, max – min ≈ 3℃)

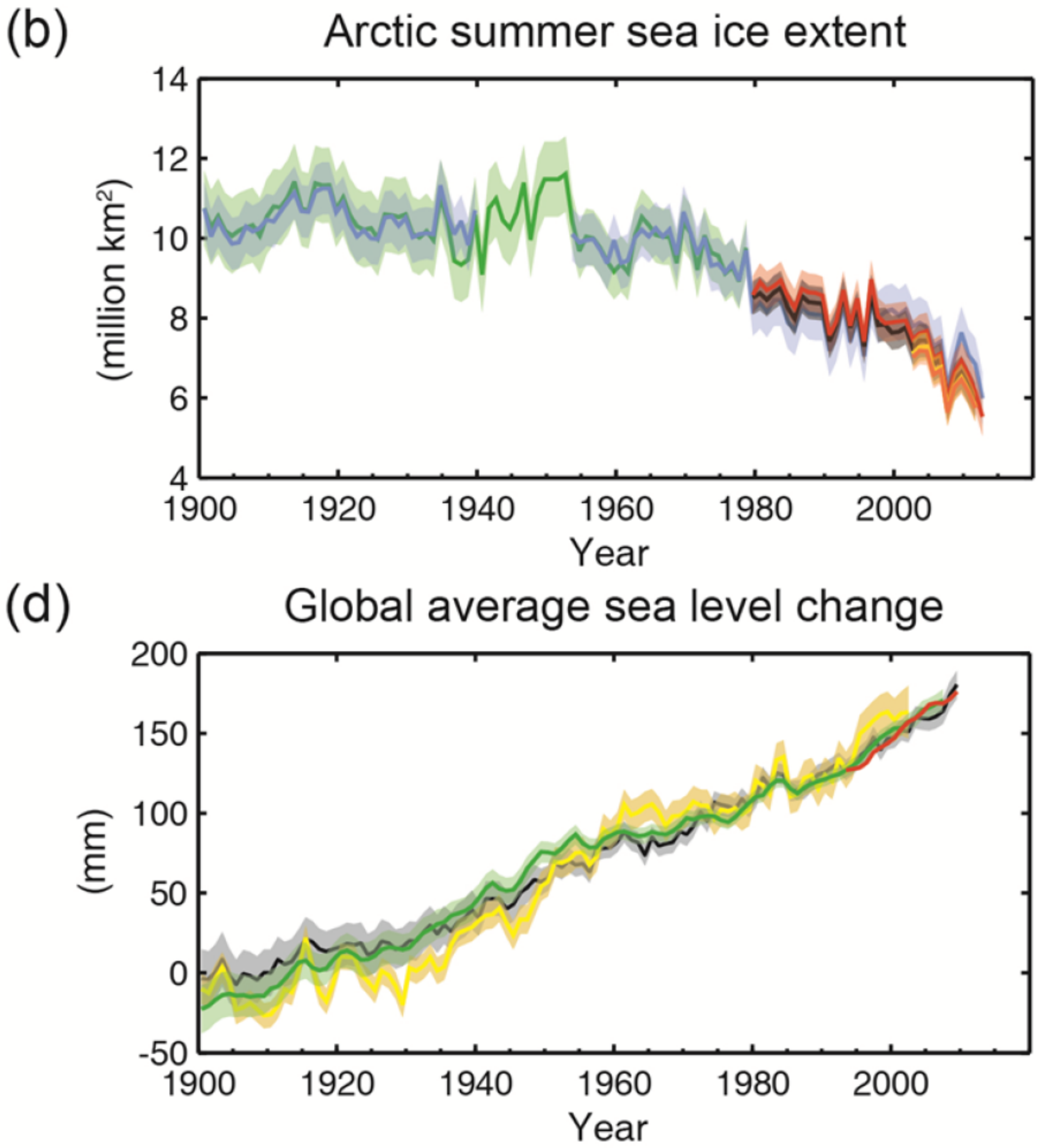
(Ed Hawkins, Univ. Reading, https://www.climate-lab-book.ac.uk)

# Observed regional temperature increase




(IPCC AR5, SPM, 2013)

# Observations: Arctic sea ice, global sea level



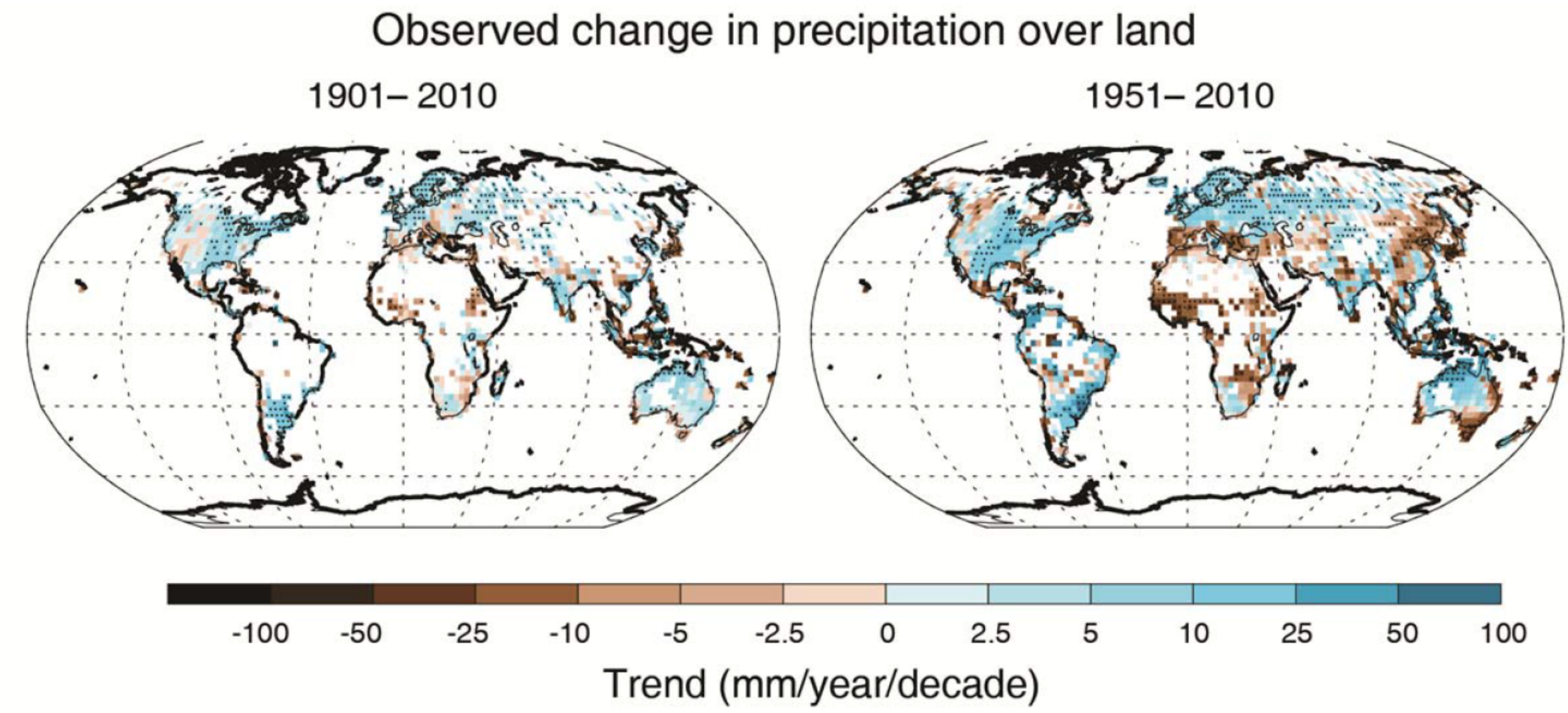

(IPCC AR5, SPM, 2013)

*" The observed linear relationship implies a sustained loss of 3 ± 0.3 square meters of September sea-ice area per metric ton of $CO_2$ emission. „*

*Notz and Stroeve, Science, 2016*

(September Arctic sea ice figures for 1984 and 2016 from nsidc.org)

# Observed regional precipitation changes




(IPCC AR5, SPM, 2013)

# Observed change in precipitation extremes

(Fig. 1a from O'Gorman: Precipitation Extremes Under Climate Change, Current Climate Change Reports, 2015)

Change of annual maximum of daily precipitation per global temperature increase of 1K

# Causes for climate change

## Natural forcings

- Volcanic eruptions
- Variations of solar activity
- Variations of Earth's orbital parameters (Milankovic cycles)

