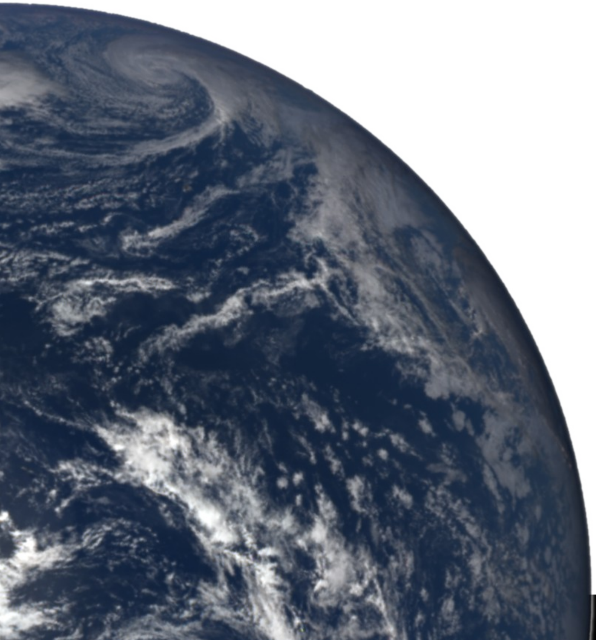
A Hacker's Guide to Climate Change

What do we know and how do we know it?



Katja Bigge

Institute of Environmental Physics
University of Heidelberg

Robert Gieseke

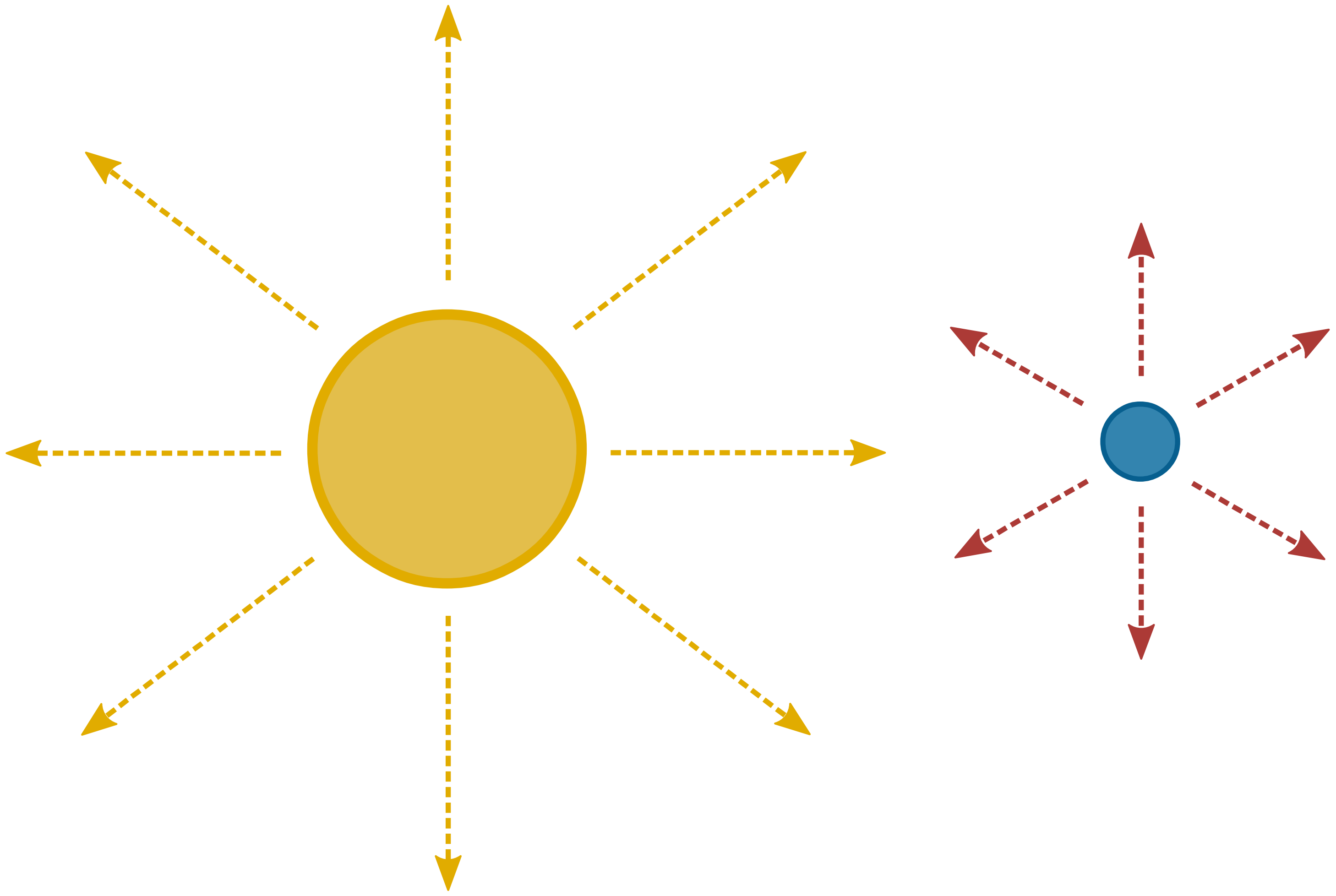
Sven Willner

Potsdam Institute for Climate Impact Research

PIK

@openclimatedata

Image (earth): https://epic.gsfc.nasa.gov/



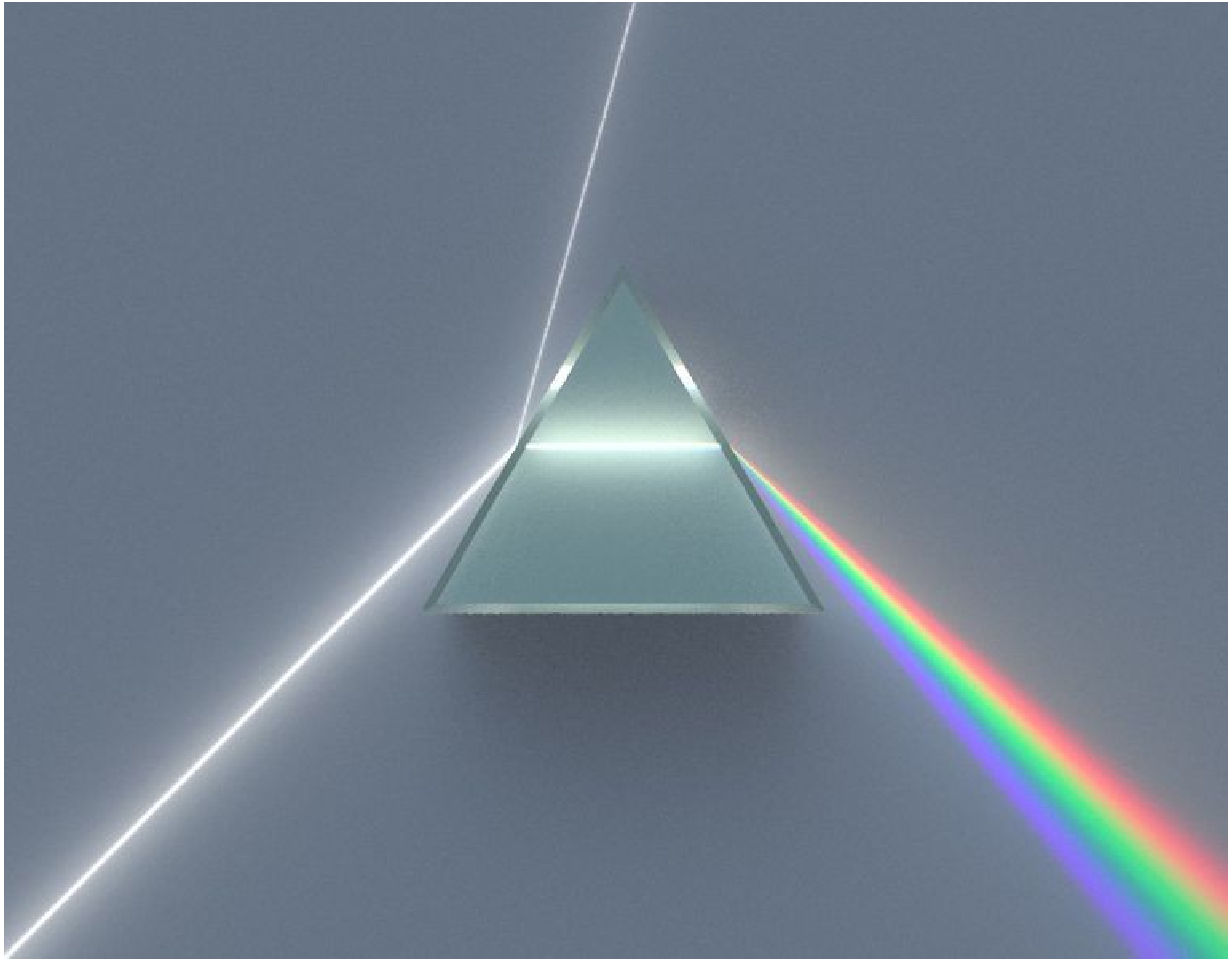
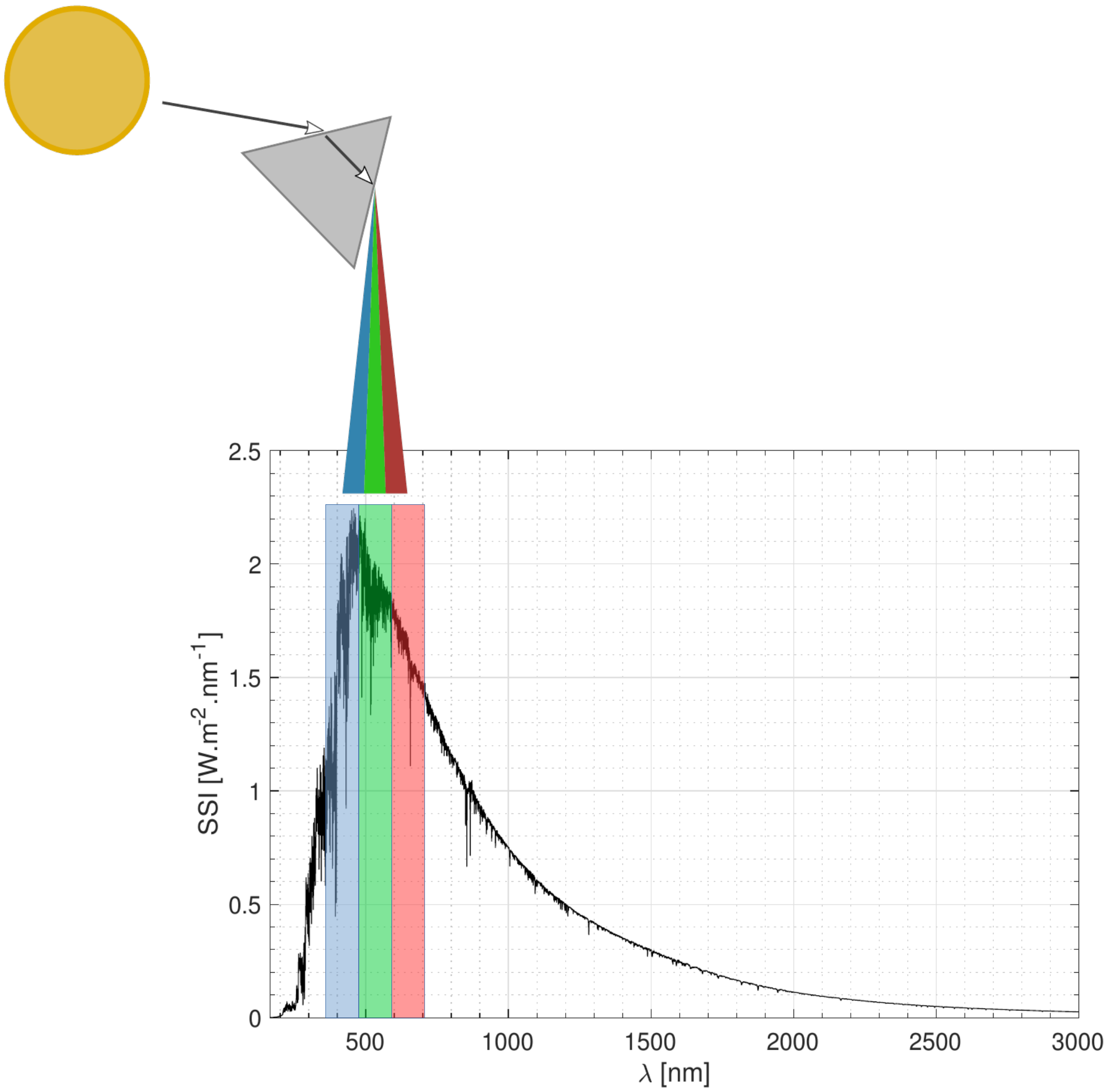
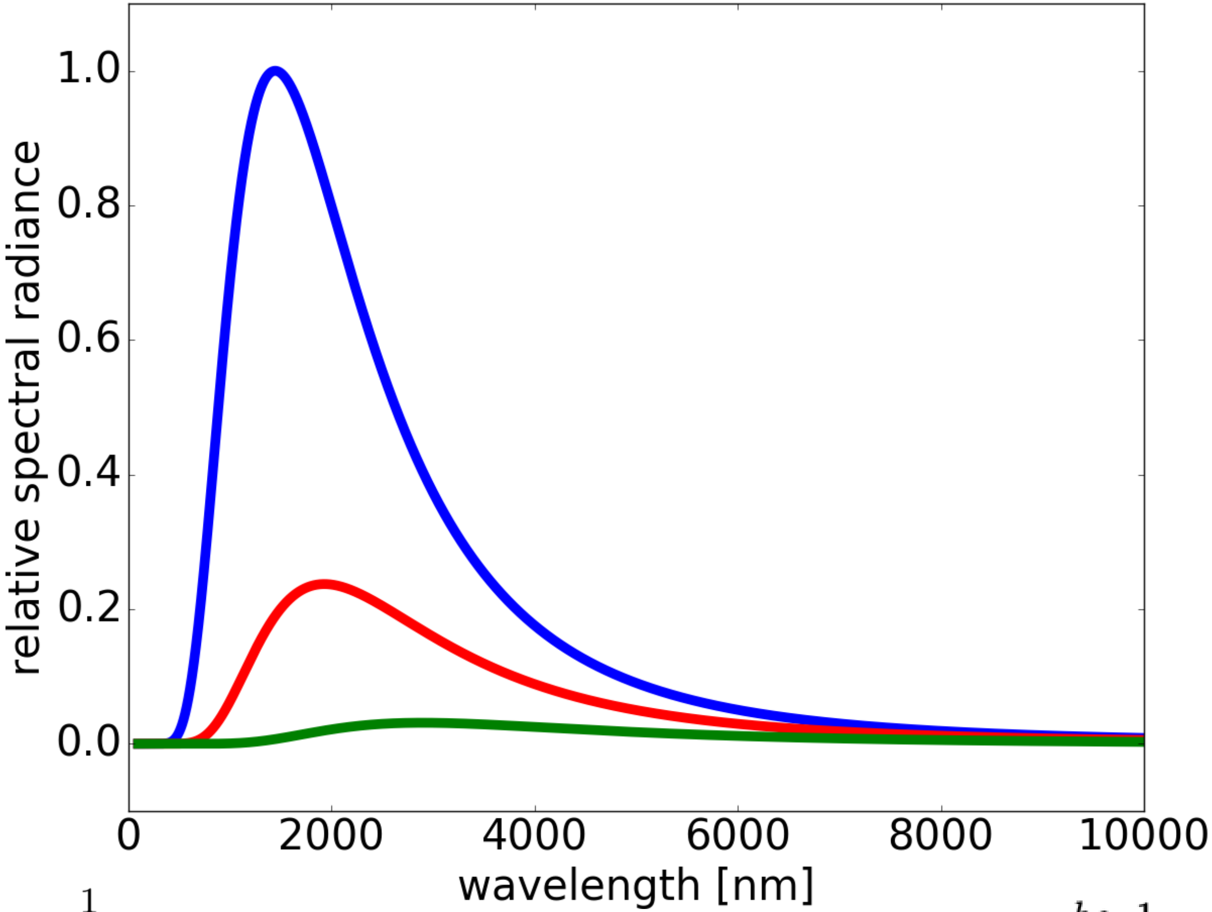


Image: https://commons.wikimedia.org/wiki/File:Dispersive_Prism_Illustration.jpg



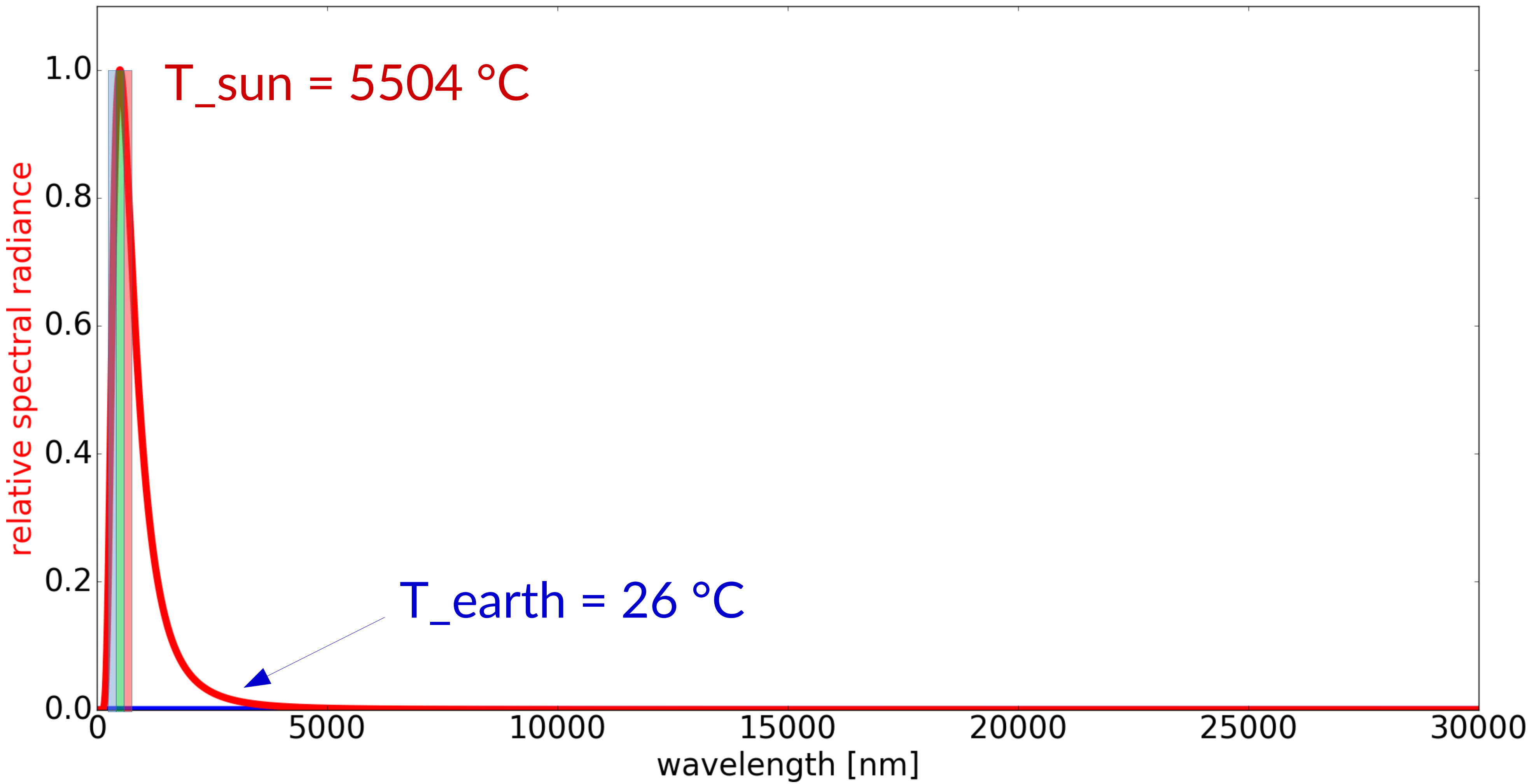
Soruce: Mefta et.al. Spectrum solar_ISS, CNRS (2017)