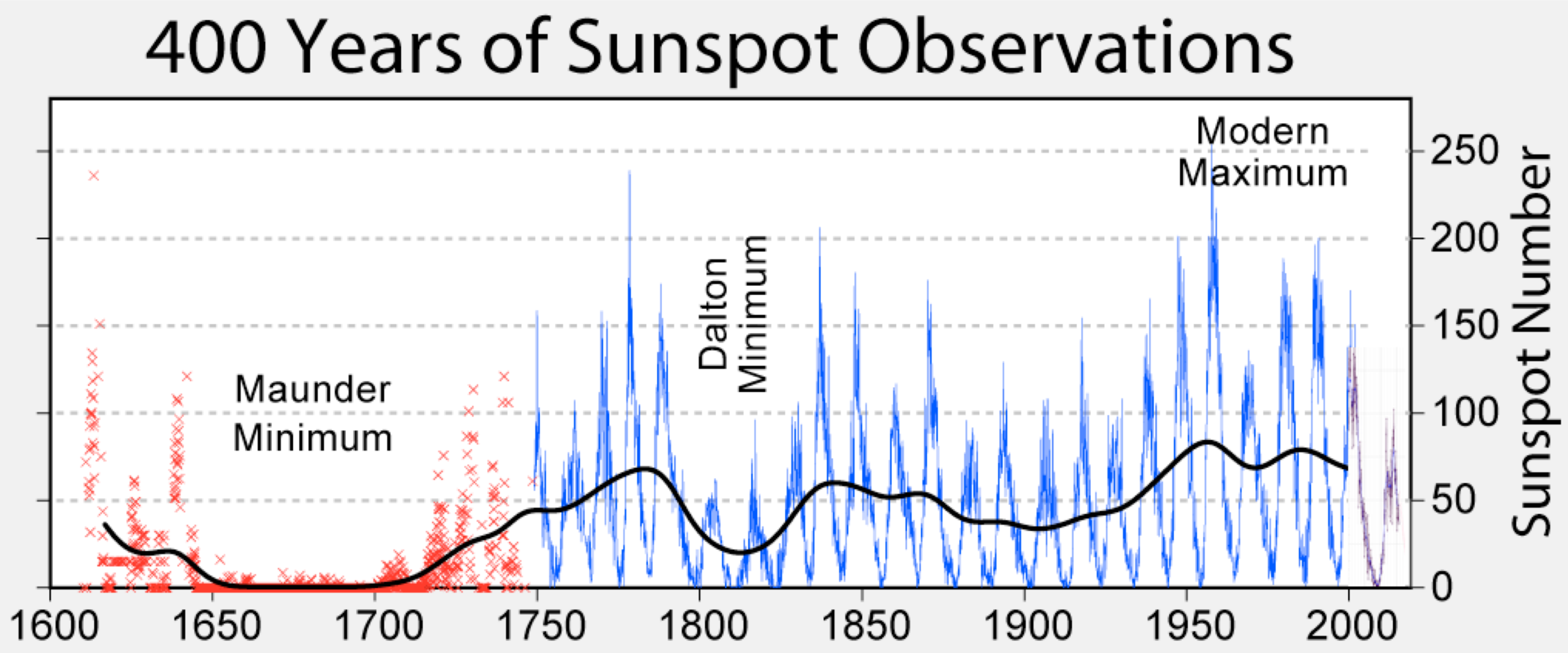
## Anthropogenic forcings

- Fossil fuel burning (coal, oil, gas) (e.g., $CO_2$, $SO_2$, soot)
- Methane emissions (e.g. from fossil fuel production and transport, livestock farming, landfills)
- Land use changes (e.g. deforestation, urbanisation)

*Attention, this list is by no means complete ...*
*and there is internal variability of the climate system*

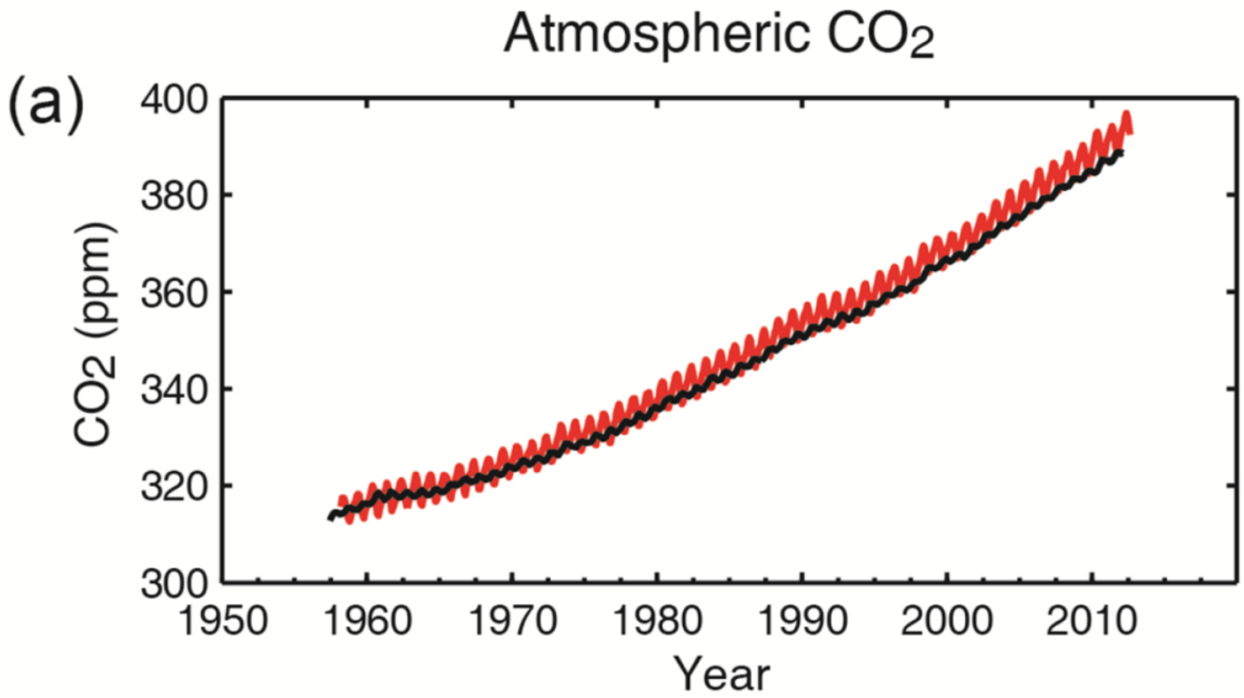
# The eruption of Mount Pinatubo

In the year after the eruption of Mt. Pinatubo, global surface temperature decreased by about 0.4$^{o}$C.




(source: Wikipedia)

# $CO_2$ in the atmosphere




(IPCC AR5, SPM, 2013)

| | |
|---|---|
| **Jul. 17, 2021** | **418.87 ppm** |
| **Jul. 17, 2020** | **414.43 ppm** |
| 1 Year Change | 4.44 ppm (1.07%) |

(www.co2.earth)

# Greenhouse gases in ice cores

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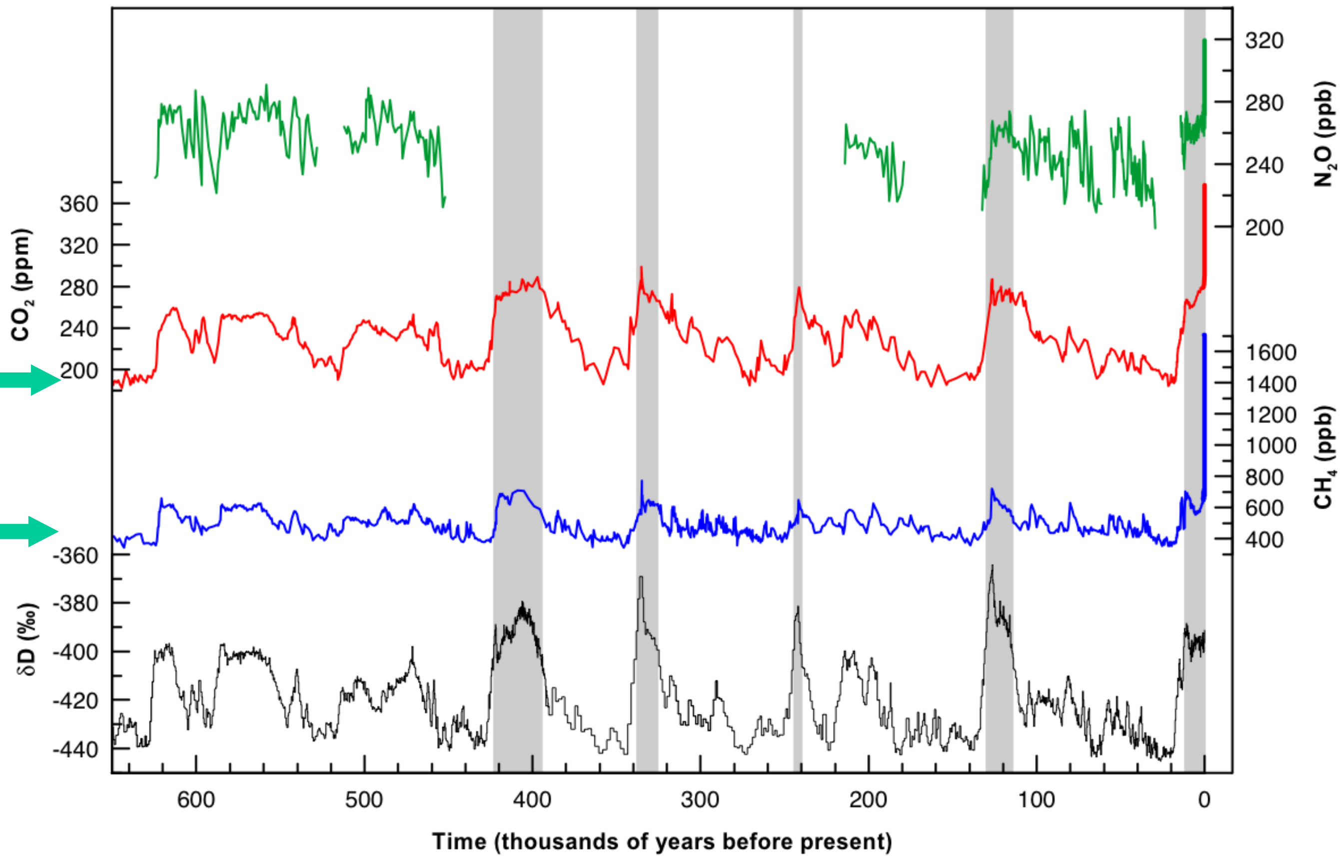
$CO_2$

$CH_4$




(IPCC, 2007)

# Svante Arrhenius (1859-1927)

THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

[FIFTH SERIES.]

*APRIL* 1896.

XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* *By* Prof. SVANTE ARRHENIUS *.

One may now ask, How much must the carbonic acid vary according to our figures, in order that the temperature should

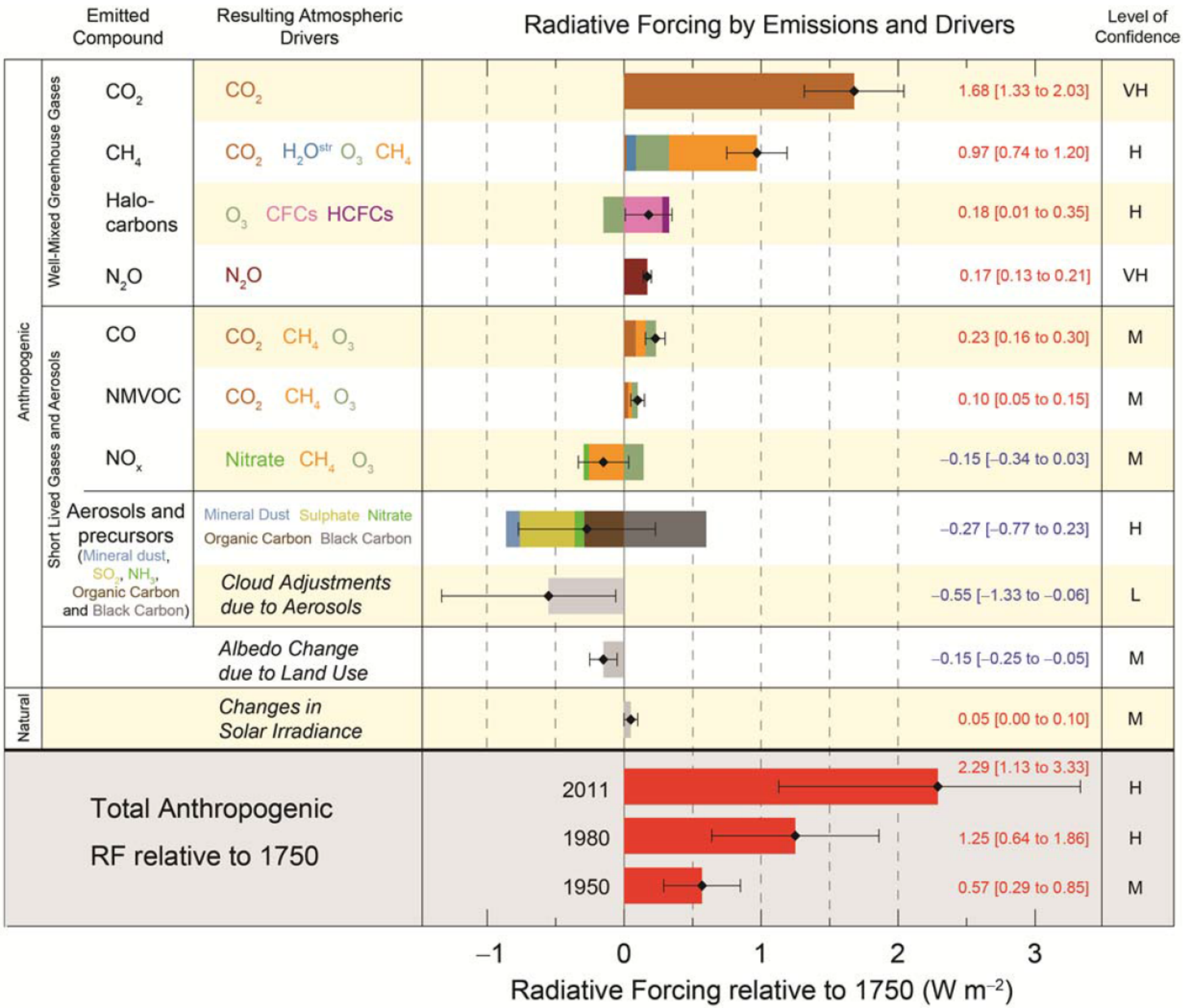
*See Tyndall Lecture by Raymond Pierrehumbert, AGU, 2012:*
*https://www.youtube.com/watch?v=RICBu_P8JWI*

*Or read https://history.aip.org/climate/Radmath.htm*

4°–5° C.). The demands of the geologists, that at the genial

# Radiative forcings of the climate system






(IPCC AR5, SPM, 2013)

# Climate models

# Radiative-Convective Equilibrium



(Fig. 7 from Kiehl and Trenberth: Earth's annual global mean energy budget, Bulletin of the American Meteorological Society, 1997)

# A remarkably robust prediction with an RCE-Modell

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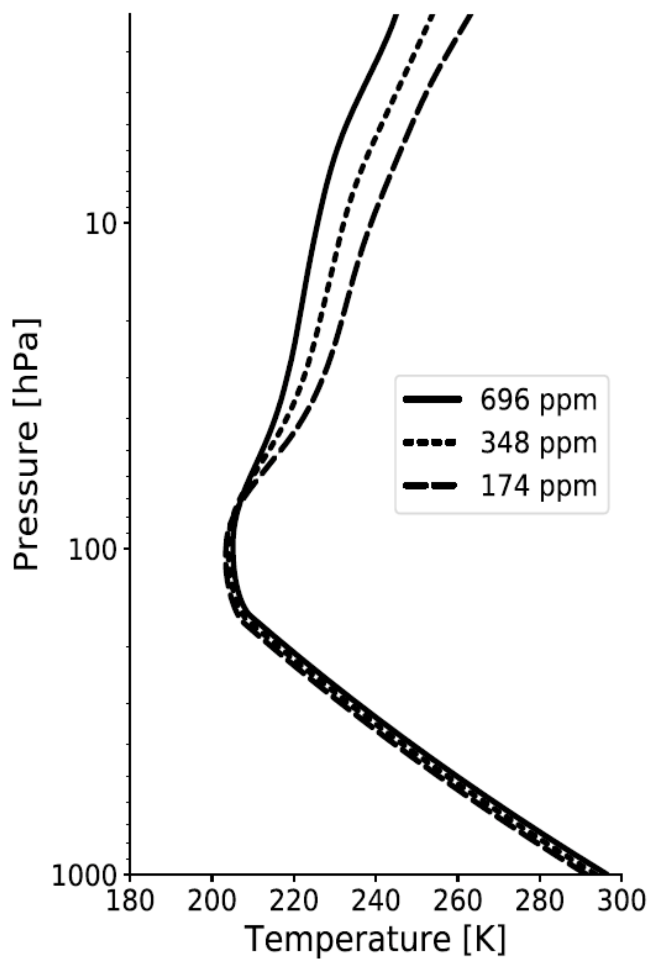
(Fig. 16 from Manabe & Wetherald (JAS, 1967)




Manabe & Wetherald (JAS, 1967) estimated a warming of 2,7 K for a doubling of the atmospheric $CO_2$ concentration. We (Kluft et al., J. Climate, 2019) repeated their calculations, arriving at 2,8 K.

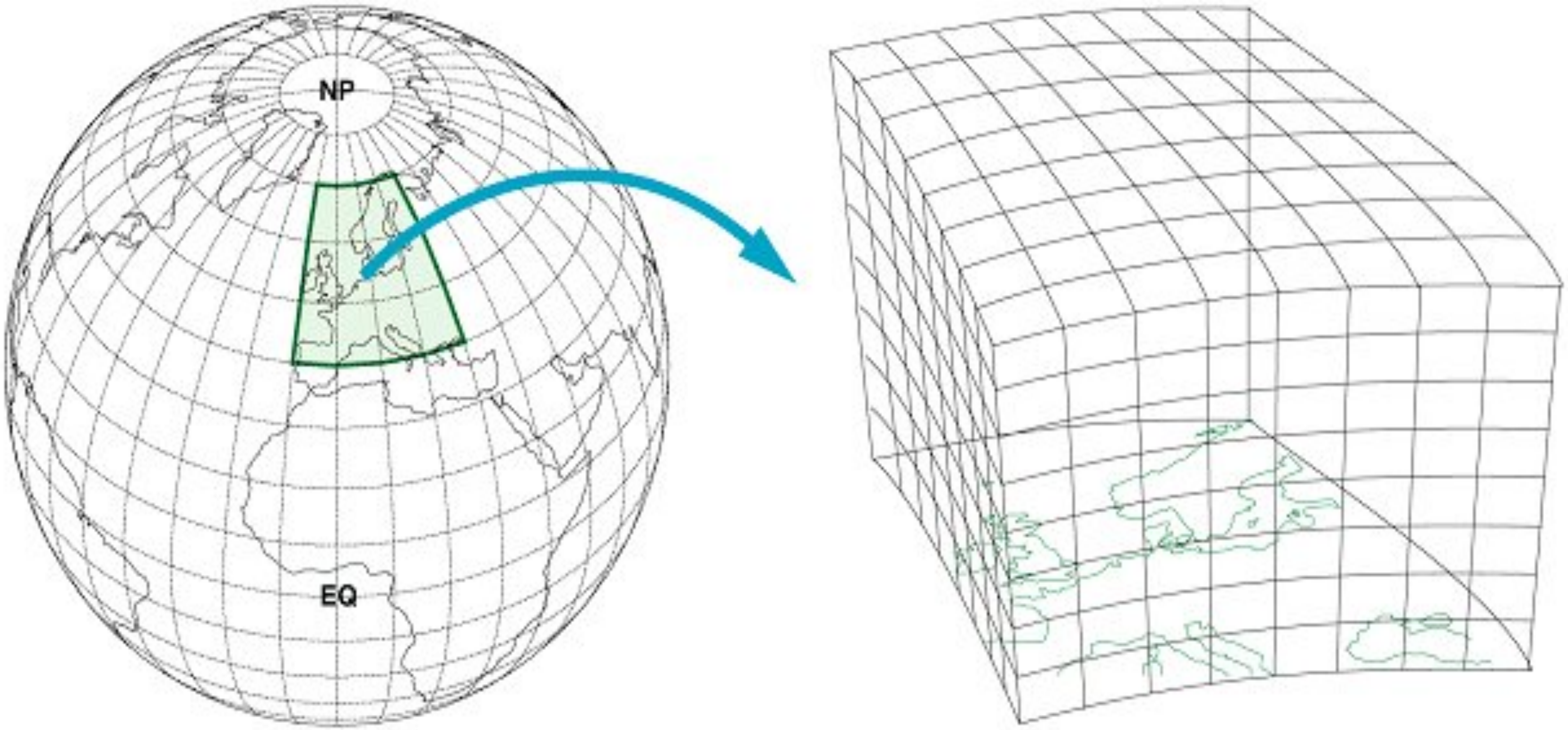
# Model equations for the atmosphere (and ocean)