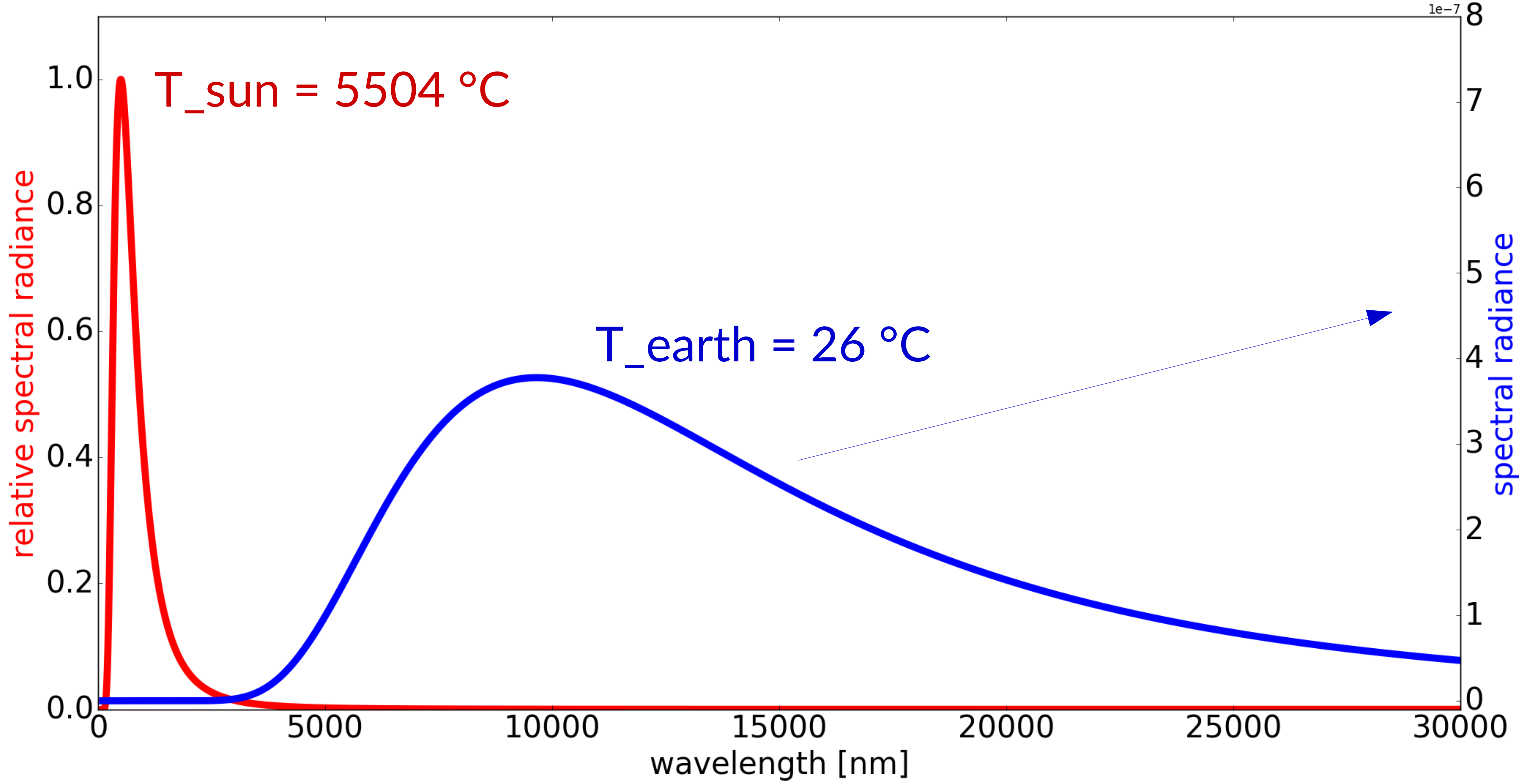
Planck's law - 1900

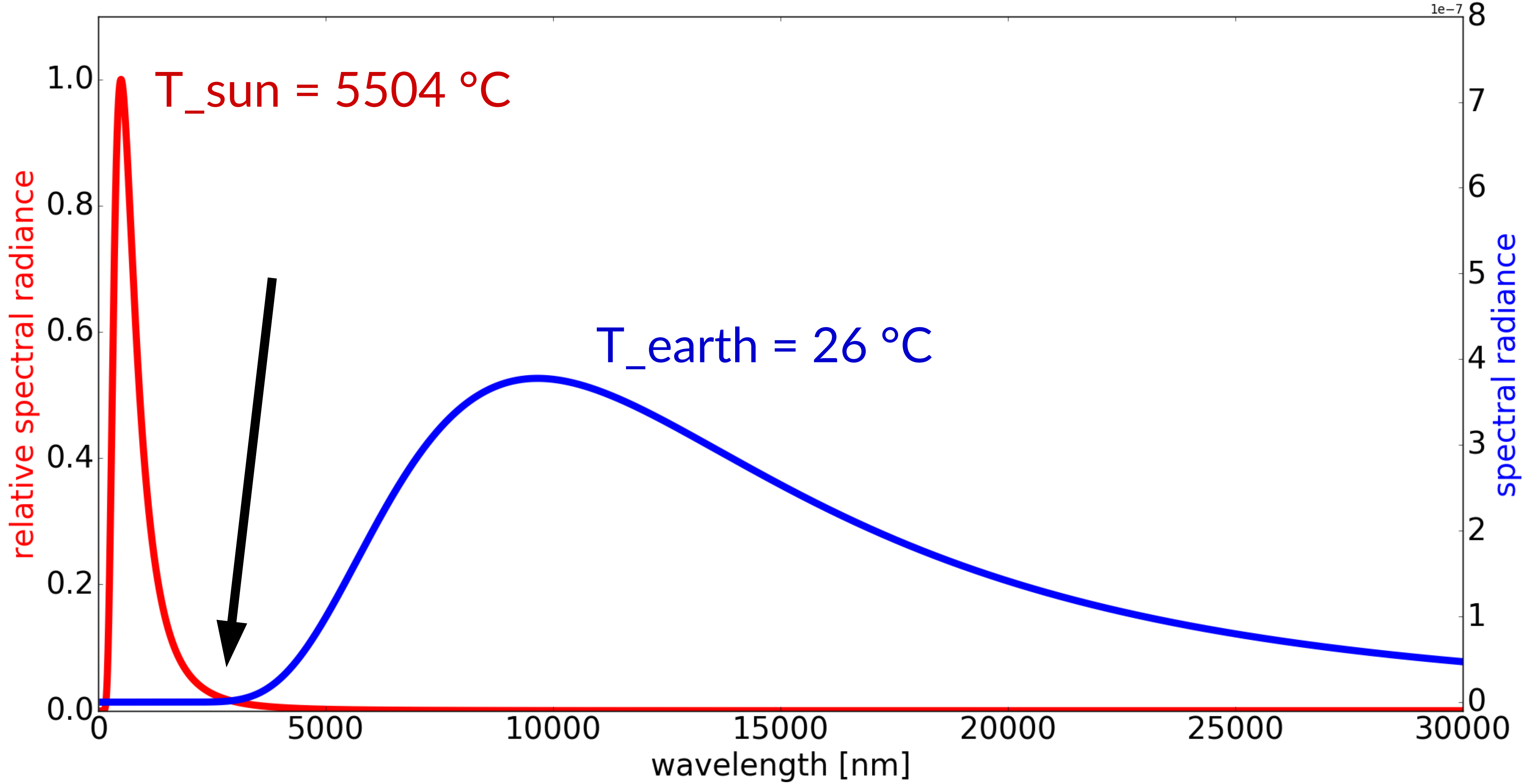


$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{exp(\frac{hc\lambda}{k_B T}) - 1}$$

$$\lambda_{\max} = \frac{hc}{x}\frac{1}{kT} = \frac{2.89776829 \times 10^6 \text{ nm} \cdot \text{K}}{T}.$$


T_sun = 5504 °C
T_earth = 26 °C
relative spectral radiance
wavelength [nm]
0.0
0.2
0.4
0.6
0.8
1.0
0
5000
10000
15000
20000
25000
30000


T_sun = 5504 °C
T_earth = 26 °C
relative spectral radiance
spectral radiance
wavelength [nm]
1e−7
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6
7
8
0
5000
10000
15000
20000
25000
30000



T_sun = 5504 °C
T_earth = 26 °C
relative spectral radiance
spectral radiance
1e−7
wavelength [nm]
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6
7
8
0
5000
10000
15000
20000
25000
30000

Albedo ≈ 0

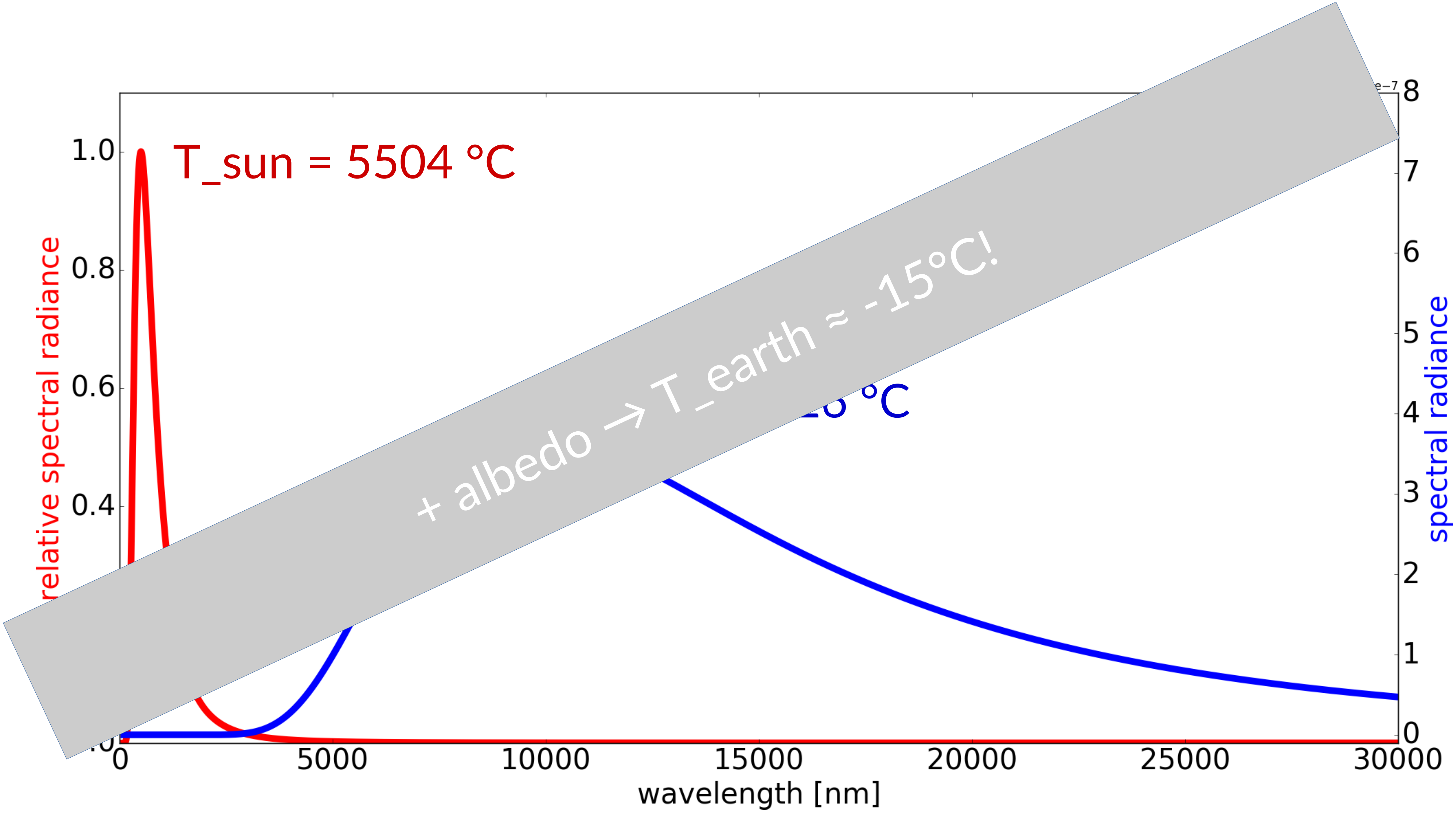
Albedo ≈ 1

Albedo ≈ 0

Albedo ≈ 0.3

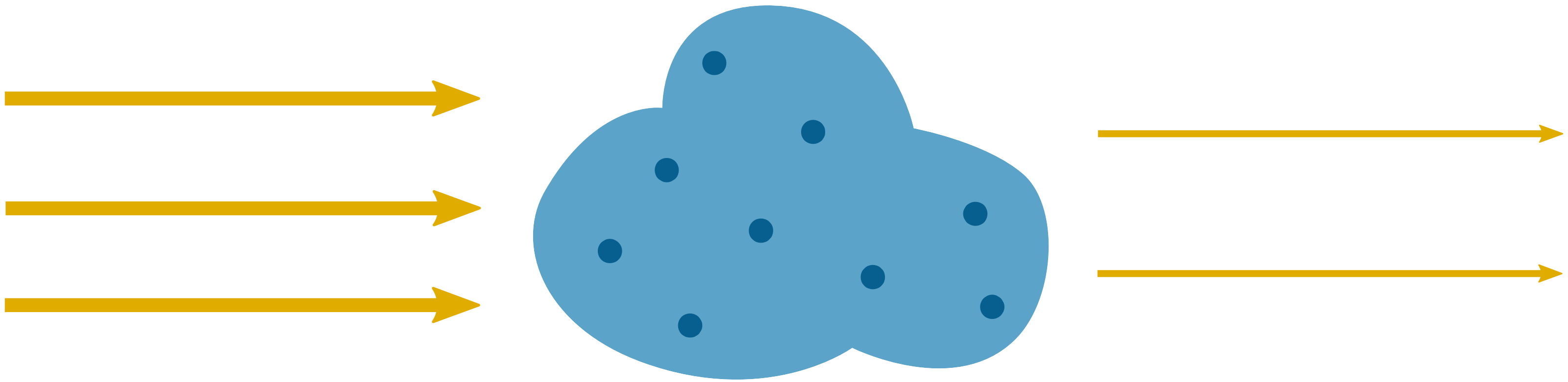
Albedo ≈ 1

Image (earth): https://epic.gsfc.nasa.gov/



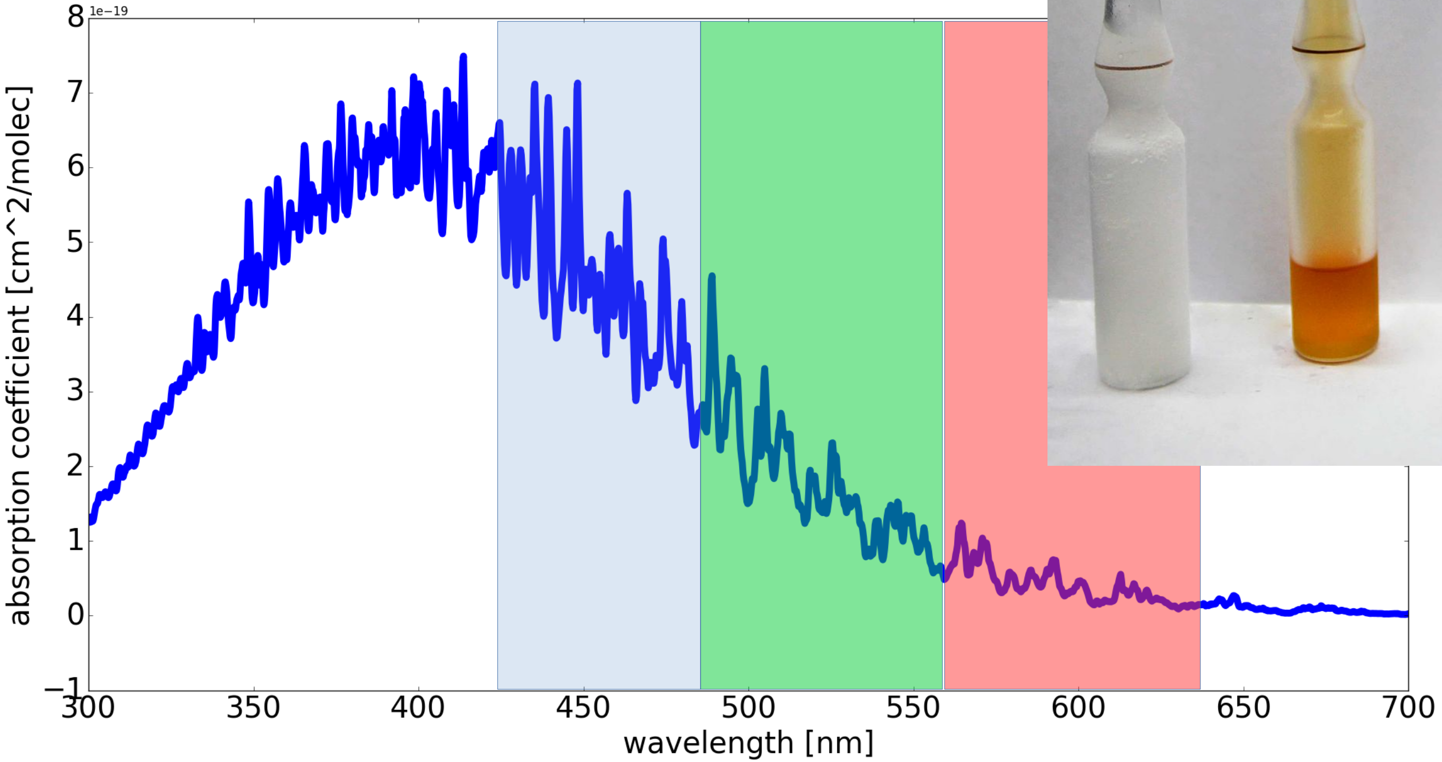
T_sun = 5504 °C
+ albedo → T_earth ≈ -15°C!
relative spectral radiance
spectral radiance
wavelength [nm]
1.0
0.8
0.6
0.4
0
5000
10000
15000
20000
25000
30000
1e−7
8
7
6
5
4
3
2
1
0