$$
\begin{aligned}
\frac{\partial \mathbf{v}}{\partial t} &= -(f+\xi)\mathbf{k}\times\mathbf{v} - \nabla K - \dot{\eta}\frac{\partial \mathbf{v}}{\partial \eta} - \frac{R_d T}{p}\nabla p - \nabla\phi + \mathbf{F}_{\mathbf{v}} \\
\frac{\partial T}{\partial t} &= -\mathbf{v}\cdot\nabla T - \dot{\eta}\frac{\partial T}{\partial \eta} + \frac{R_d}{C_p}\frac{T}{p}\frac{dp}{dt} + F_T \\
0 &= \frac{\partial \phi}{\partial \eta} + \frac{R_d T}{p}\frac{\partial p}{\partial \eta} \\
\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) &= -\nabla\cdot\left(\mathbf{v}\frac{\partial p}{\partial \eta}\right) - \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) + F_\rho \\
\frac{\partial}{\partial t}\left(c_i\frac{\partial p}{\partial \eta}\right) &= -\nabla\cdot\left(\mathbf{v}\,c_i\frac{\partial p}{\partial \eta}\right) - \frac{\partial}{\partial \eta}\left(\dot{\eta}\,c_i\frac{\partial p}{\partial \eta}\right) + F_{c_i} \\
& \qquad (i = 1, 2, 3, \dots)
\end{aligned}
$$

$\xi$ : vorticity; $K$ : kinetic energy; $\eta$ : vertical coordinate; $c_i$ : mixing ratio of tracer $i$
$F$ : external forcing. Other symbols have their conventional meanings.

can‘t be solved analytically …

... but numerically.




However, sub-grid scale processes need to be parameterized.

# What is the equation for a tree …?

(Picture of trees)

# Global temperatures – simulated and observed

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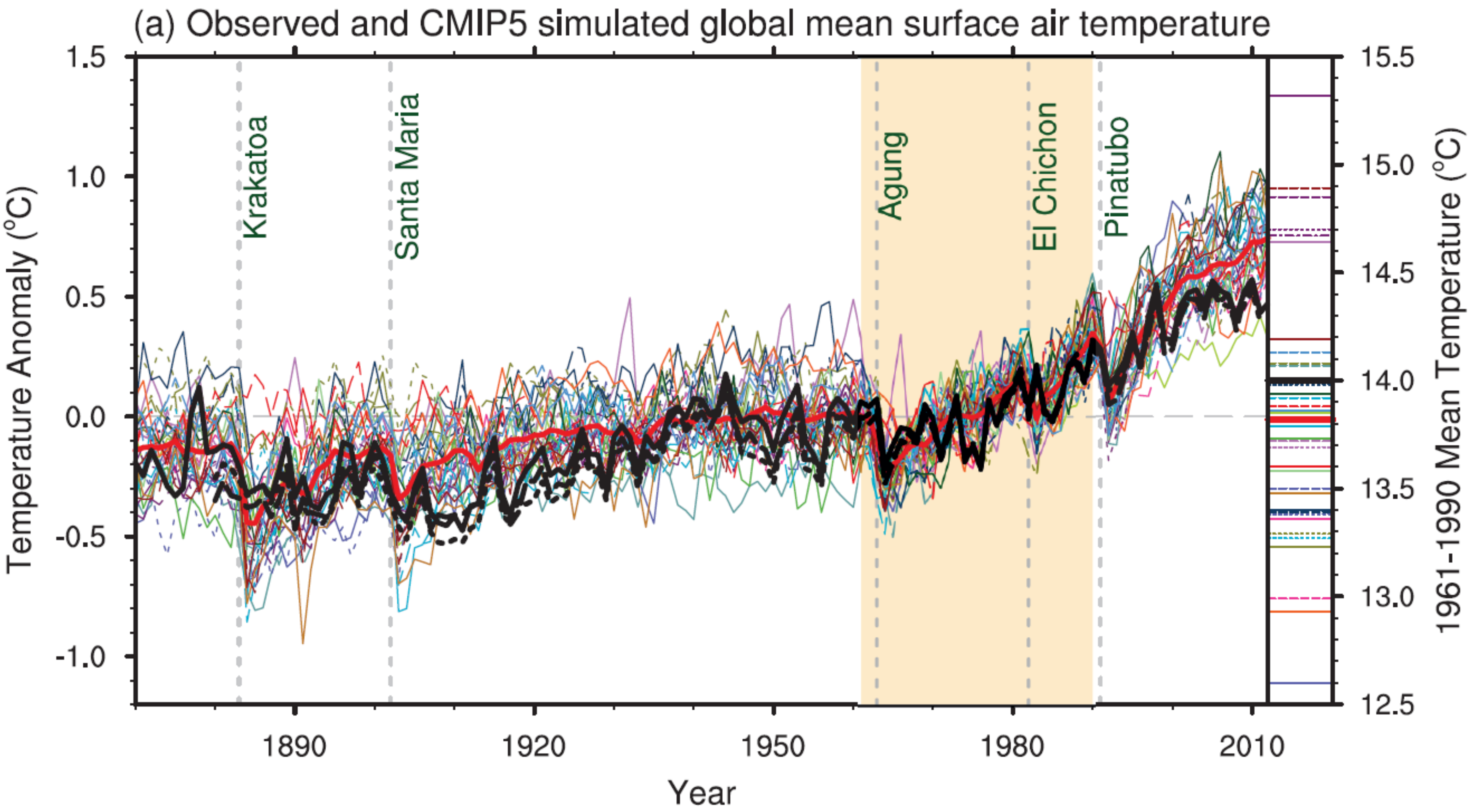
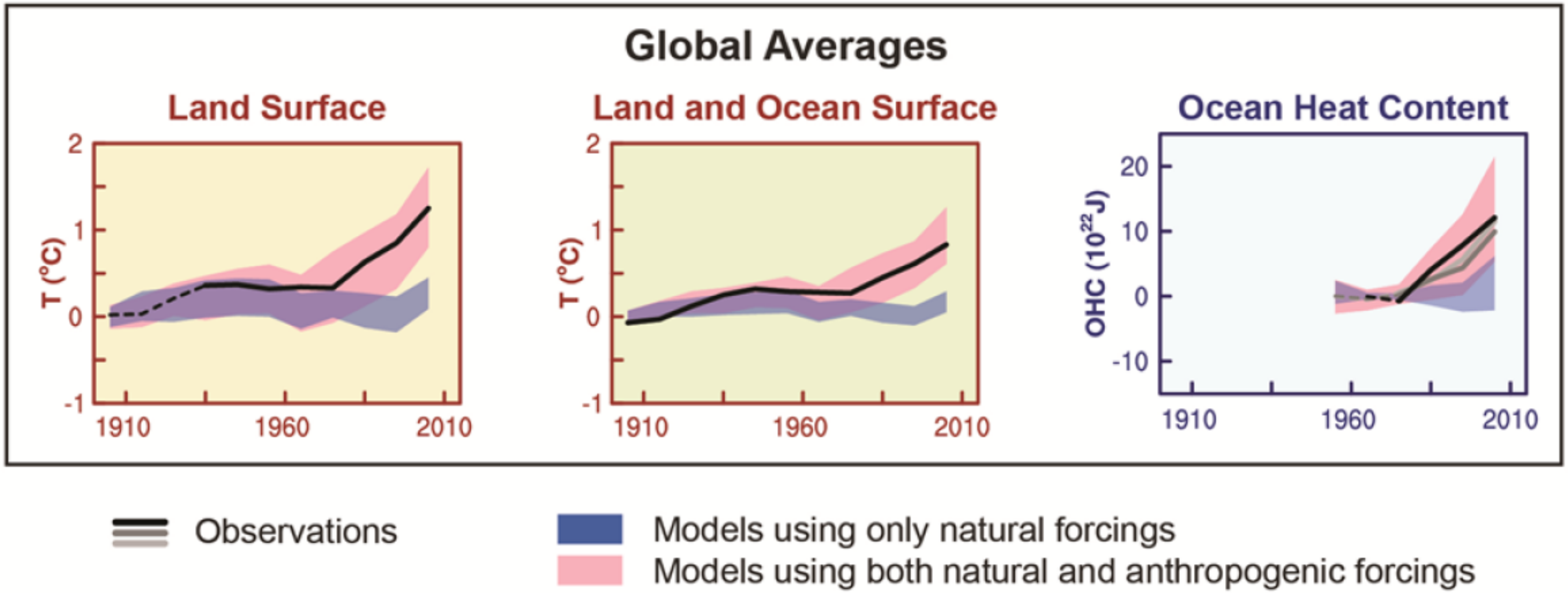



(IPCC AR5, WG1, Fig. 9.8, 2013)

# Is the temperature increase anthropogenic?




(IPCC AR5, SPM, 2013)

# Climate sensitivity

Climate sensitivity: Temperature increase $\Delta T$ resulting from a radiative forcing $\Delta F$ at the tropopause.

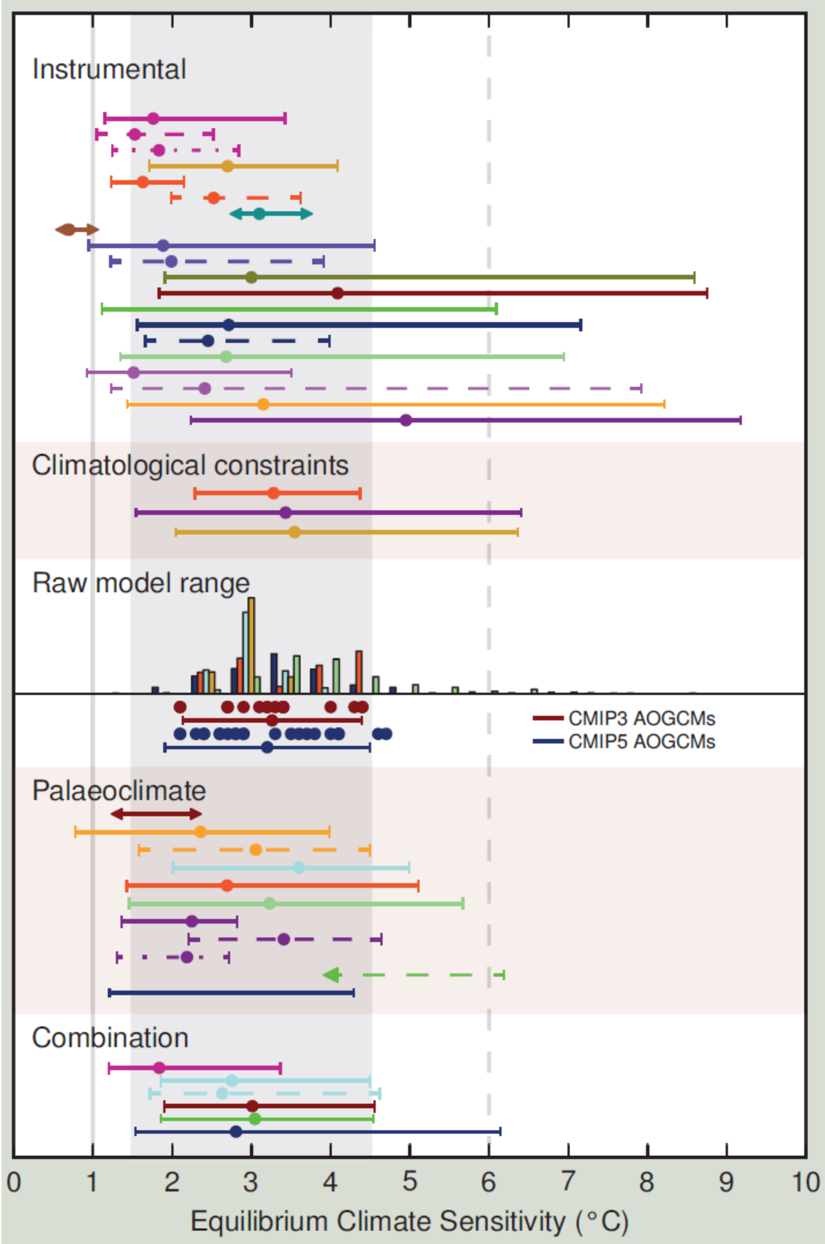
Usually defined as Temperature increase for a doubling of the atmospheric $CO_2$ concentration (for which a radiative forcing of $\Delta F \approx 3.7\ W/m^2$ is assumed).

According to IPCC AR5, equilibrium climate sensitivity (ECS) is likely between 1.5 and 4.5 °C.

A recent study (Sherwood et al., Rev. of Geophysics, 2020) has narrowed this to between 2.6 and 3.9 °C.

Several recent global climate models have sensitivities above these ranges.

I'm curious to see the upcoming IPCC assessment on this topic.




(IPCC AR5, WG1, TFE.6, Fig.1, 2013)

## One important reason for differences in climate sensitivity among models?

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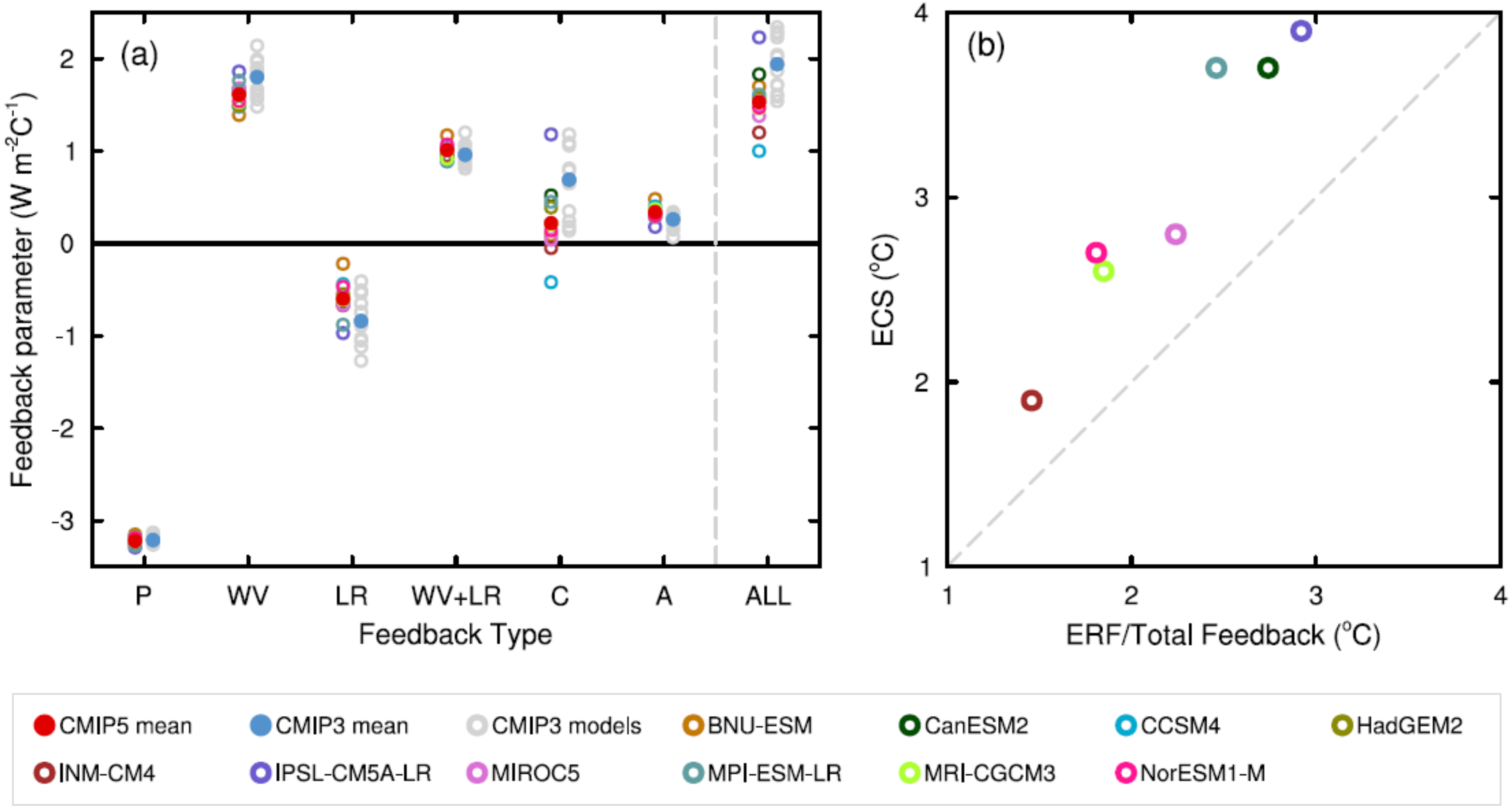



(IPCC AR5, WG1, Fig.9.43, 2013)