Lambert-Beer law: 1729/1852



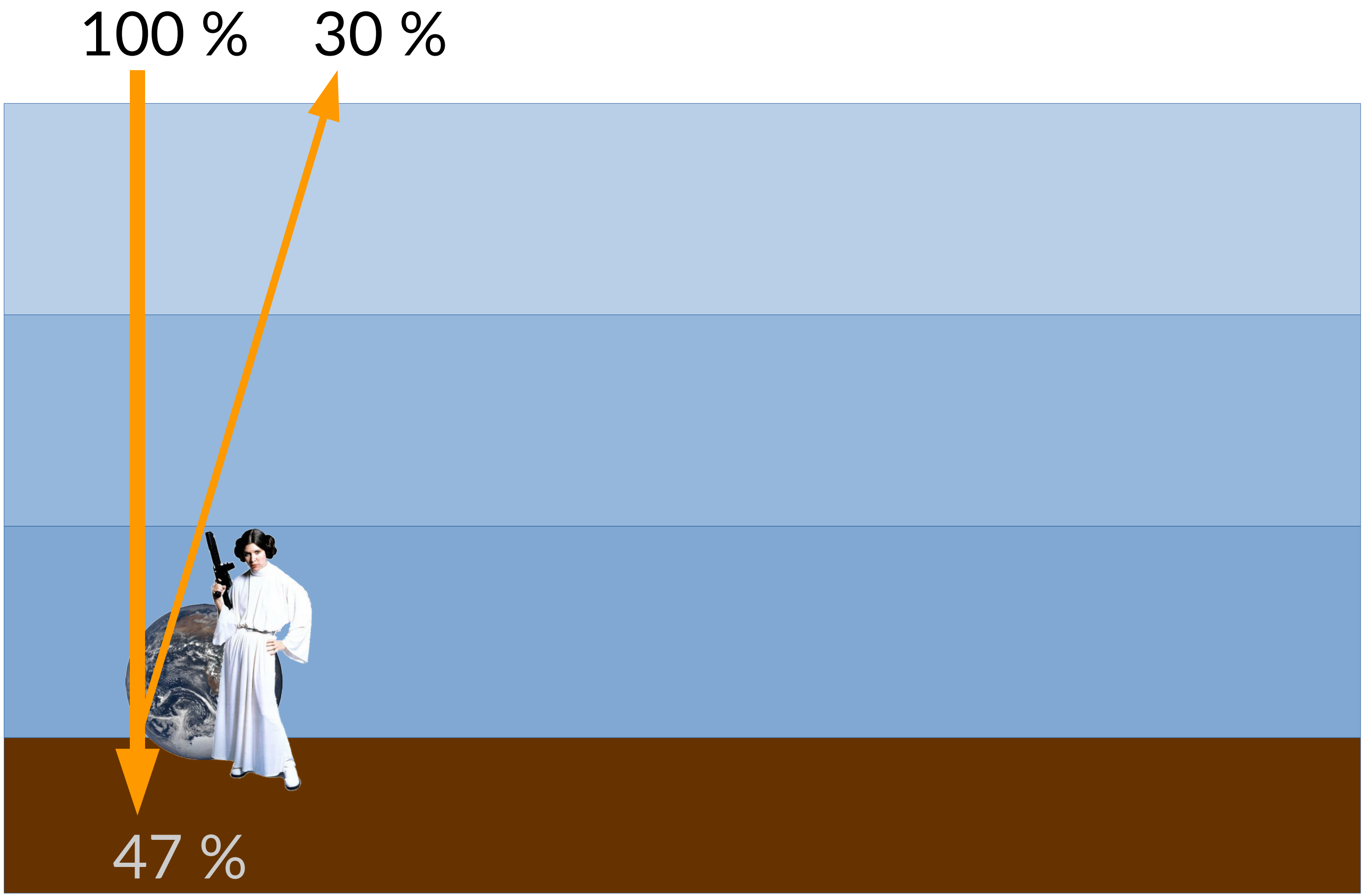
$$I = I_0 \cdot e^{-\sigma \rho L}$$

NO_2

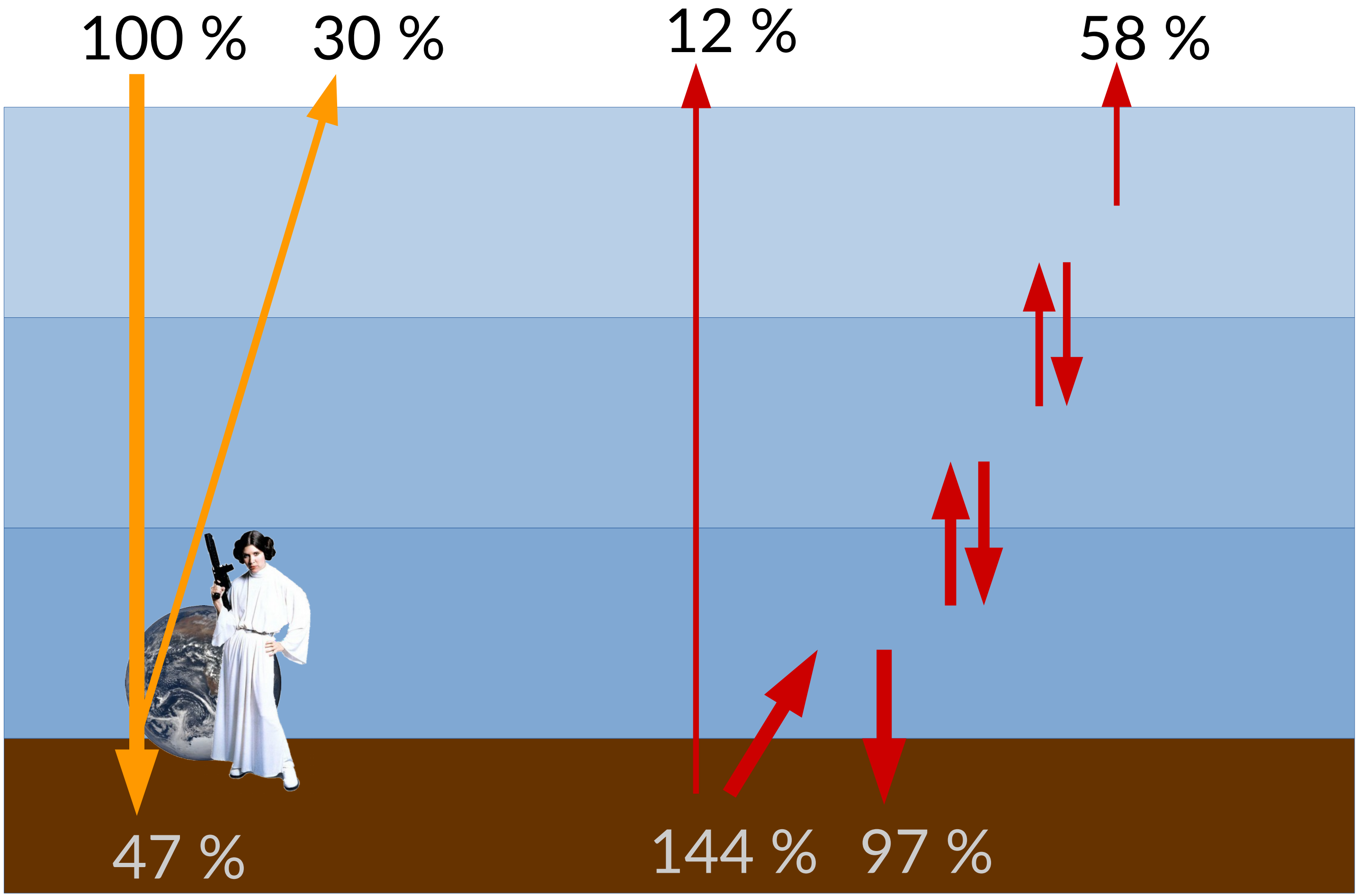


1e−19
absorption coefficient [cm^2/molec]
8
7
6
5
4
3
2
1
0
−1
300
350
400
450
500
550
600
650
700
wavelength [nm]

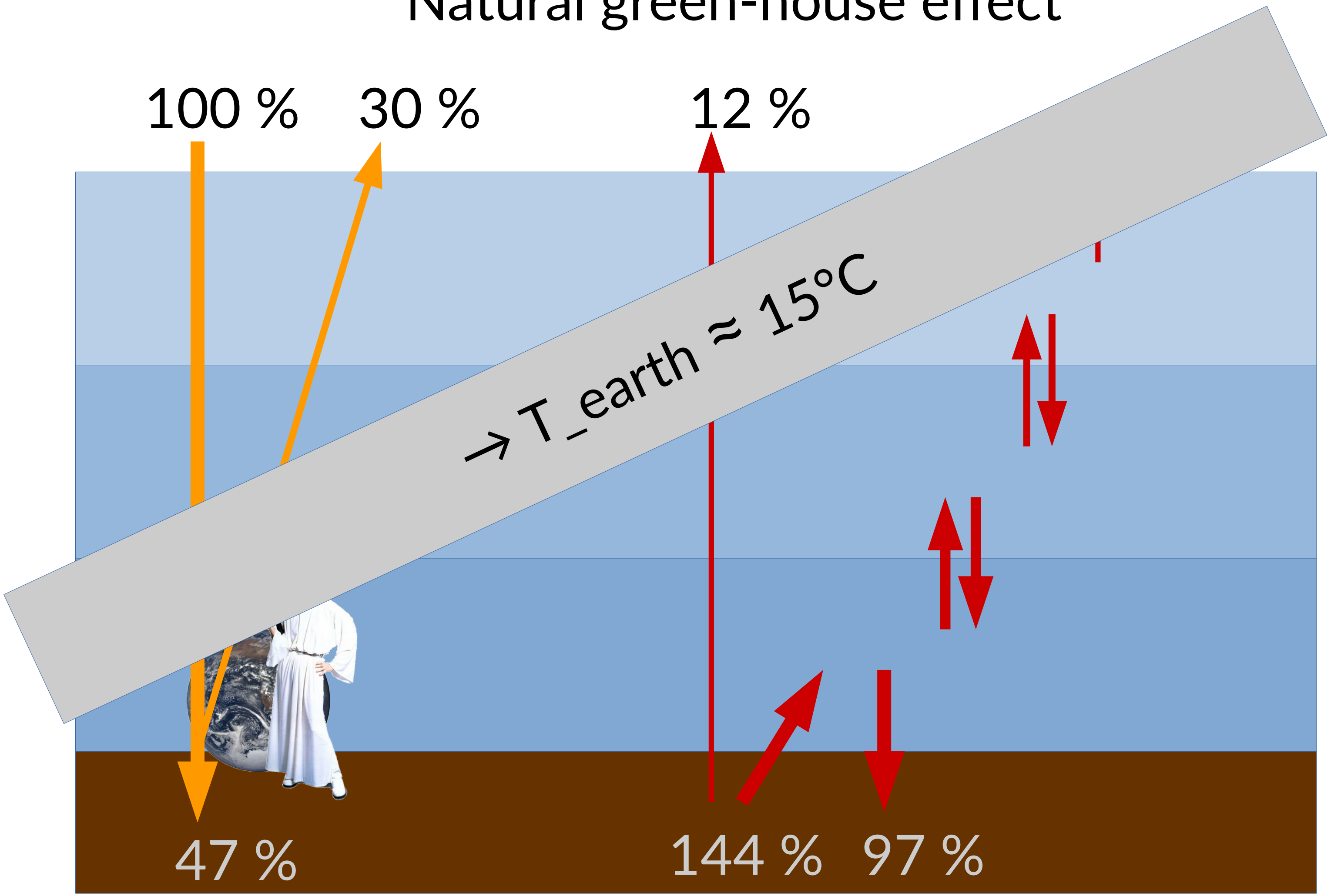
Natural green-house effect



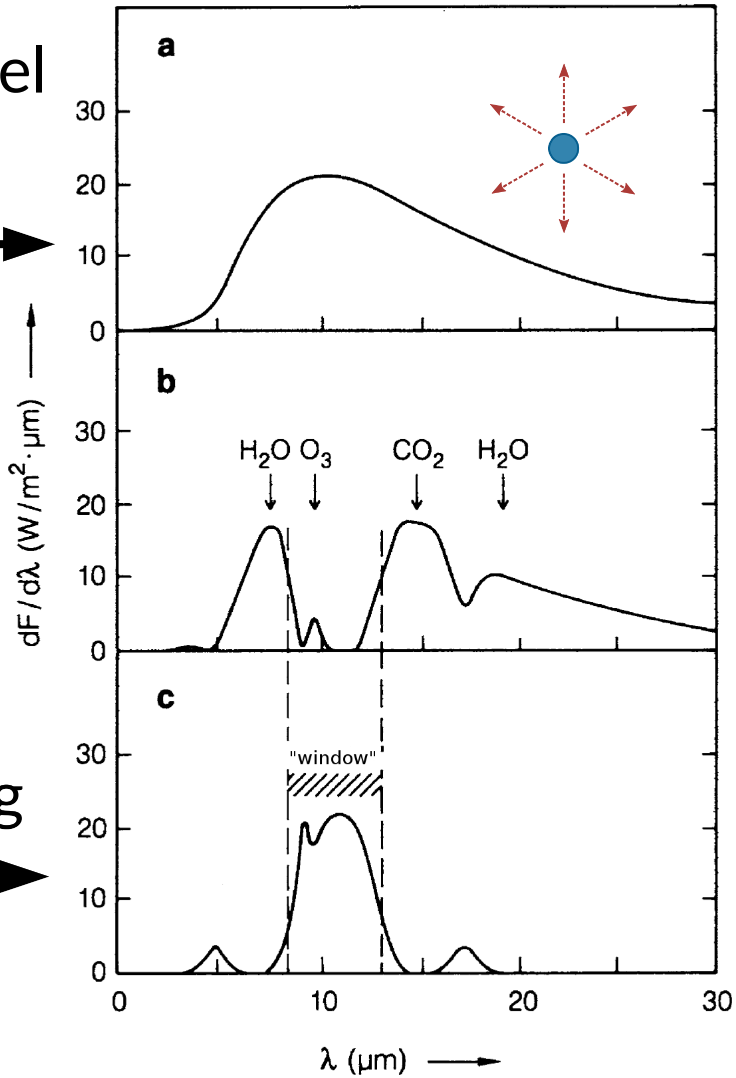
Natural green-house effect



Natural green-house effect

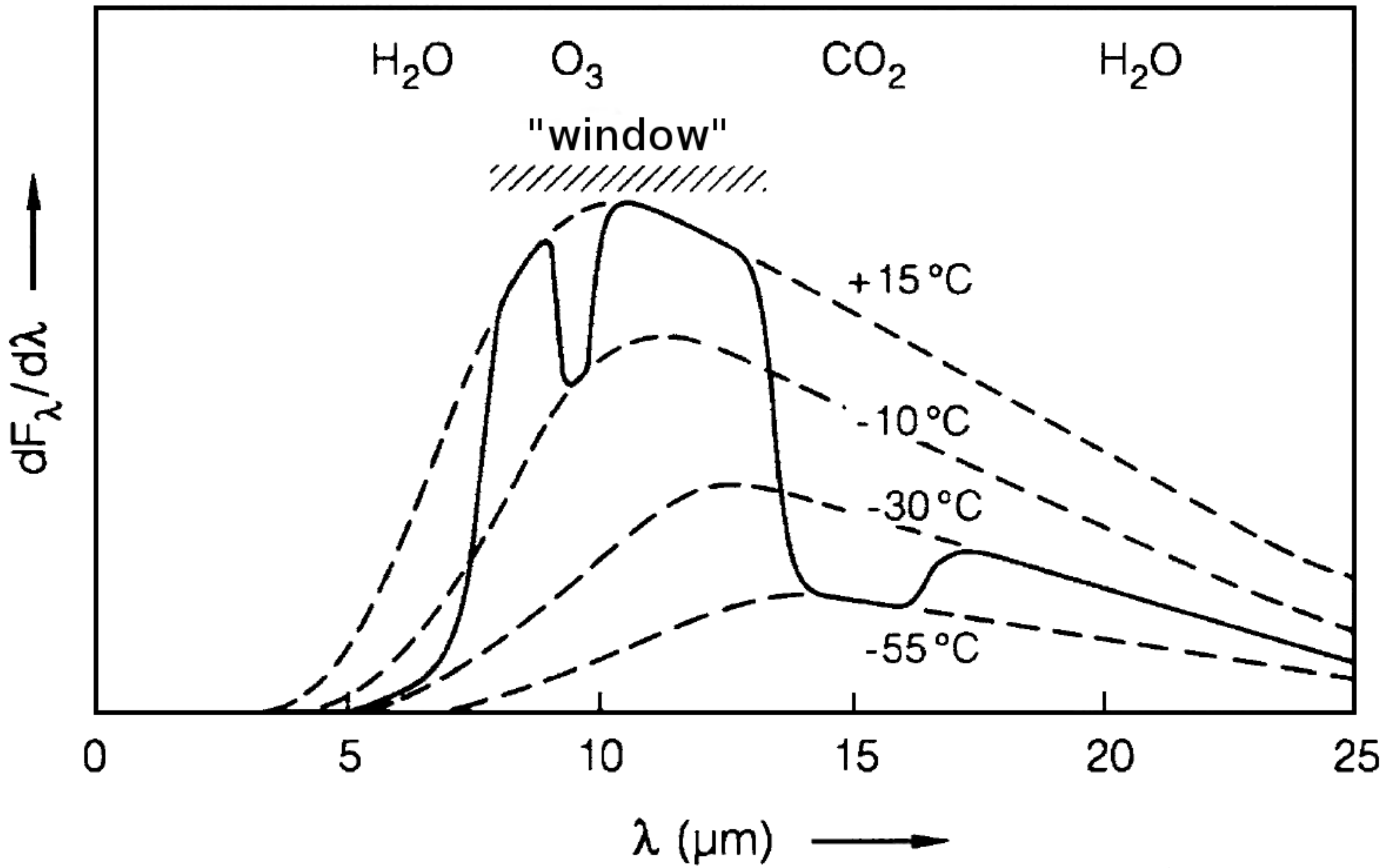


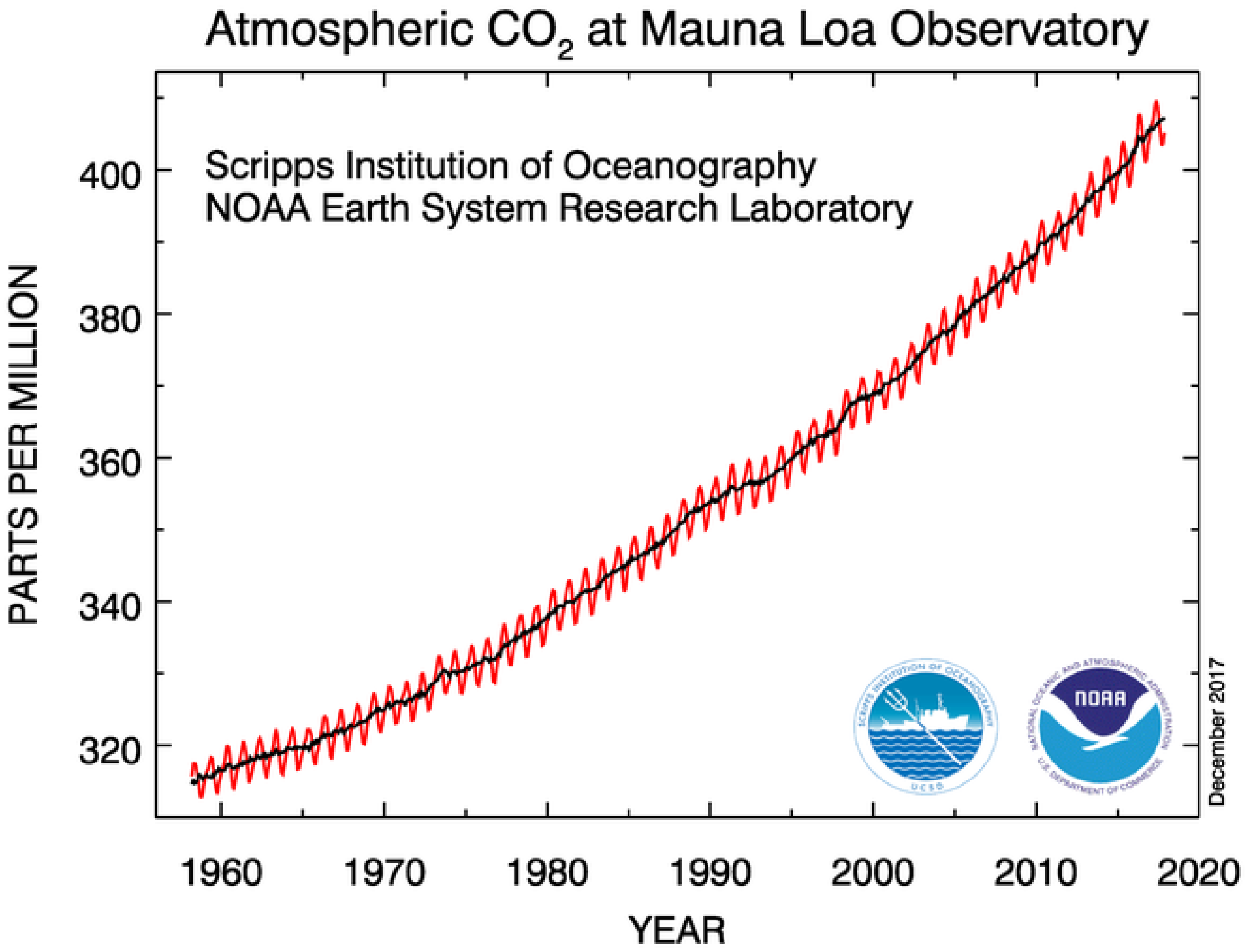
Ground-level up



Atmospheric down

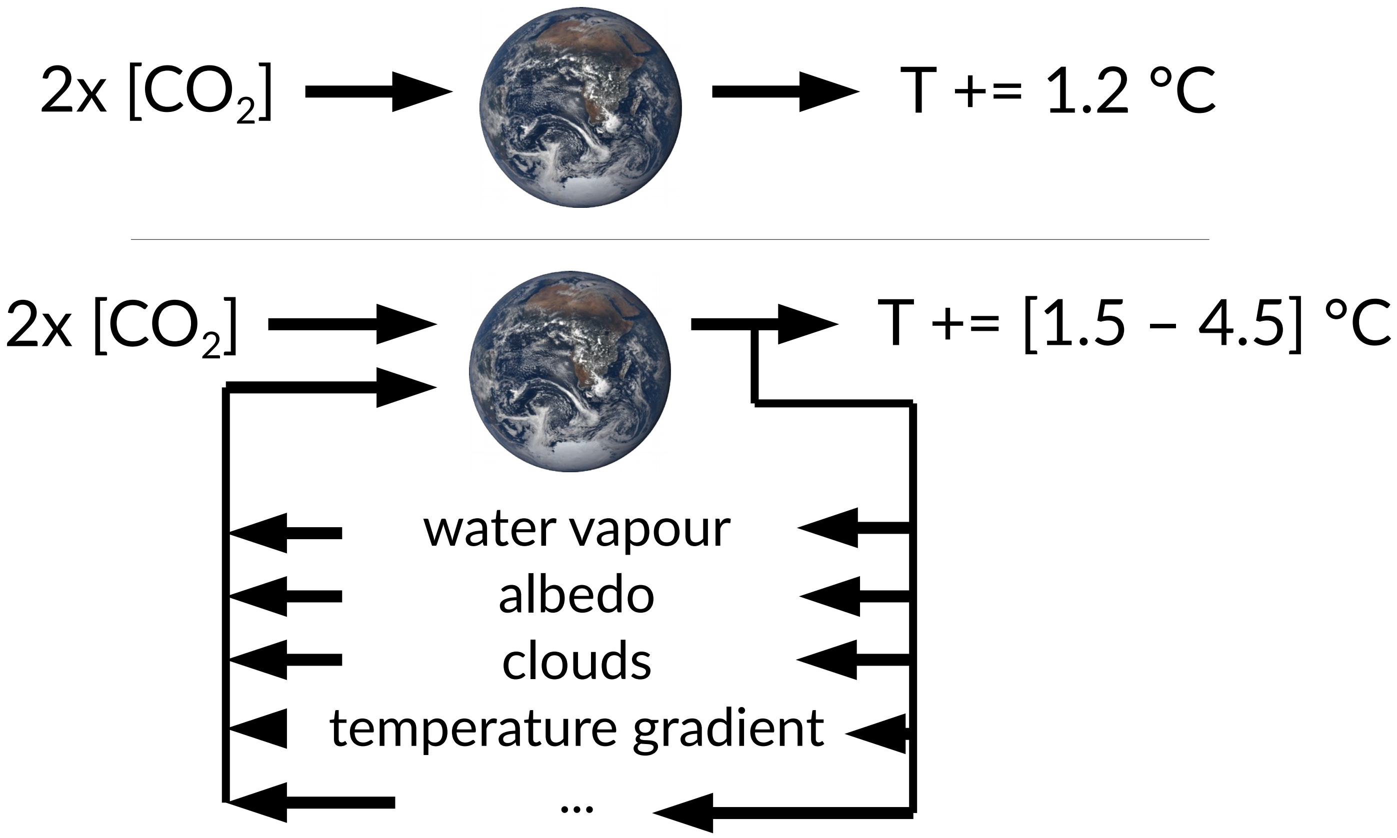
Net outgoing


H2O
O3
CO2
H2O
"window"
+15 °C
-10 °C
-30 °C
-55 °C
dFλ/dλ
0
5
10
15
20
25
λ (µm)