# Projections of future climates

# RCPs: $CO_2$ emissions and concentrations

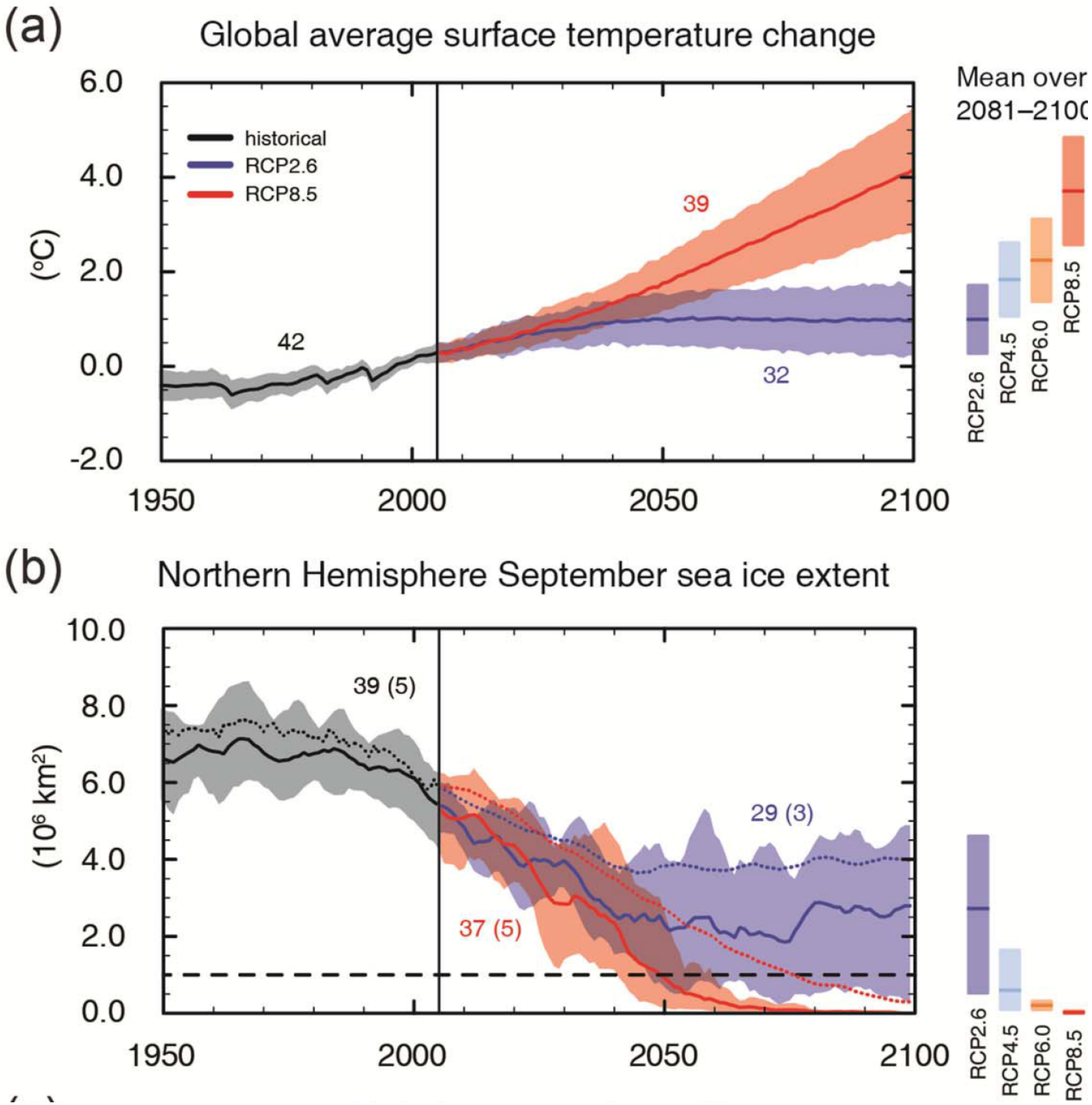


(Fig. 3 from van Vuuren et al., The representative concentration pathways: an overview Climatic Change, 2011)

*Green: RCP2.6  Red: RCP4.5  Black: RCP6.0  Blue: RCP8.5*

*RCP8.5 close to SRES A2, RCP4.5 close to SRES B1*

# Projections: global temperature, Arctic sea ice




(IPCC AR5, SPM, 2013)

# Cumulative $CO_2$-emissions and global temperature

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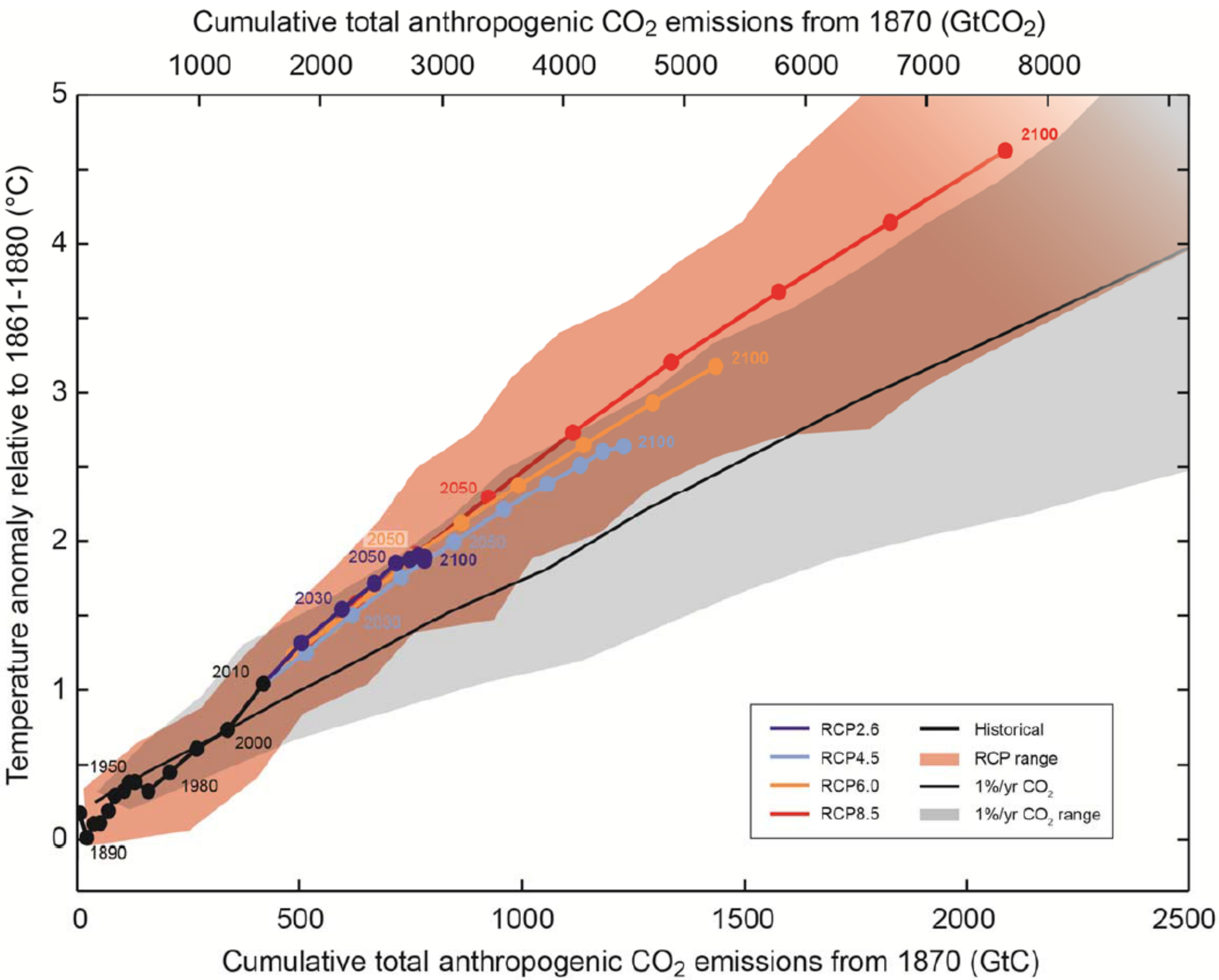



(IPCC AR5, SPM, 2013)

# How much can we still emit?

*Remaining budget (from 2015):*

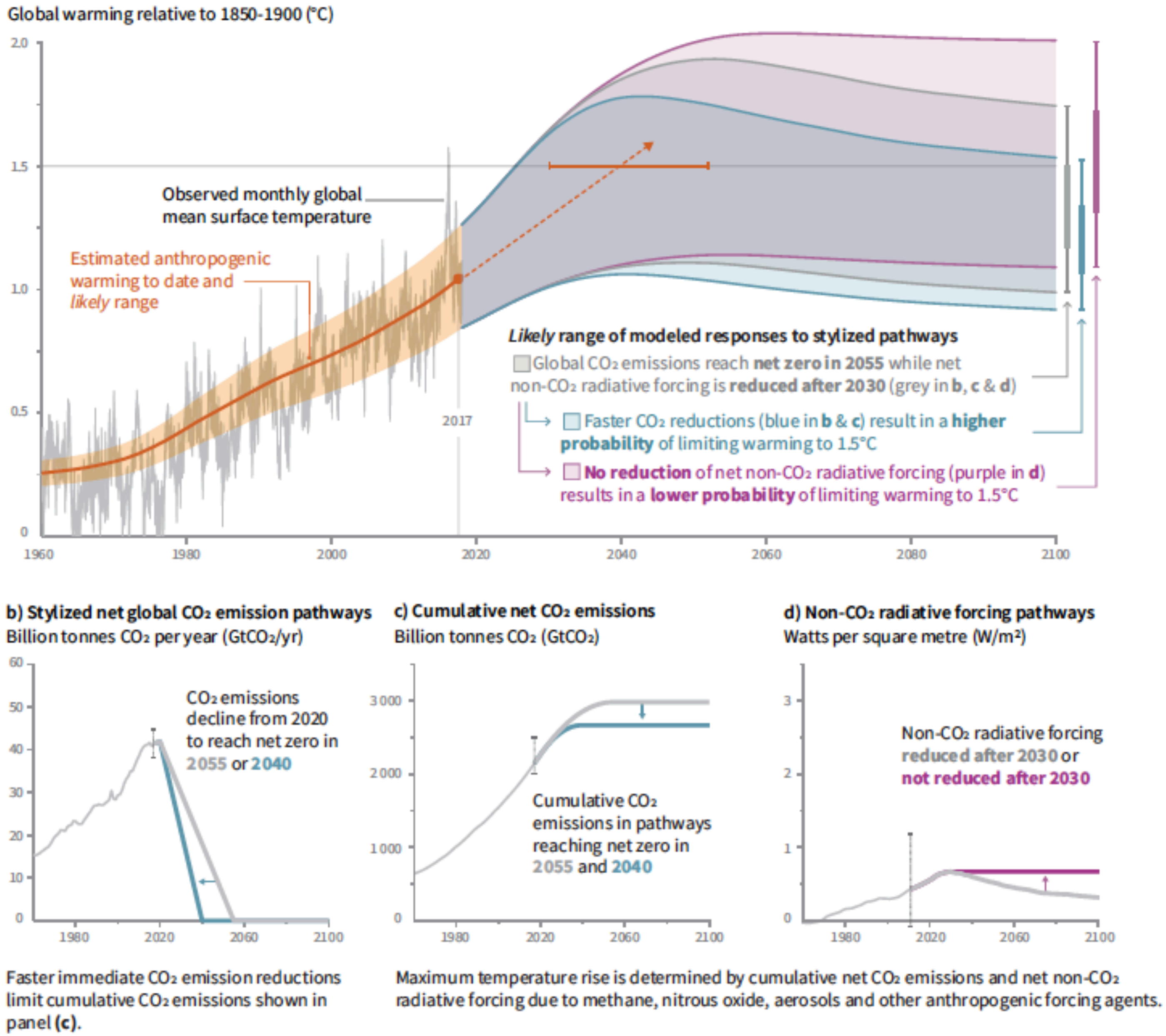
$\Delta T<1.5$℃: 650±130 Gt($CO_2$)
$\Delta T<2$℃: 1300±130 Gt($CO_2$)

*Current emission rate:*

~40 Gt($CO_2$)/yr

(Lawrence et al., Nature Communications, 2018)

# How much can we still emit?




*„In model pathways with no or limited overshoot of 1.5C, global net anthropogenic CO2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range). For limiting global warming to below 2C CO2 emissions are projected to decline by about 25% by 2030 in most pathways (10–30% interquartile range) and reach net zero around 2070 (2065–2080 interquartile range). Non-CO2 emissions in pathways that limit global warming to 1.5Cshow deep reductions that are similar to those in pathways limiting warming to 2C.“*

…

*„Most 1.5℃ and 2℃ pathways are heavily reliant on CDR (Carbon Dioxide Removal) at a speculatively large scale before mid-century.“*

(IPCC, 2018: Global Warming of 1.5˚C; Fig. SPM.1; SPM, C.1; Section 2.6.3)

# Projections, temperature and precipitation

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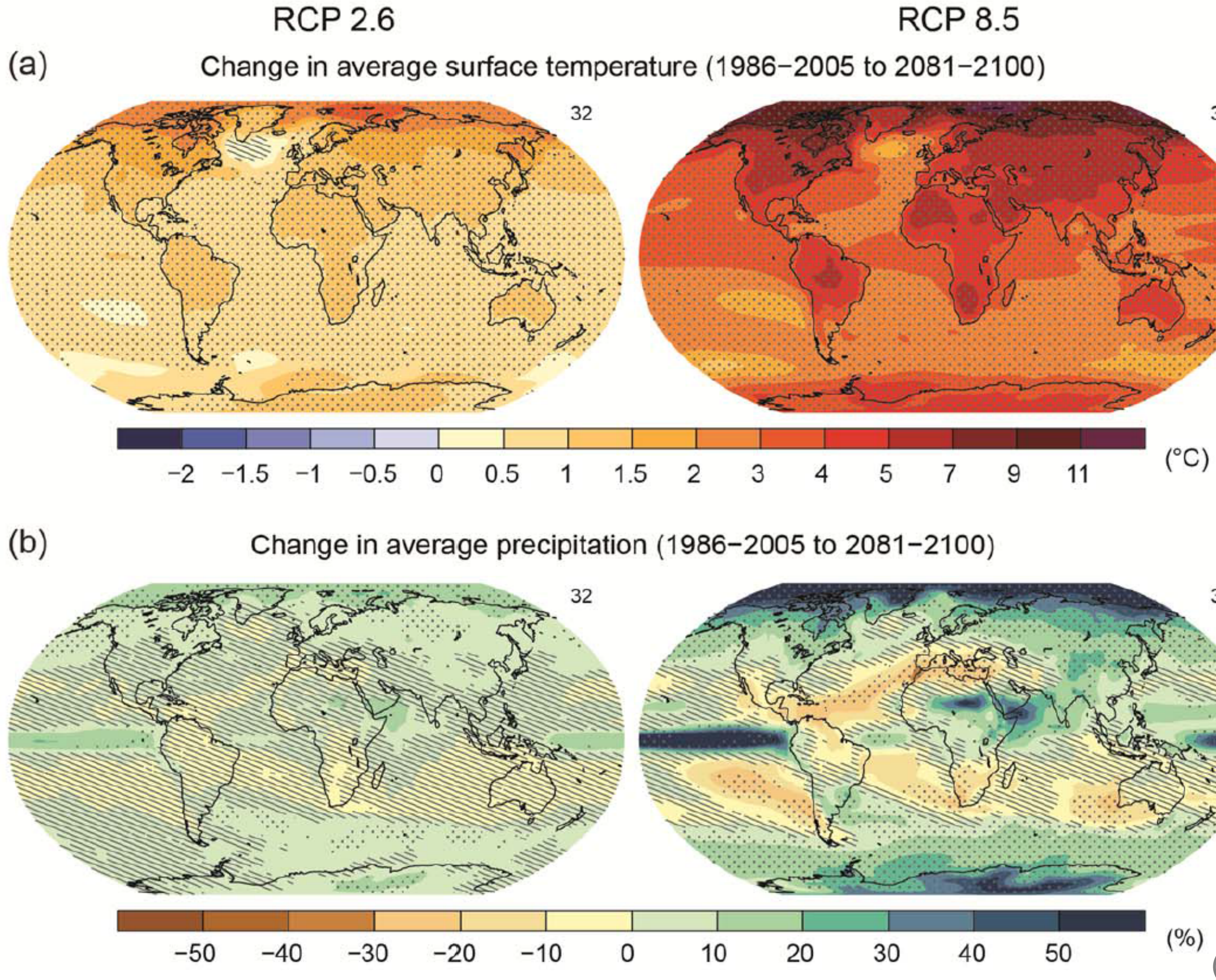


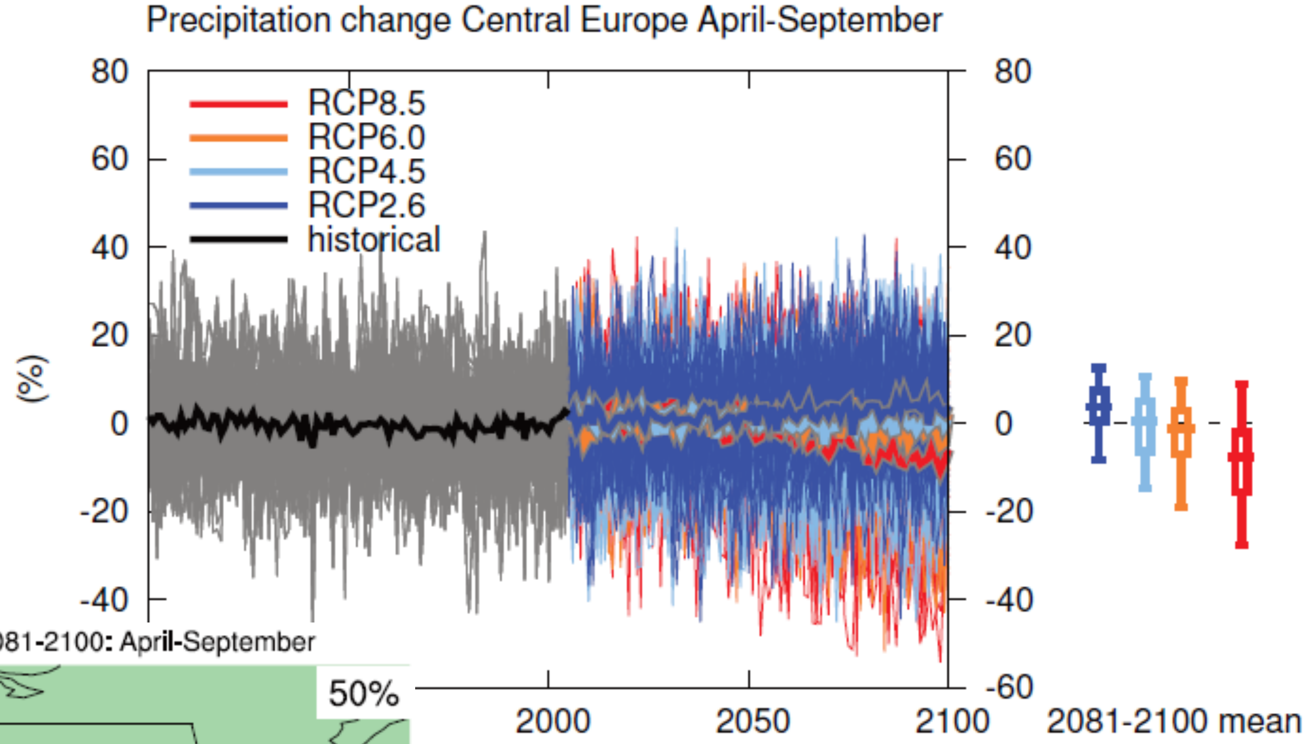

(IPCC AR5, SPM, 2013)