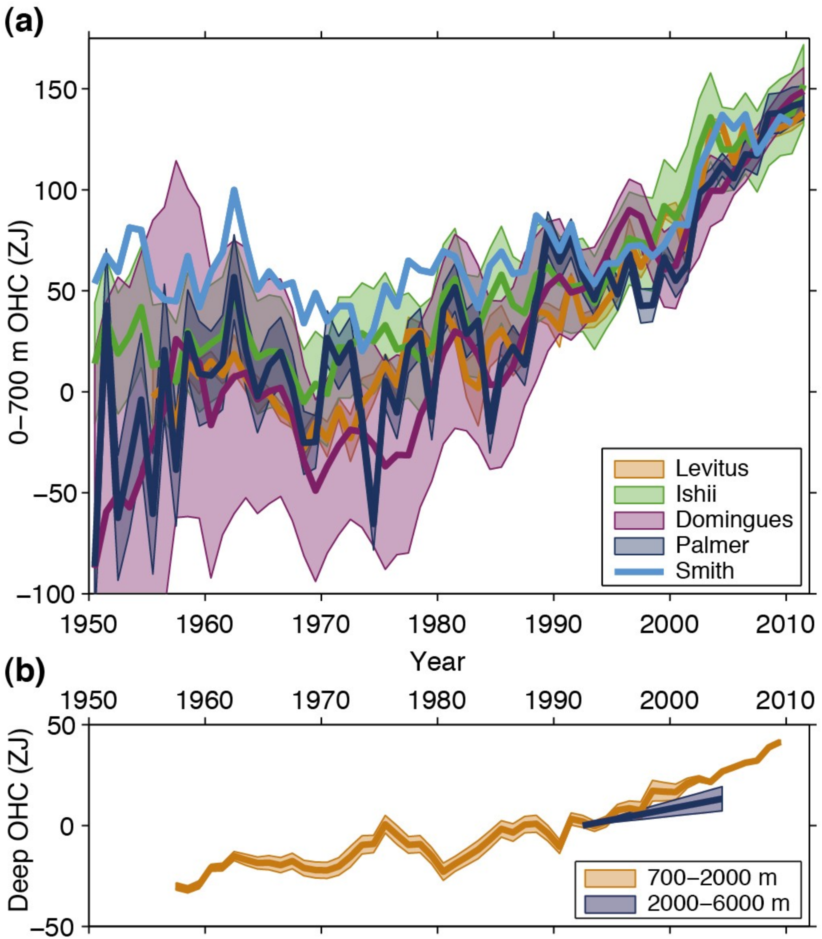
Current CO2 level (September 2017): 402.50 ppm

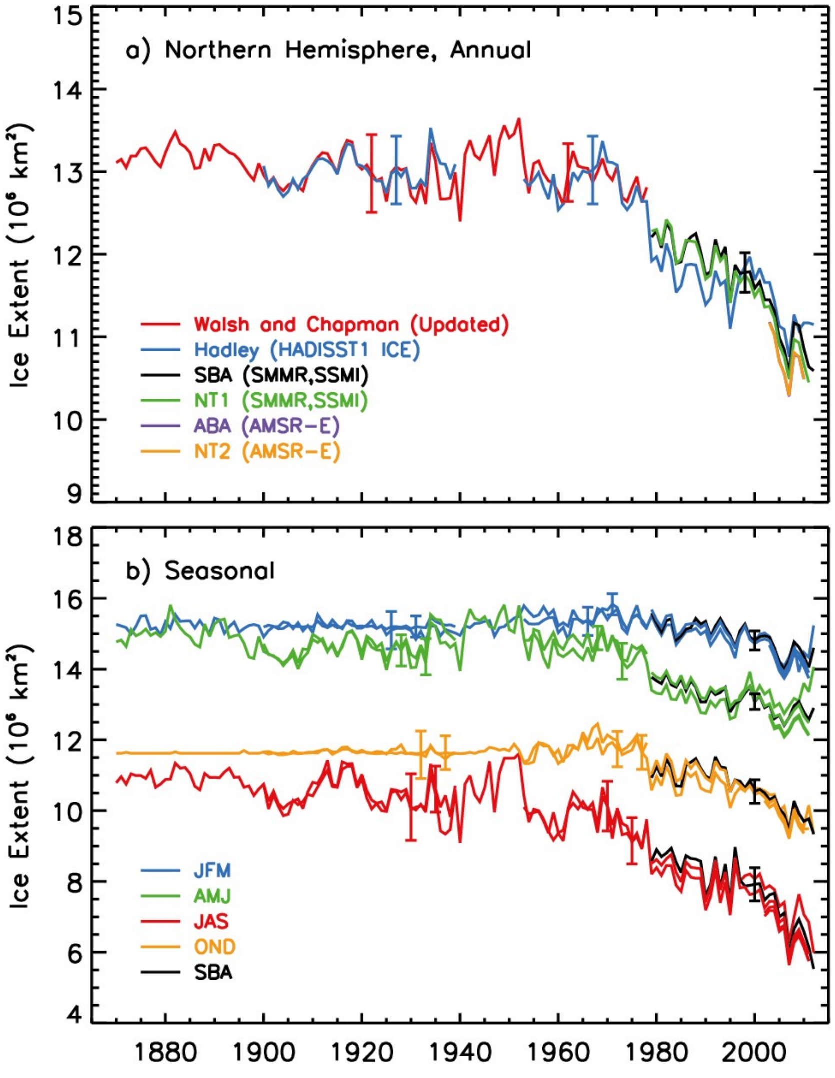
Climate sensitivity



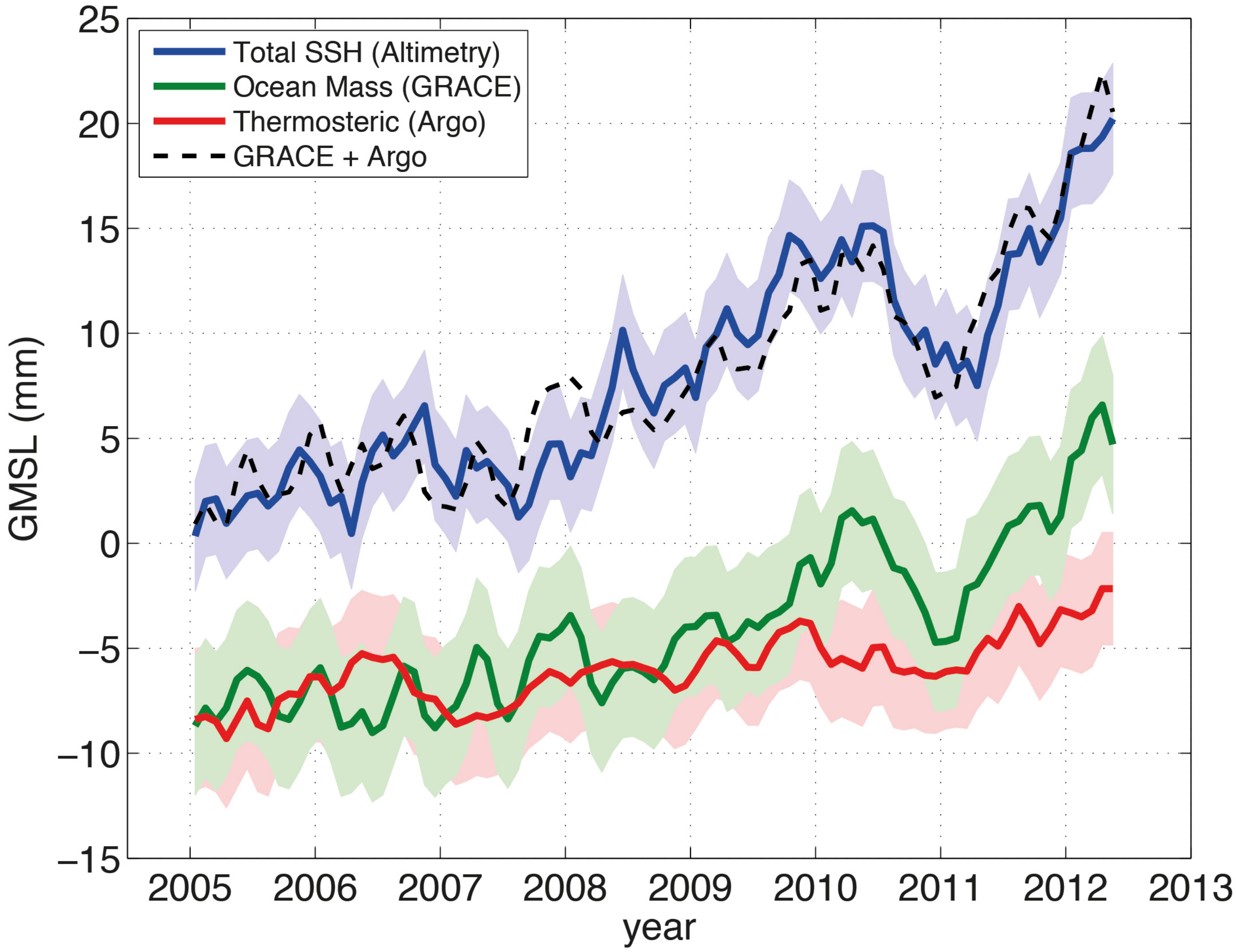
Where does the energy go?

~93 %:

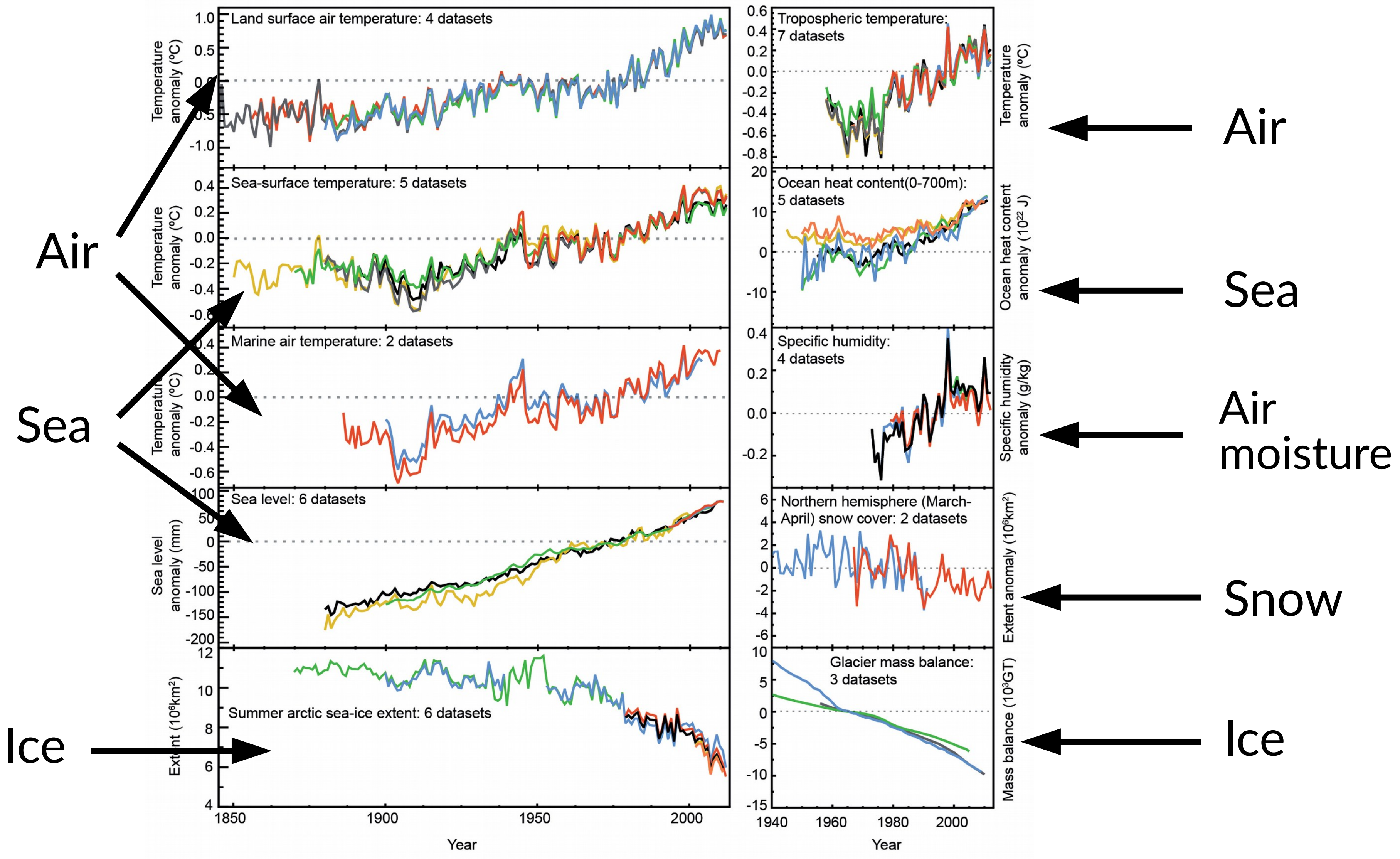




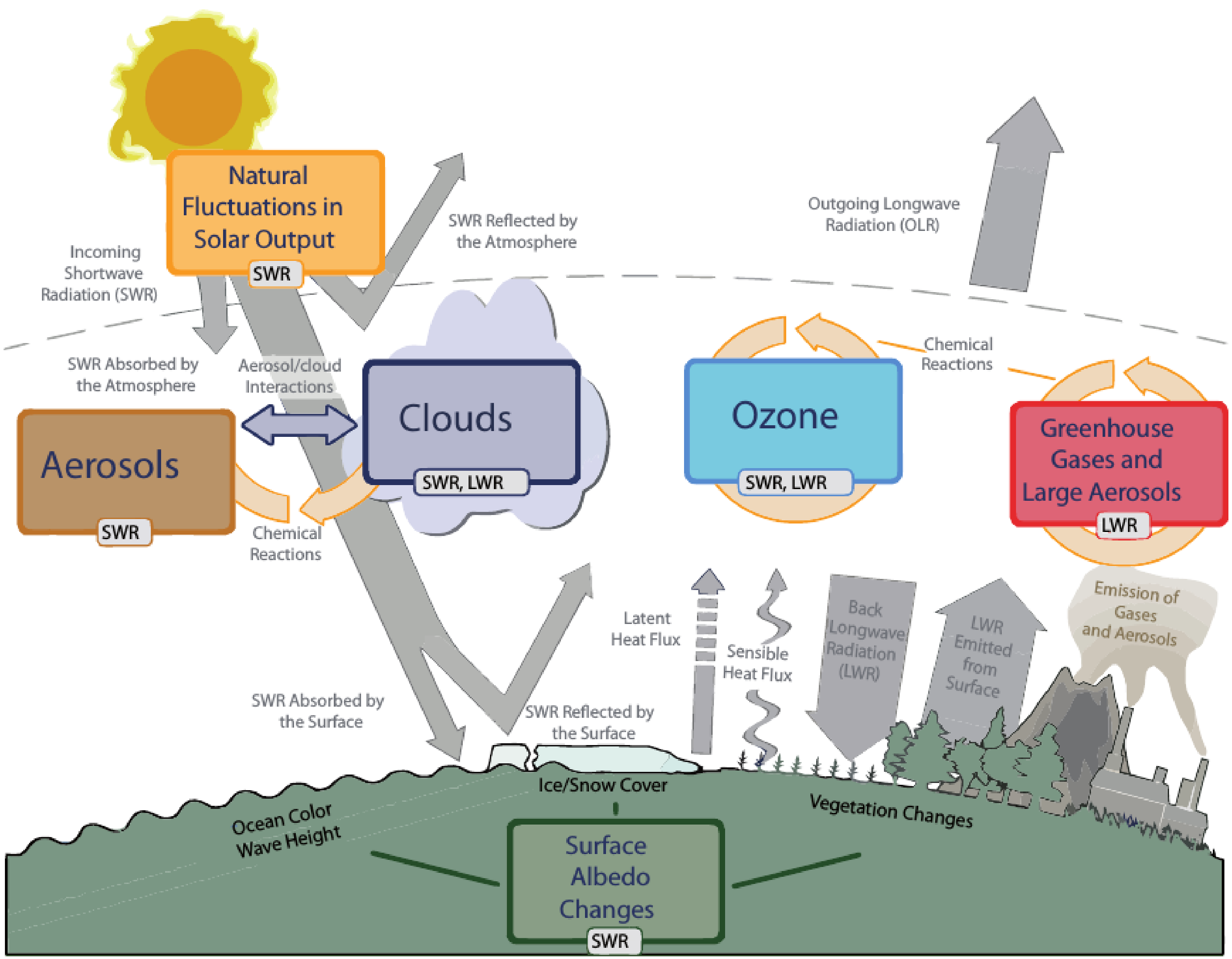
Source: IPCC AR5 WG1, Fig. 4-03



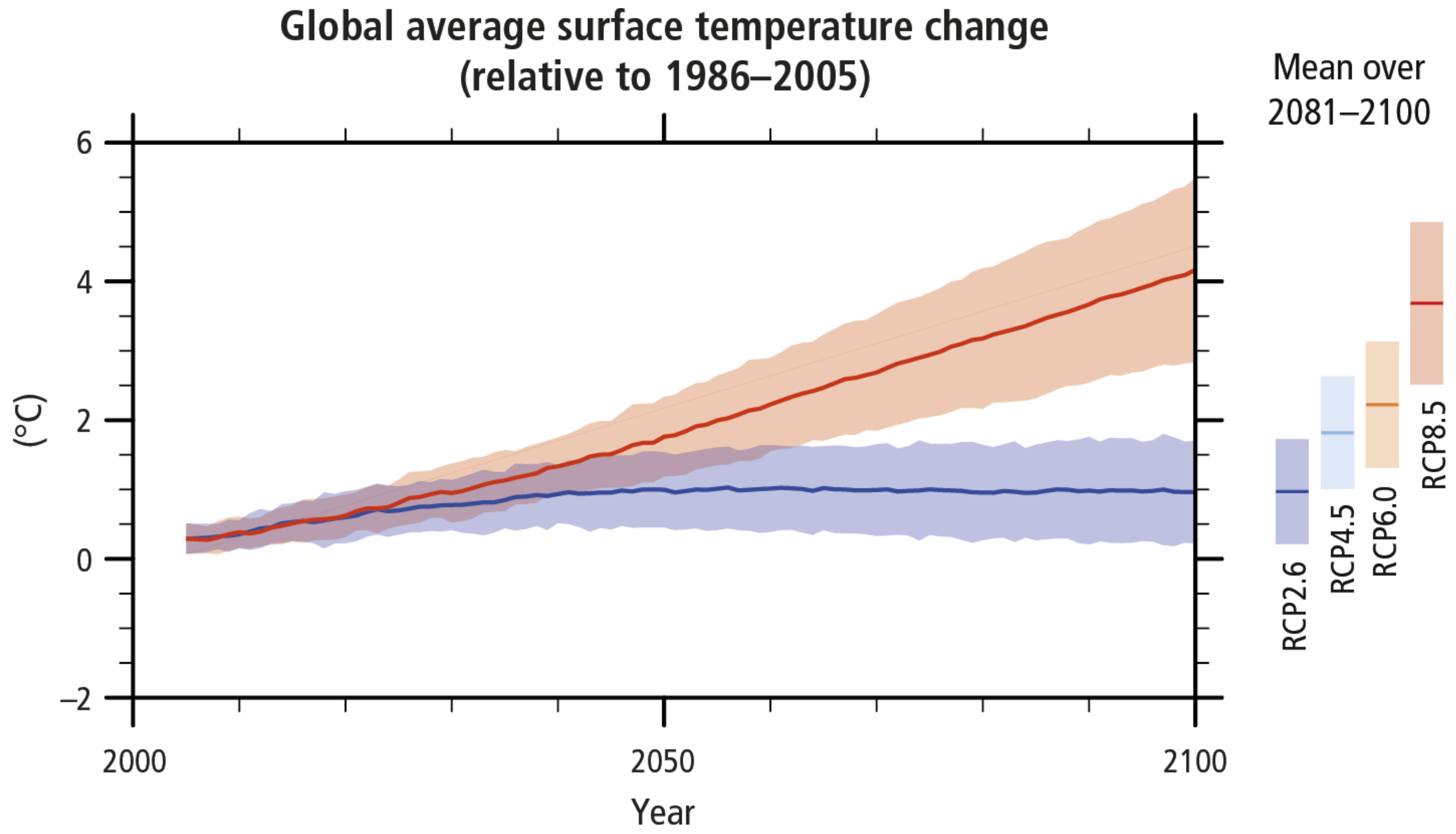
Source: IPCC AR5 WG1, Fig. 13-06



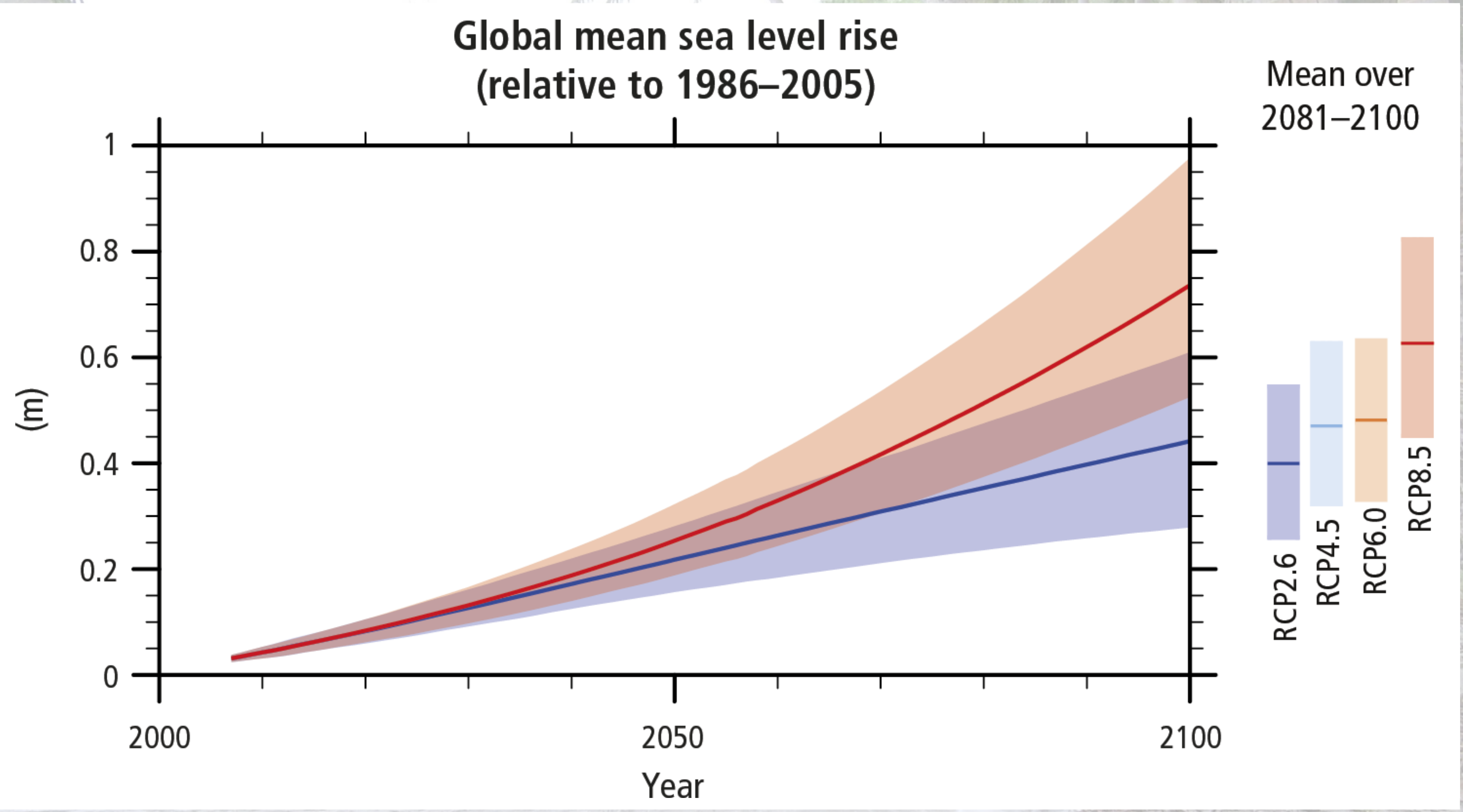
Source: IPCC AR5 WG1, Fig. FAQ-2.1



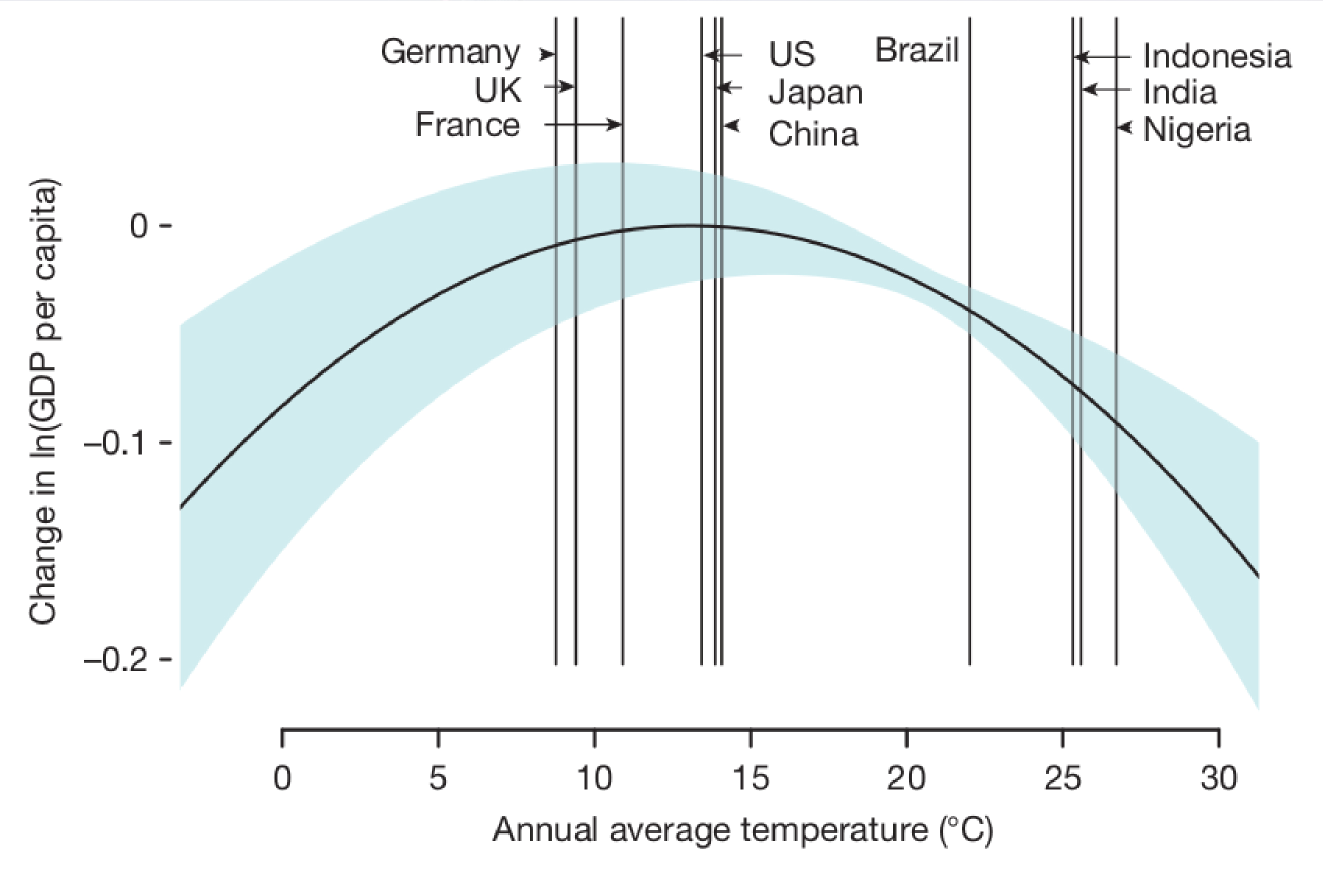
Source: IPCC AR5 WG1, Fig. 1.1



Source: IPCC Assessment Report 4, Synthesis Report, SPM, 2013

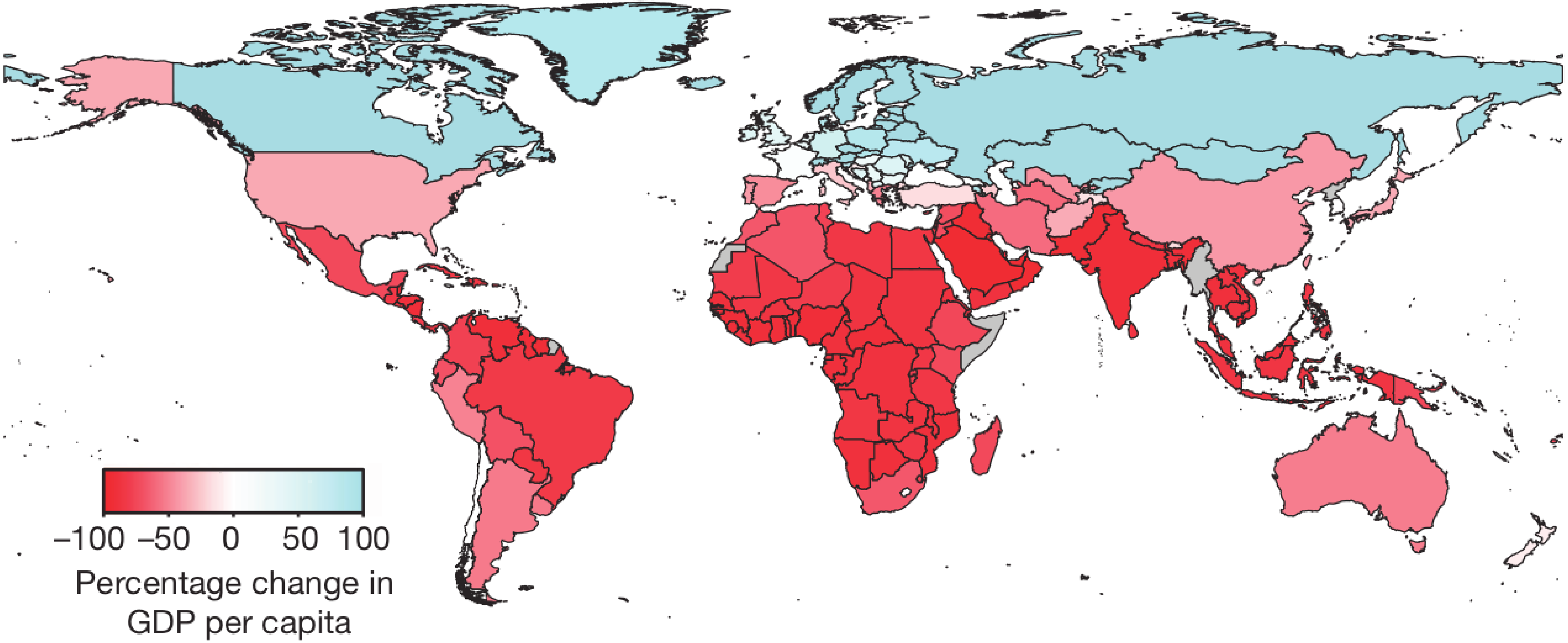


Source: IPCC Assessment Report 4, Synthesis Report, SPM, 2013



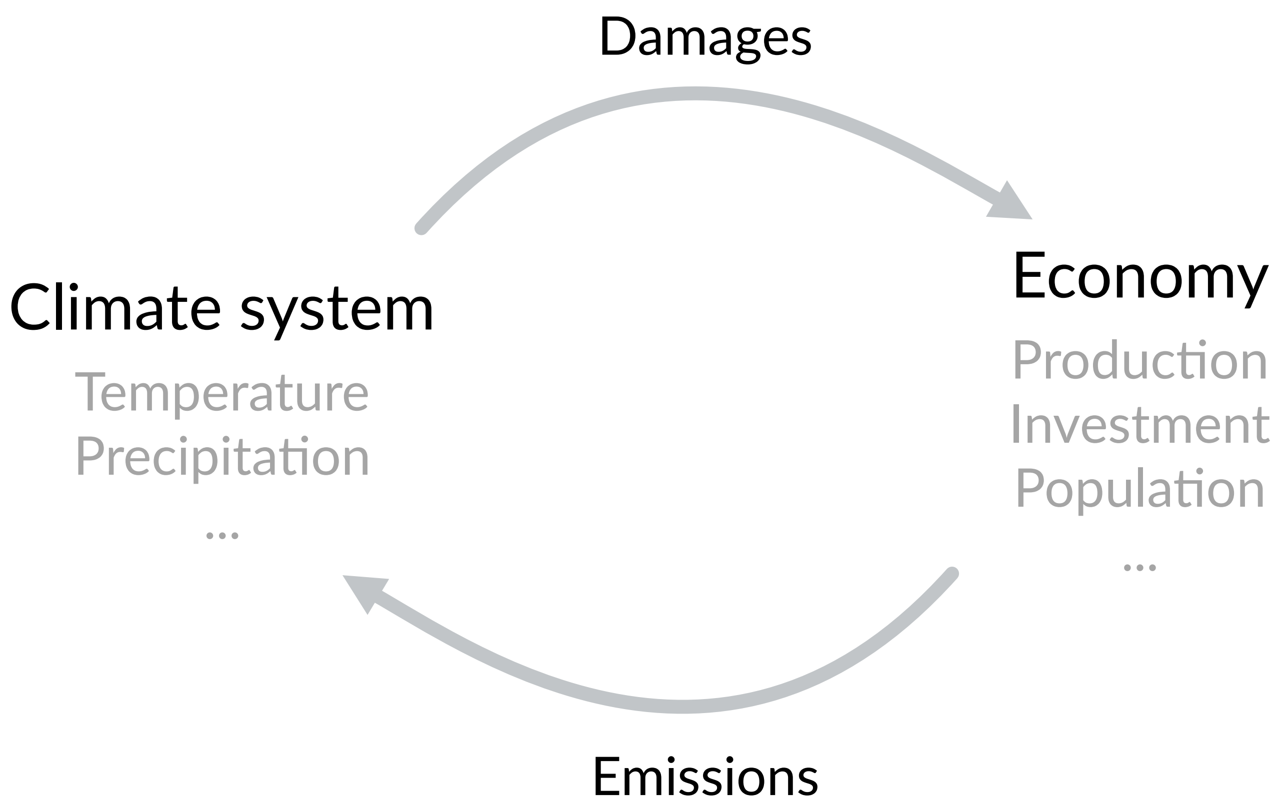
Source: Burke, Hsiang, Miguel. Global non-linear effect of temperature on economic production, Nature (2015)

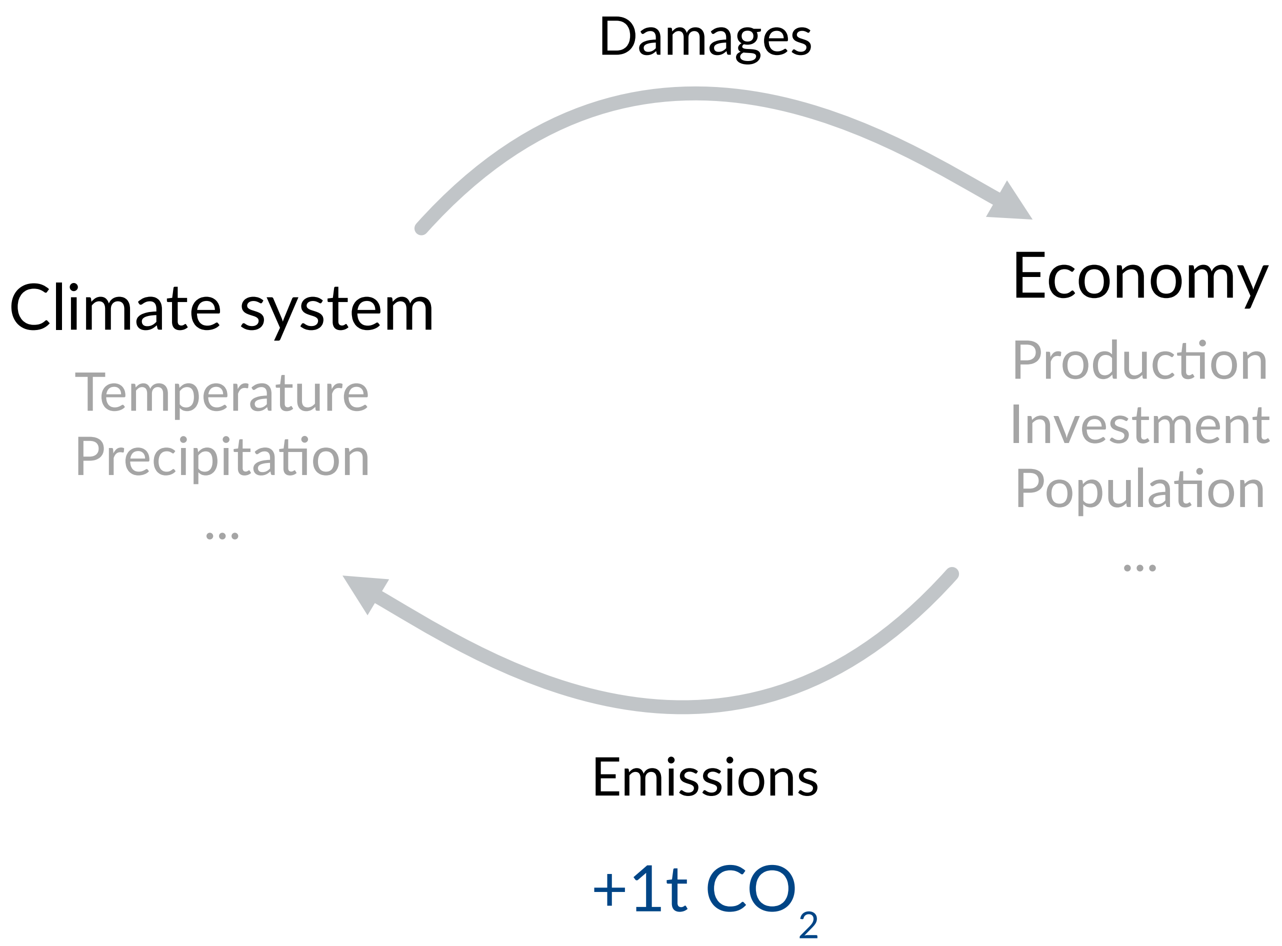
Image (cropped): Wikimedia Commons / Diliff, CC



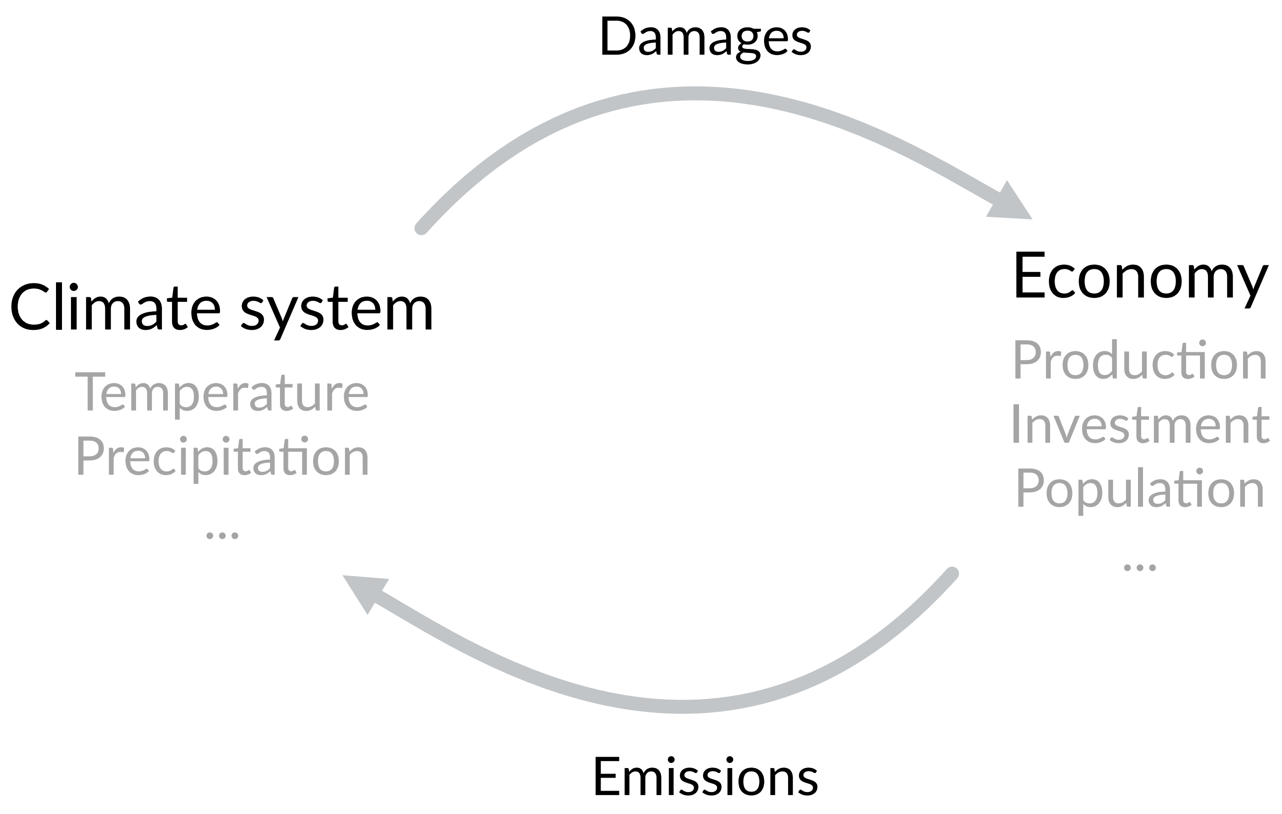
Source: Burke, Hsiang, Miguel. Global non-linear effect of temperature on economic production, Nature (2015)

Social Cost of Carbon


Damages
Climate system
Temperature
Precipitation
...
Economy
Production
Investment
Population
...
Emissions


Damages
Climate system
Temperature
Precipitation
...
Economy
Production
Investment
Population
...
Emissions
+1t CO_2

+Social Cost of Carbon



+1t CO_2

Social cost of carbon SCC

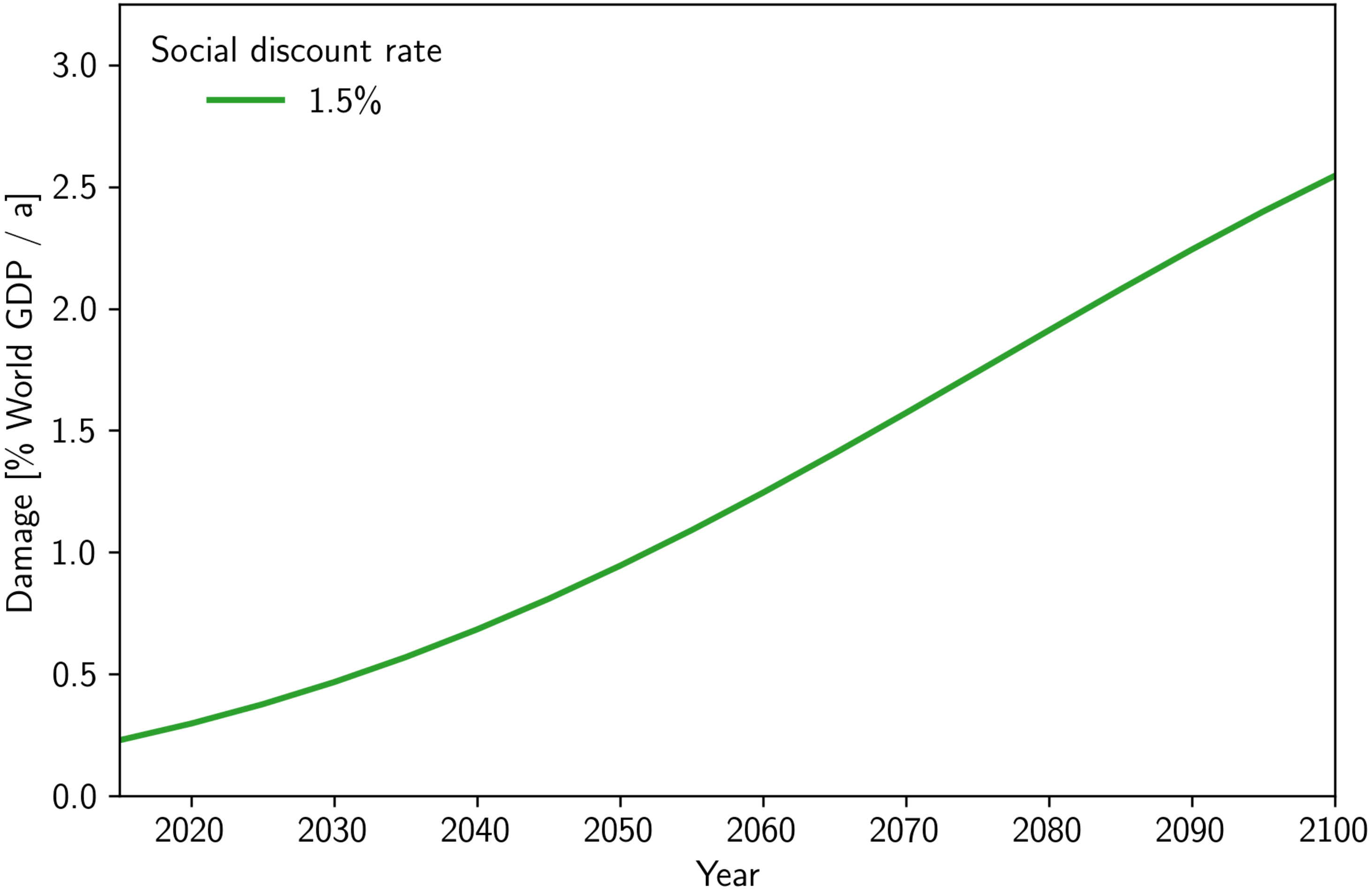
Climate damages D

Temperature T

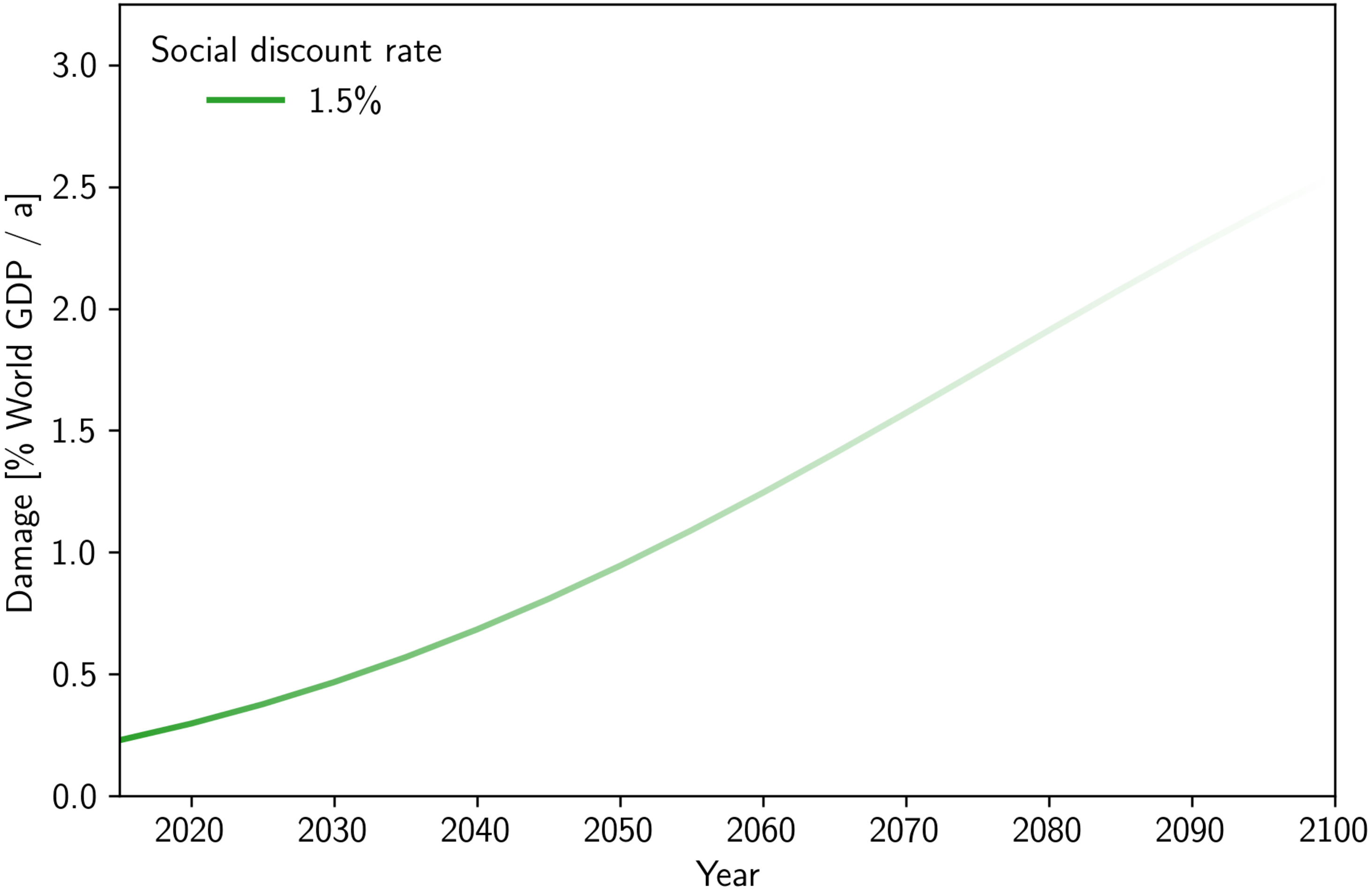
$$SCC(t_0) \equiv \int_{t_0}^{\infty} \left(\frac{1}{1+r}\right)^{(t-t_0)} \frac{dD(T(t))}{dT(t)} \frac{dT(t)}{dE(t_0)} dt$$

Social discount rate r

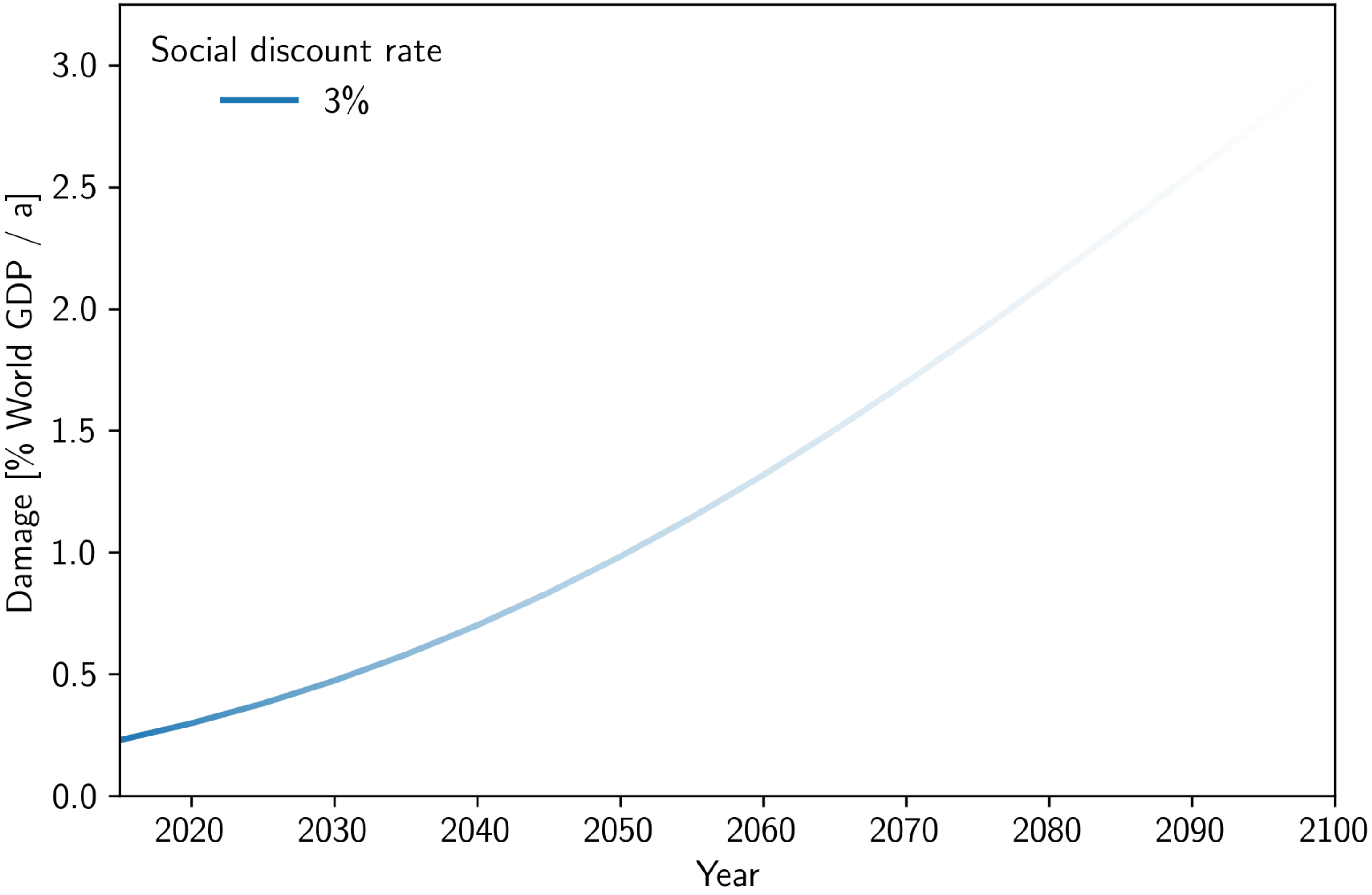
Carbon emissions E



Model used: DICE, Nordhaus, W. The Climate Casino. Yale University Press. (2013).



Model used: DICE, Nordhaus, W. The Climate Casino. Yale University Press. (2013).



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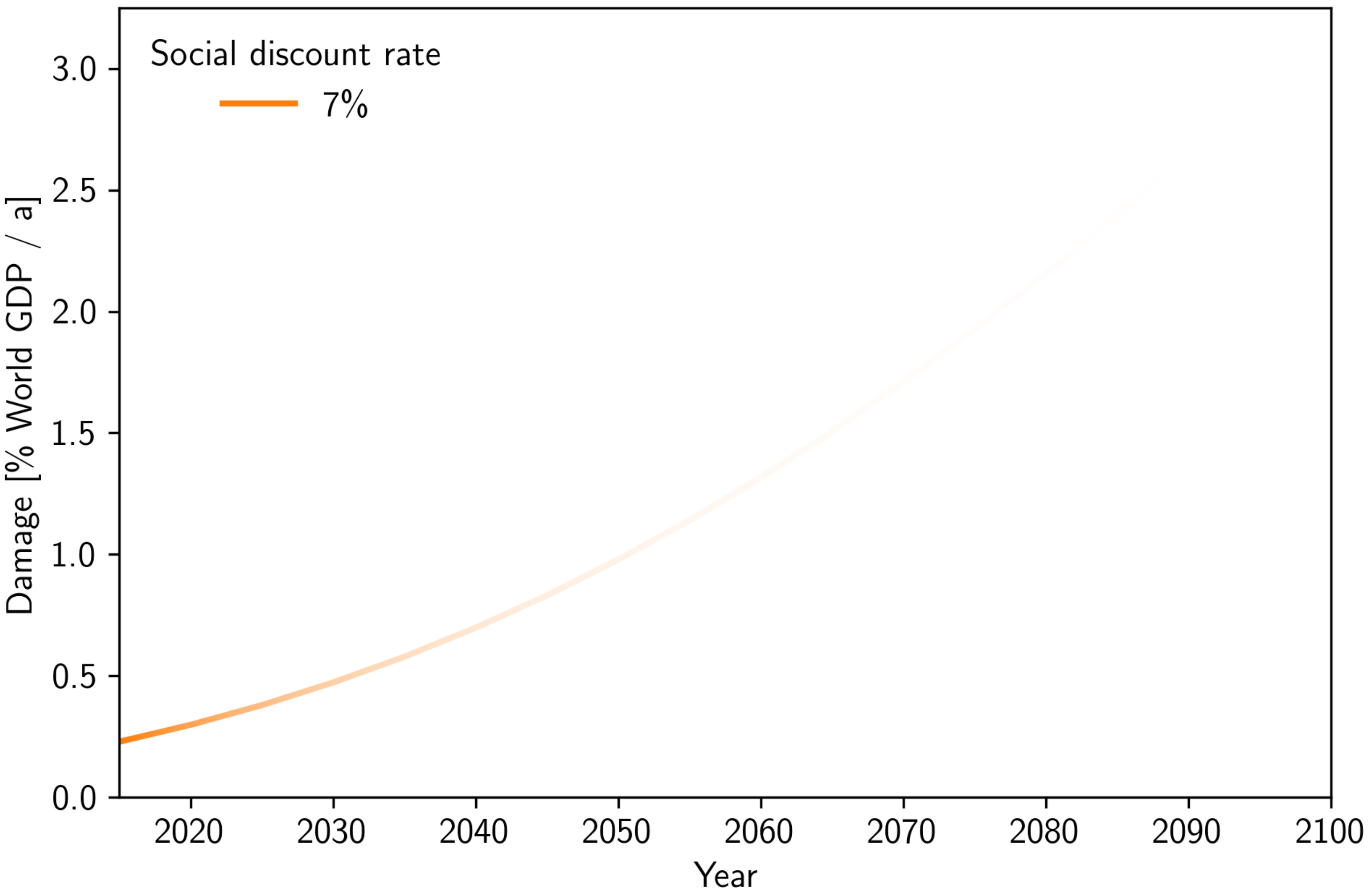

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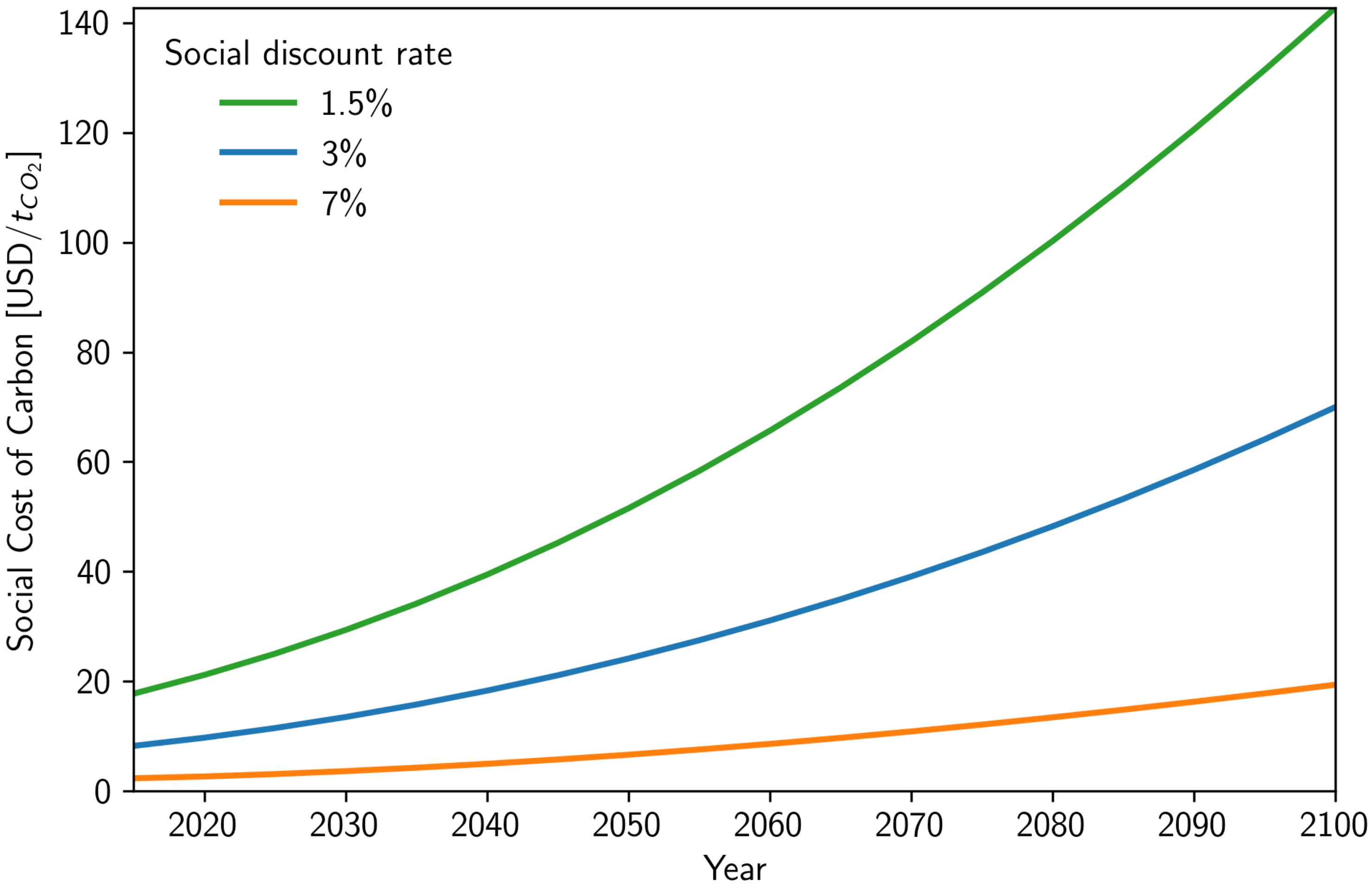