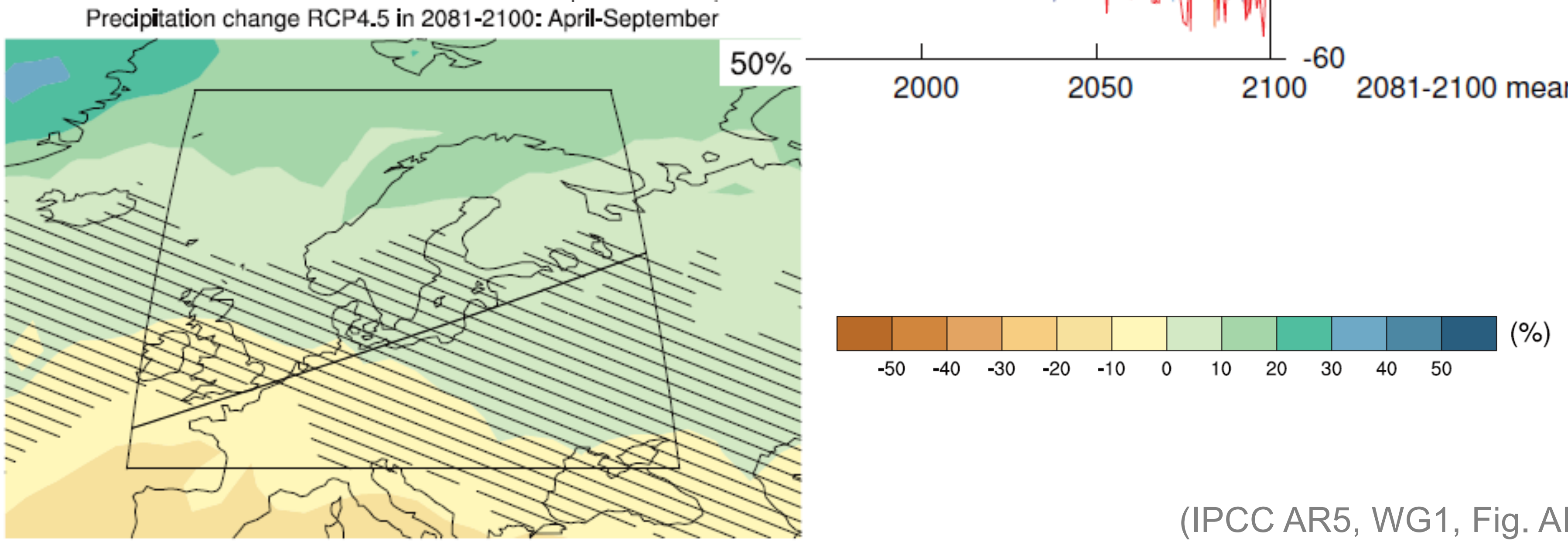
# Why (and how much) it rains more under warming?

(Fig. 7 from Kiehl and Trenberth: Earth's annual global mean energy budget, Bulletin of the American Meteorological Society, 1997)

Latent heating from condensation balances tropospheric radiative cooling to space. This cooling (by $CO_2$ und $H_2O$) increases under current GHG induced warming of 1℃ by about 2%. Likewise react latent heating and precipitation. So global precipitation increases less than humidity (about 7%/1℃ following Clausius-Clapeyron) under warming. Precipitation is constrained by energy, not humidity.

# Precipitation changes in central Europe, summer




(IPCC AR5, WG1, Fig. AI39, 2013)

# Projections of different models

Winter mean zonal wind in 850 hPa (gray isolines, 5 m/s) und its change in the 21. century under strong $CO_2$ increase

(Fig. 4 from Shepherd et al., Atmospheric circulation as a source of uncertainty in climate change projections, Nature Geoscience, 2014)

# 50-year trends (2010-2060) simulated with the CCSM3 model

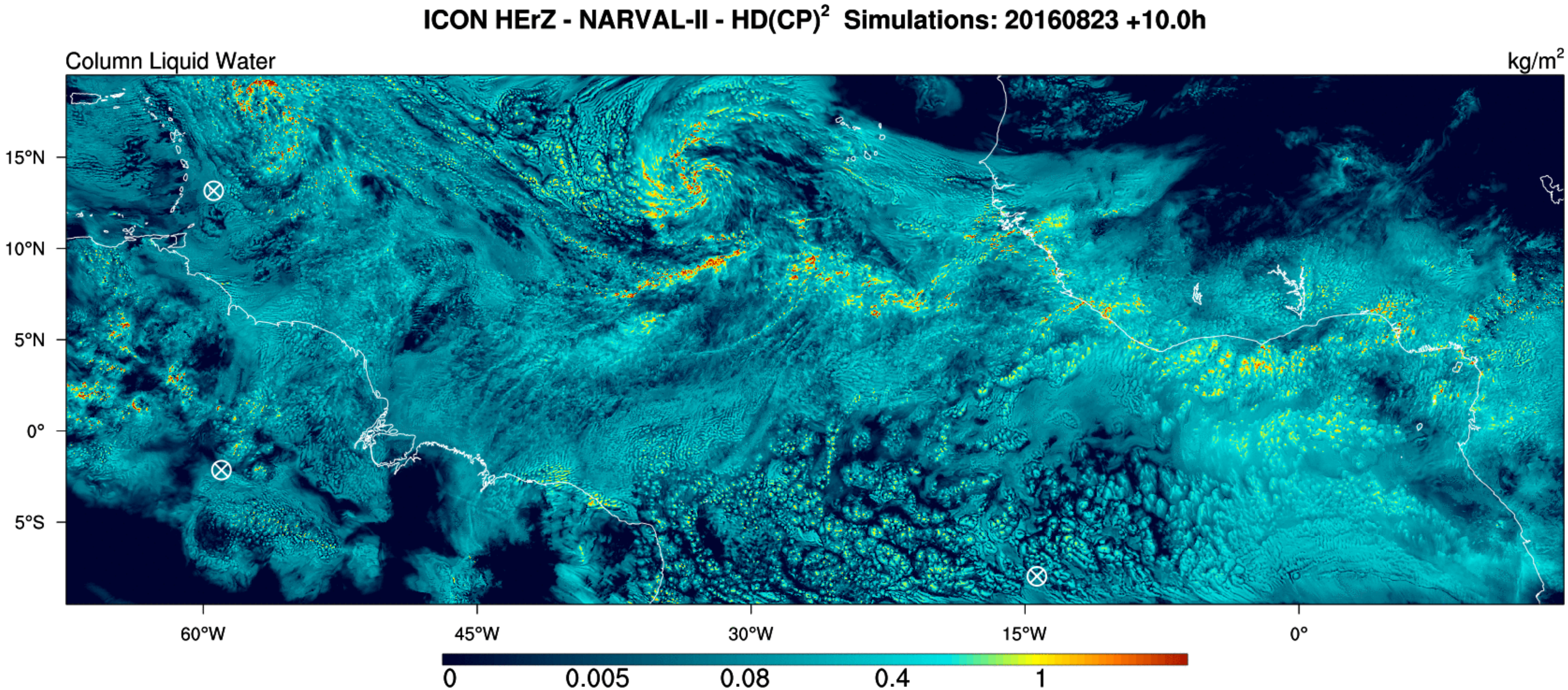
(Fig. 10a from Deser et al., Projecting North American Climate over the Next 50 Years: Uncertainty due to Internal Variability J. Climate, 2013)

# Projections of different models



(Fig. 1 from Stevens & Bony, What Are Climate Models Missing, Science, 2013)

# *Tropical Atlantic in ICON, August, 23, 2016*




Simulation by Daniel Klocke (DWD) and vizualization by Matthias Brueck (MPI-M)

# Will extreme events increase with global warming?

| | |
|---|---|
| • Heat waves: | very likely, globally |
| • Extreme precipitation: | very likely in mid-latitude and tropical land areas |
| • Coastal floodings: | very likely |
| • Droughts: | likely in sub-tropical regions |
| • Tropical storms: | uncertain |
| • Extratropical storms: | uncertain |

(IPCC AR5, Tab. SPM.1, 2013)

# What we know and what not

- „It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century.“ (IPCC AR5)
- A doubling of atmospheric $CO_2$ likely causes global warming between 2.6 and 3.9 ℃ (Sherwood et al., 2020; between 1.5 and 4.5 ℃., IPCC AR5)
- The temperature increase until the end of this century depends largely on the cumulative GHG emissions. In order to reach the 2 (or 1,5) ℃-limit future cumulative $CO_2$ emissions should not be larger than 1200 (550) Gt $CO_2$ emittiert werden. In the past, humans have emitted about 2000 Gt, currently about 40 Gt per year.
- Precipitation has likely already decreased in dry regions and increased in wet regions. This trend will very likely continue. (IPCC, AR5) Global mean precipitation is expected to increase by about 2% per 1℃ global warming.
- Currently, sea level rises by about 3 mm per year. A melting of Greenland would increase sea level by about 7m of Antarctica by more than 40m.
- Several weather extremes will likely increase.
- The global thermodynamics of climate change are well understood, how warming affects the weather (in particular circulation) less good.
- I expect there will be surprises. Understanding the system better is the best preparation.

***Thank you very much !***