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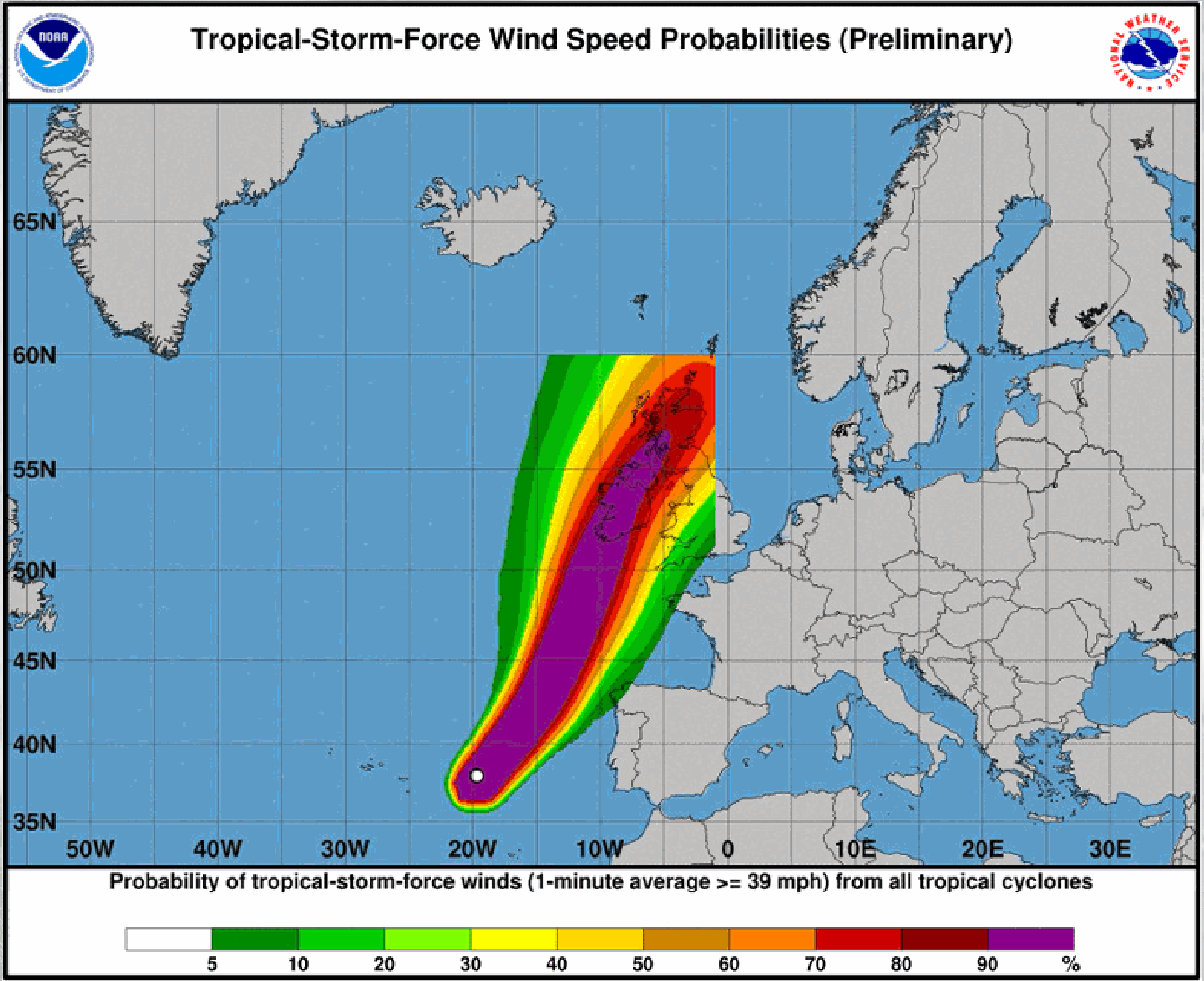

Source: National Hurricane Center (www.nhc.noaa.gov)

Image (cropped): Wikimedia Commons / NASA, CC

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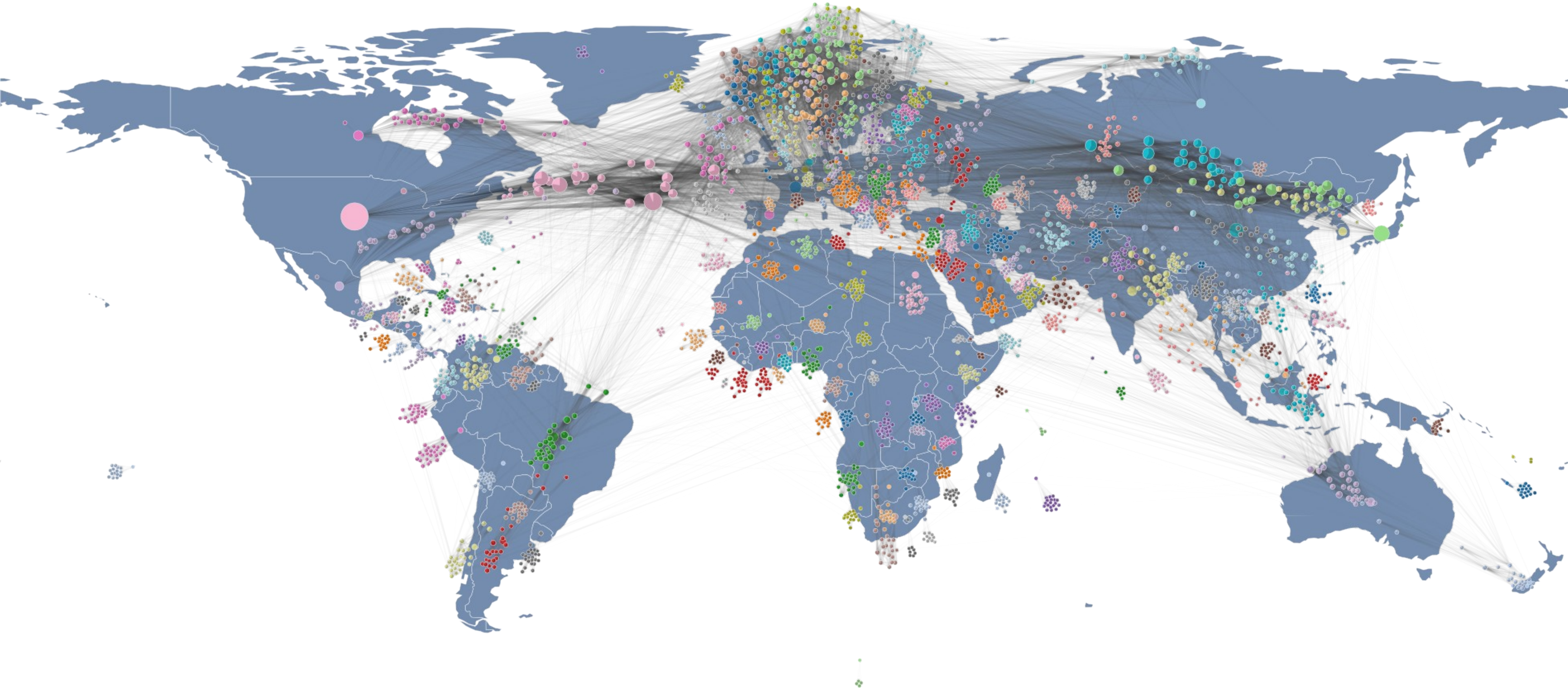
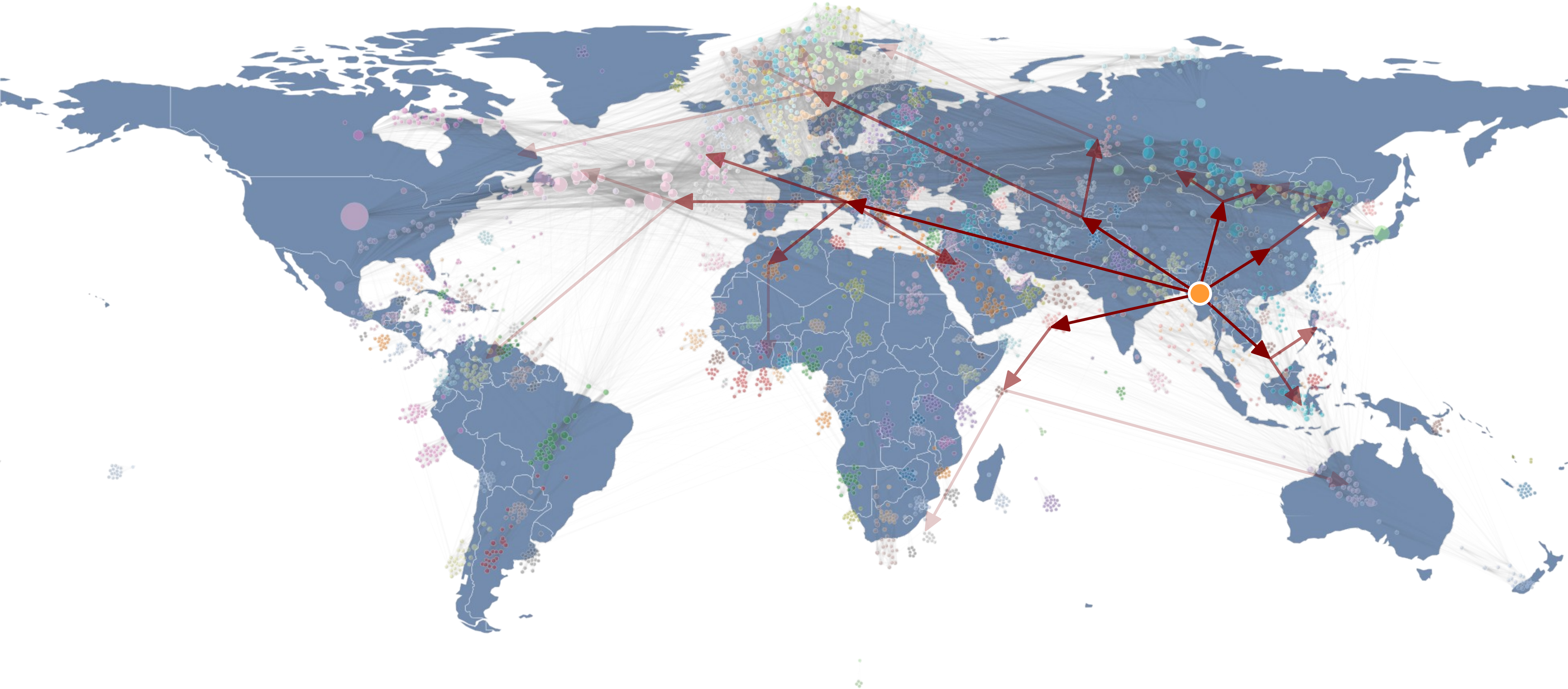


Data source: Lenzen, Moran, Kanemoto, Geschke. Building eora: a global multi-region input–output database at high country and sector resolution, Econ. Sys. Res. (2013)



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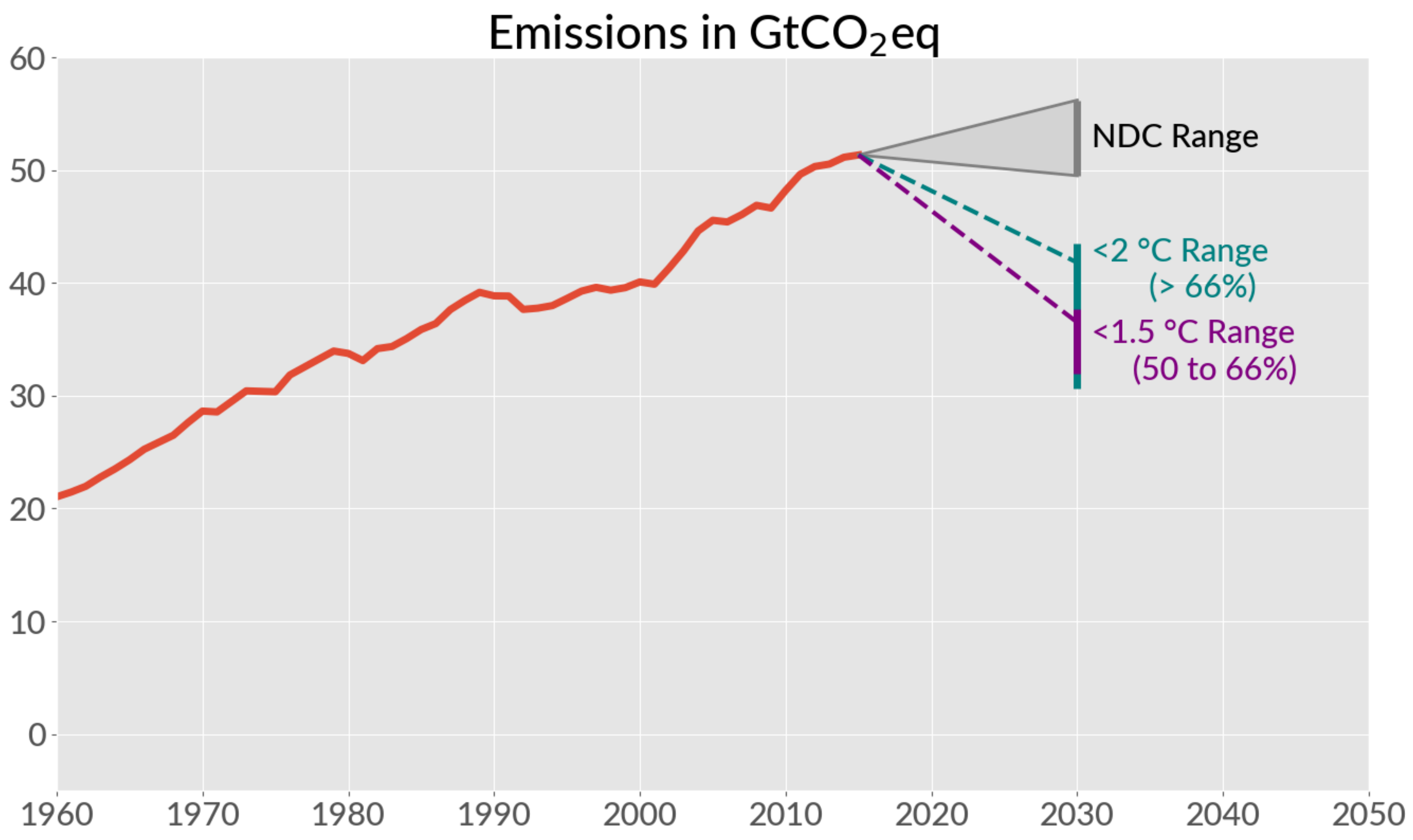
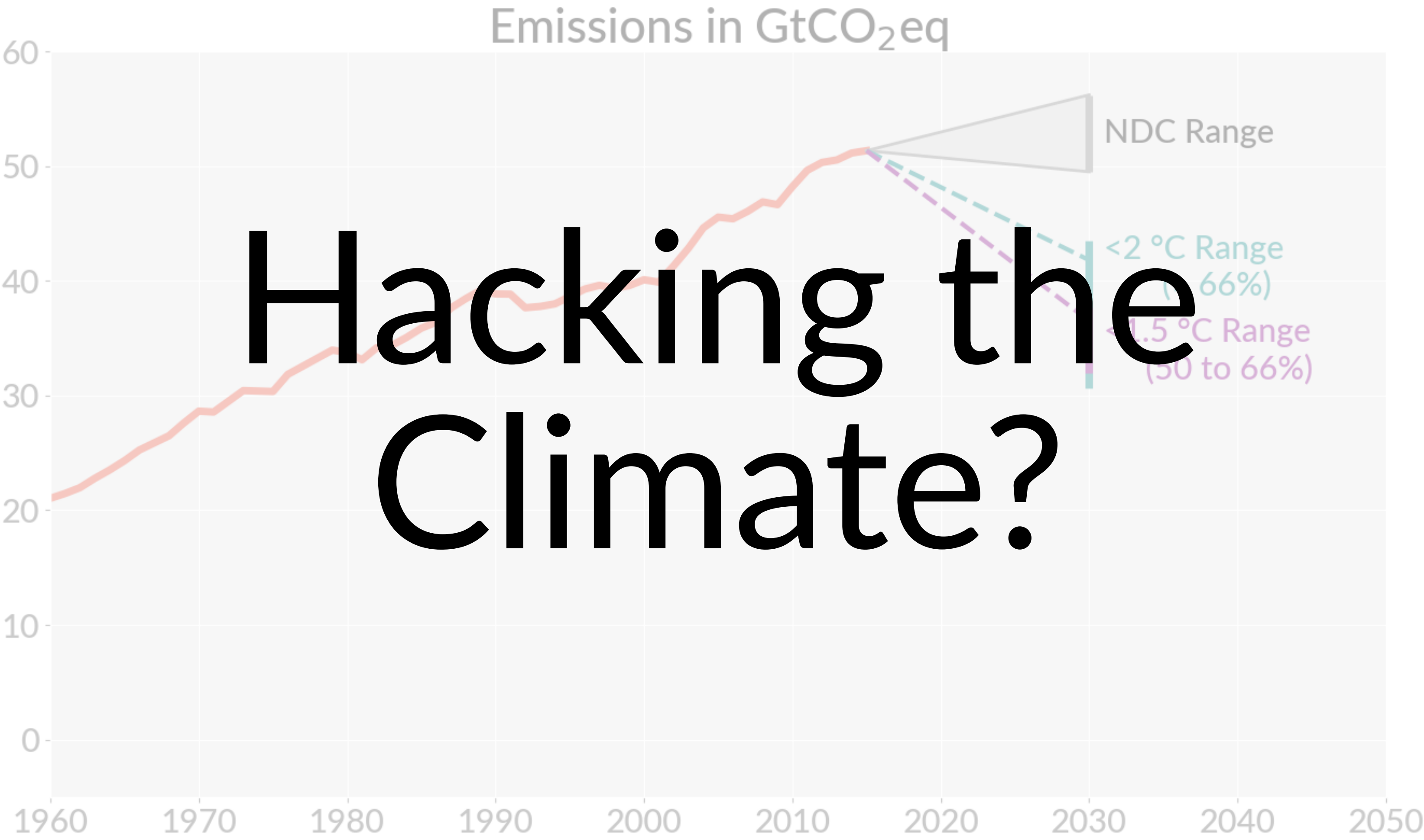


Source: PRIMAP-hist / Global Carbon Budget (2017) / UNEP Gap Report (2017)

Hacking the Climate?



Source: PRIMAP-hist / Global Carbon Budget (2017) / UNEP Gap Report (2017)

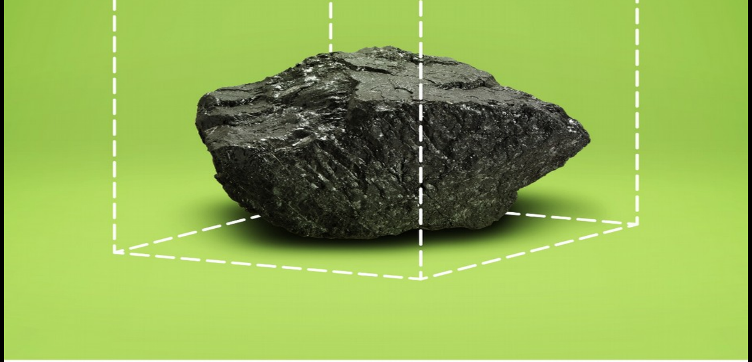
THE NEW YORKER

ANNALS OF SCIENCE NOVEMBER 20, 2017 ISSUE

CAN CARBON-DIOXIDE REMOVAL SAVE THE WORLD?

CO_2 could soon reach levels that, it's widely agreed, will lead to catastrophe.

By Elizabeth Kolbert



MATT CHASE FOR WIRED

ABBY RABINOWITZ AND AMANDA SIMSON SCIENCE
12.10.17 07:00 AM

THE DIRTY SECRET OF THE WORLD'S PLAN TO AVERT CLIMATE

The Economist

Subscribe

Sucking up carbon

Greenhouse gases must be scrubbed from the air

SPIEGEL ONLINE

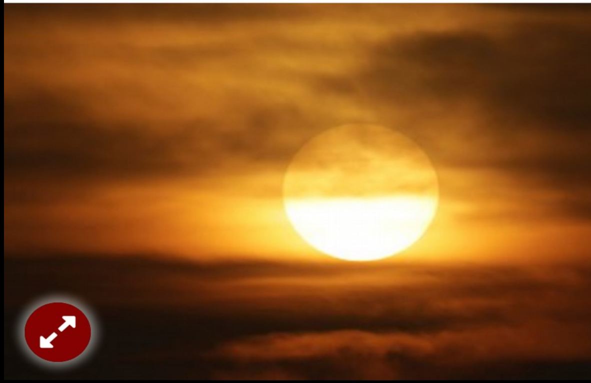
WISSENSCHAFT

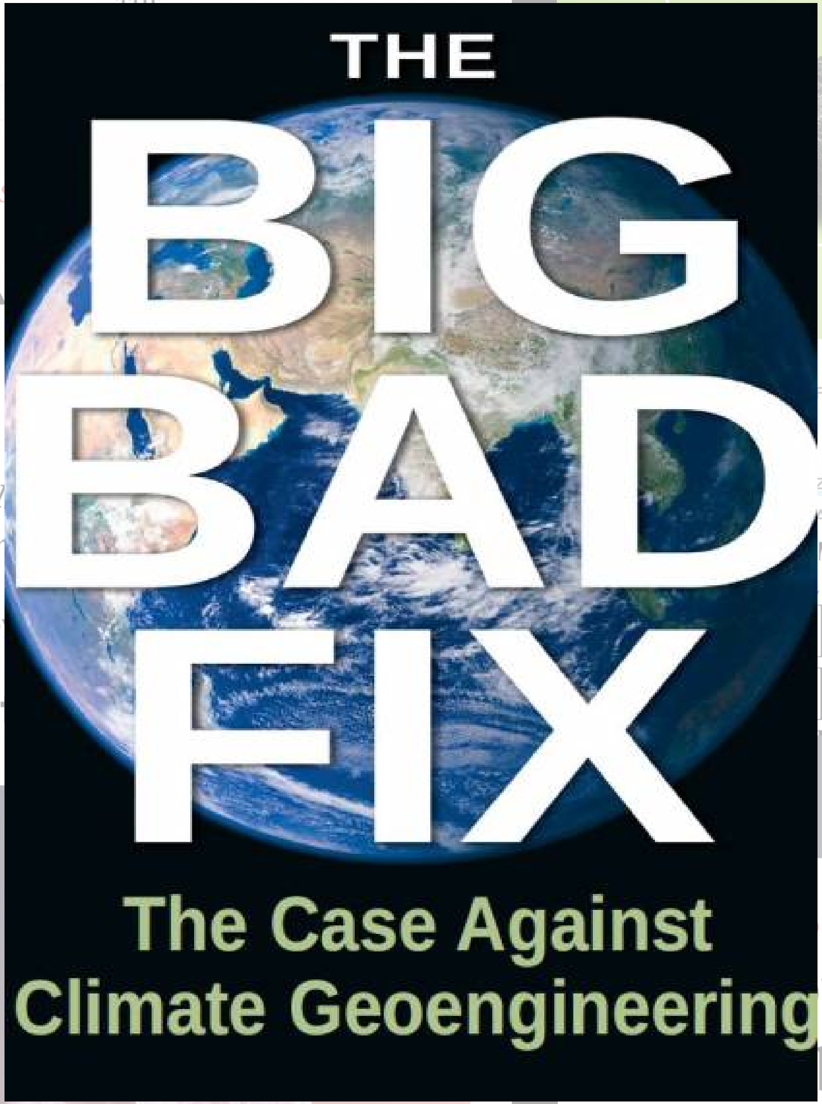
Geoengineering-Experiment

US-Forscher will Sonnenverdunklung testen

Den Klimawandel mit feinen Partike Luft stoppen - kann das funktioniere Interview erklärt Harvard-Forscher D Keith sein Ballon-Experiment - und w die Erforschung von Geoengineering wichtig ist.

Von Christopher Schrader





AGU PUBLICATIONS

Earth's Future

COMMENTARY
10.1002/2016EF000454

Special Section:
Crutzen +10: Reflecting upon 10 years of geoengineering research

Key Points:
- Solar geoengineering has been a focus of inquiry for over 50 years
- Sustained progress in "geoengineering" research will depend on sustained social and material support for experimental work
- Future trajectories for carbon dioxide removal technologies may differ dramatically from those for solar geoengineering technologies

Corresponding author:
K. Caldeira, kcaldeira@carnegiescience.edu

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Reflecting on 50 years of geoengineering research

Ken Caldeira[1] and Govindasamy Bala[2]

[1]Department of Global Ecology, Carnegie Institution, Stanford, California, USA, [2]Centre for Atmospheric and Oceanic Sciences, Indian Institute of Science, Bangalore, India

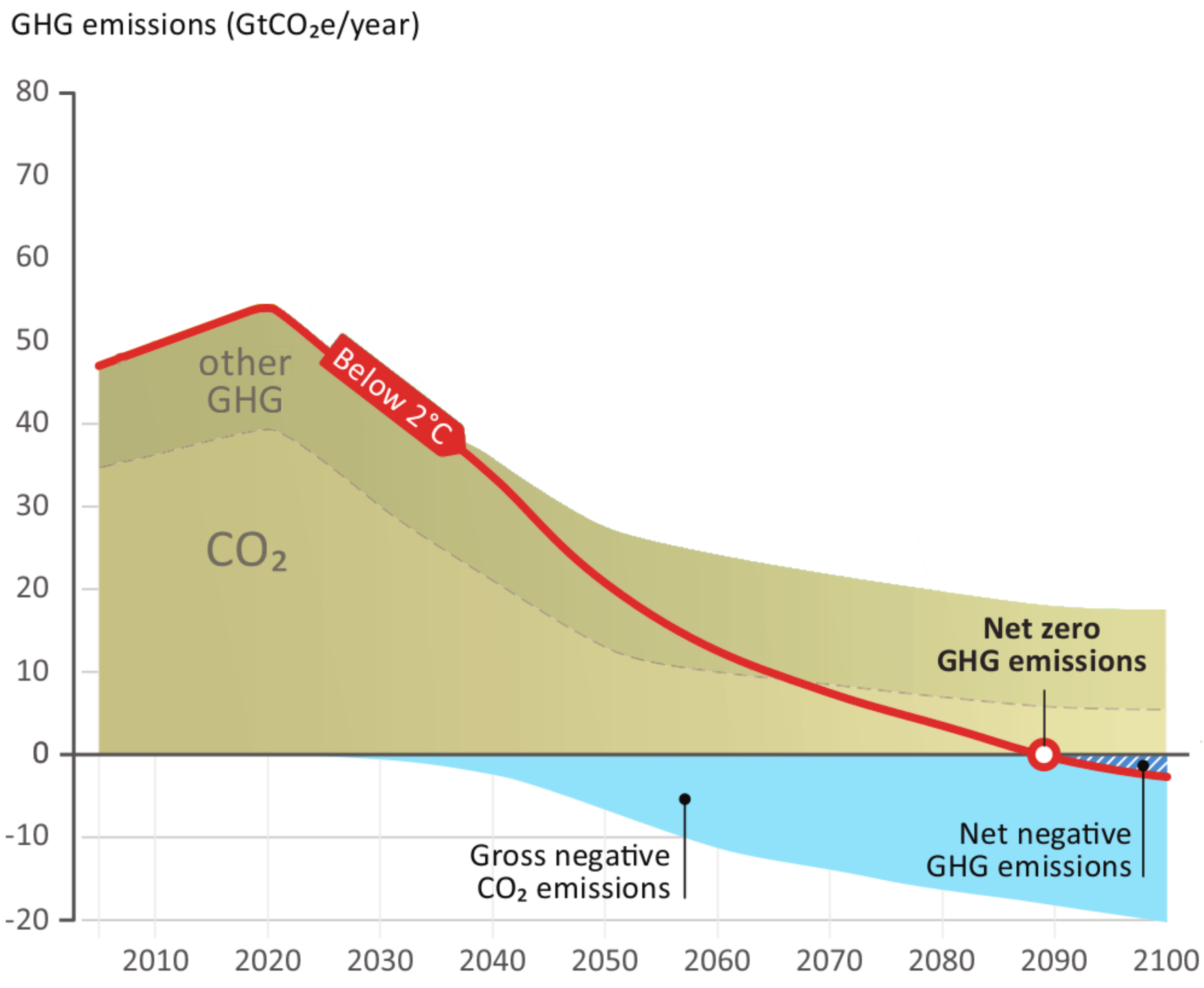
Abstract *Earth's Future* invited "leading experts in the field of geoengineering research to contribute brief reflections (2–5 pages) on the development of the discussion over the past decade and to consider where it may be going in the next 10 years." Responding to this request, we offer the following text in the spirit of reflections that emphasize our personal roles and viewpoints. The primary focus of many of our comments is solar geoengineering and not carbon dioxide removal (CDR). Thus, this text is not intended to comprise a comprehensive review or set of carefully documented analyses. Our primary conclusion is that sustained progress in "geoengineering" research will depend on social and material support for experimental work that can provide the observational basis for improved modeling and analysis, and, potentially, development and deployment of systems that may help protect the environment and improve human well-being. Relevant issues, and potential future trajectories, for CDR technologies may differ dramatically from those for solar geoengineering technologies.

1. The Past

The charge to reflect on developments over the past decade indicates a young person's view of history. Rather than use *Crutzen's* [2006] paper as the opportunity for decadal-scale reflection, we could just as well be using the 1965 President's Science Advisory Committee (PSAC) report to then-President Lyndon Johnson [*President's Science Advisory Committee*, 1965] as a jumping off point to reflect on the evolution of the field on the half-century time scale. The PSAC report raised the possibility of albedo geoengineering to offset CO_2-induced climate change, but did not even consider emissions reduction. Arguably, the history of geoengineering goes deeper than the history of emissions reductions. Geoengineering options discussed in that report included putting reflecting particles over the oceans and modifying cirrus clouds. Geoengineering goals considered included preventing global warming and inhibiting the formation of hurricanes.

Mikhail Budyko's proposal to place aerosols in the stratosphere was first described in his 1977 book "Climatic Changes" [*Budyko*, 1977]. The book originally appeared in the Russian language in 1974. Budyko estimated that about 200,000 tons of sulfur would need to be placed in the stratosphere to offset the warming that occurred between 1920 and 1940. He opined, "Thus in the near future climate modification will become necessary in order to maintain current climatic conditions." He continued, "These measures of climate modification are intended for preventing or weakening climatic changes that may ensue in several decades as a result of man's economic activity. Such modification, however, is not beyond the capacity of modern technology. In the near future it will apparently be possible to modify the climate, … producing a drop in global temperature of several degrees." Budyko suggested that the sulfur content of fuels in stratospheric flights could be tuned to maintain a stable climate. Budyko saw active climate management as a moral imperative, writing, "If we agree that it is theoretically possible … it becomes incumbent on us to develop a plan for climate modification that will maintain existing climatic conditions … "

In 1989, James Early published an analysis suggesting that sunlight could be deflected away from the Earth with satellites placed between Earth and the sun [*Early*, 1989]. In 1992, solar geoengineering was highlighted in a 1992 report by the US National Research Council [[*National Research Council*, 1992]. This study reviewed a set of options that largely holds up today, considering concepts such as space mirrors and micro-balloons. This NRC report concluded, "These ideas might merit some further study … but do not now seem worth great effort. They should be kept in mind, however, because technological changes may make them more attractive."



Source: UNEP. The Emissions Gap Report (2017) / Jérôme Hilaire

BECCS

Bio-Energy
with
Carbon Capture
and
Storage

Image: LTB 39

LET THE CAR REMOVE CO_2 FROM THE ATMOSPHERE

Image: Bellona 2010

Source: Anderson & Peters The trouble with negative emissions (2016) Image: https://thetruesize.com

Image: LTB 211

SRM

Solar
Radiation
Management

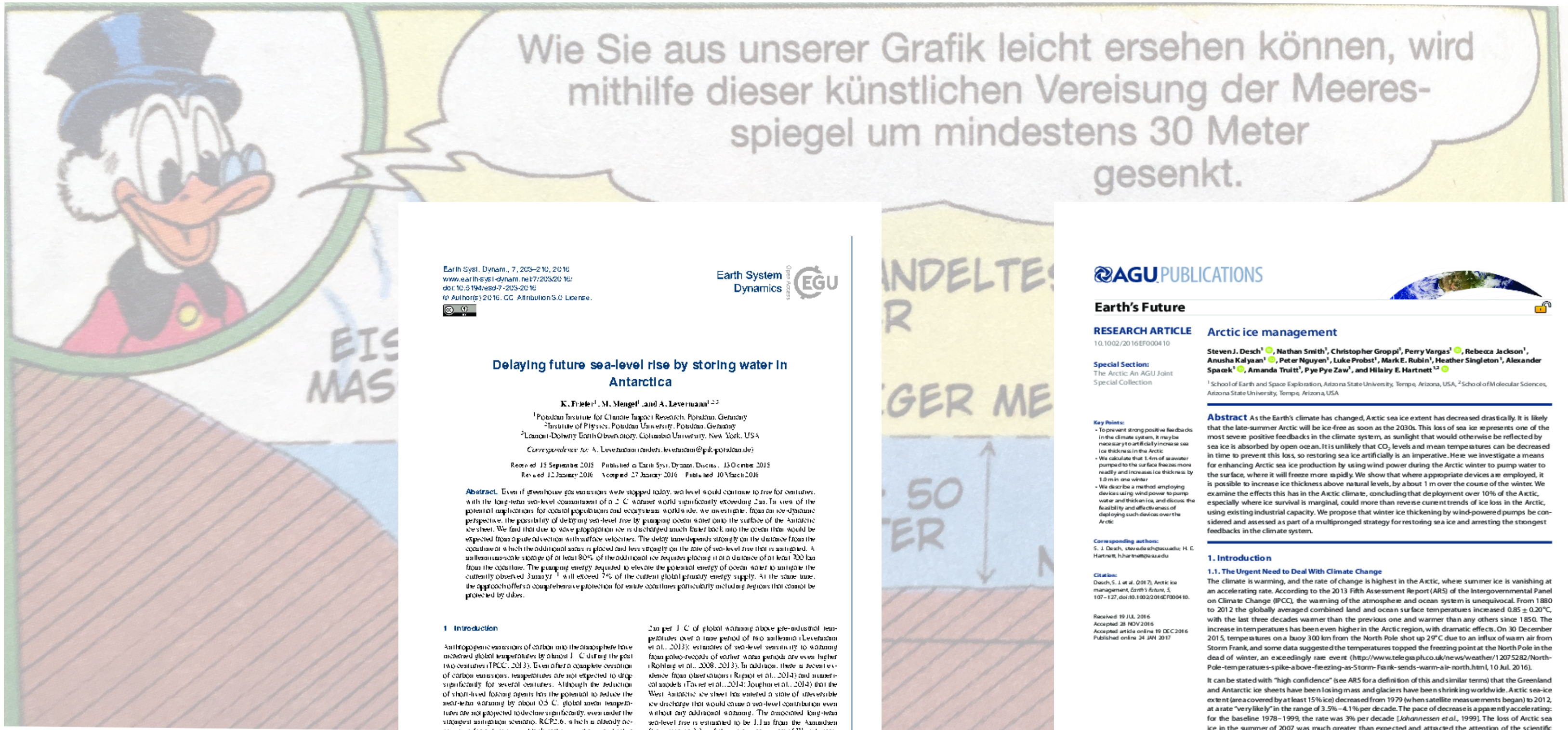
Image: LTB Spezial 26

Image: LTB Spezial 26

Image: LTB Spezial 26

Image: LTB Spezial 26

Images: LTB Spezial 26



Earth Syst. Dynam., 7, 203–210, 2016
www.earth-syst-dynam.net/7/203/2016/
doi:10.5194/esd-7-203-2016

Earth System Dynamics

Delaying future sea-level rise by storing water in Antarctica

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[2]Institute of Physics, Potsdam University, Potsdam, Germany
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Abstract. Even if greenhouse gas emissions were stopped today, sea level would continue to rise for centuries, with the long-term sea-level commitment of a 2 °C warmer world significantly exceeding 2 m. In view of the potential implications for coastal populations and ecosystems worldwide, we investigate, from an ice-dynamic perspective, the possibility of delaying sea-level rise by pumping ocean water onto the surface of the Antarctic ice sheet. We find that due to wave propagation ice is discharged much faster back into the ocean than would be expected from a pure advection with surface velocities. The delay time depends strongly on the distance from the coastline at which the additional mass is placed and less strongly on the rate of sea-level rise that is mitigated. A millennium-scale storage of at least 80 % of the additional ice requires placing it at a distance of at least 700 km from the coastline. The pumping energy required to elevate the potential energy of ocean water to mitigate the currently observed 3 mm yr^{-1} will exceed 7 % of the current global primary energy supply. At the same time, the approach offers a comprehensive protection for entire coastlines particularly including regions that cannot be protected by dikes.

1 Introduction

Anthropogenic emissions of carbon into the atmosphere have increased global temperatures by almost 1 °C during the past two centuries (IPCC, 2013). Even after a complete cessation of carbon emissions, temperatures are not expected to drop significantly for several centuries. Although the reduction of short-lived forcing agents has the potential to reduce the near-term warming by about 0.5 °C, global mean temperatures are not projected to decline significantly, even under the strongest mitigation scenario, RCP2.6, which is already accounting for reductions in black carbon, methane, and other short-lived forcers (van Vuuren et al., 2011). As a consequence of the climate system's inertia and the ice sheets' response, mitigating greenhouse-gas emissions in the future can reduce, but will not stop, sea-level rise for centuries to come (Gillett et al., 2011; IPCC, 2013; Meehl et al., 2005; Solomon et al., 2009; Wigley, 2005). Conservative estimates for this so-called sea-level commitment are of the order of 2 m per 1 °C of global warming above pre-industrial temperatures over a time period of two millennia (Levermann et al., 2013); estimates of sea-level sensitivity to warming from paleo-records of earlier warm periods are even higher (Rohling et al., 2008, 2013). In addition, there is recent evidence from observations (Rignot et al., 2014) and numerical models (Favier et al., 2014; Joughin et al., 2014) that the West Antarctic ice sheet has entered a state of irreversible ice discharge that would cause a sea-level contribution even without any additional warming. The associated long-term sea-level rise is estimated to be 1.1 m from the Amundsen Sea sector, or 3.3 m if the entire marine part of West Antarctica were affected (Bamber et al., 2009).

As a consequence, global coastal adaptation to ongoing sea-level rise will be required unless water is taken back out of the ocean. Such local protection may not be physically possible or economically feasible everywhere. In southern Florida in the USA, for example, the base rock is limestone.

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AGU PUBLICATIONS

Earth's Future

RESEARCH ARTICLE
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Special Section:
The Arctic: An AGU Joint Special Collection

Arctic ice management

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Key Points:
- To prevent strong positive feedbacks in the climate system, it may be necessary to artificially increase sea ice thickness in the Arctic
- We calculate that 1.4 m of seawater pumped to the surface freezes more readily and increases ice thickness by 1.0 m in one winter
- We describe a method employing devices using wind power to pump water and thicken ice, and discuss the feasibility and effectiveness of deploying such devices over the Arctic

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Abstract As the Earth's climate has changed, Arctic sea ice extent has decreased drastically. It is likely that the late-summer Arctic will be ice-free as soon as the 2030s. This loss of sea ice represents one of the most severe positive feedbacks in the climate system, as sunlight that would otherwise be reflected by sea ice is absorbed by open ocean. It is unlikely that CO_2 levels and mean temperatures can be decreased in time to prevent this loss, so restoring sea ice artificially is an imperative. Here we investigate a means for enhancing Arctic sea ice production by using wind power during the Arctic winter to pump water to the surface, where it will freeze more rapidly. We show that where appropriate devices are employed, it is possible to increase ice thickness above natural levels, by about 1 m over the course of the winter. We examine the effects this has in the Arctic climate, concluding that deployment over 10% of the Arctic, especially where ice survival is marginal, could more than reverse current trends of ice loss in the Arctic, using existing industrial capacity. We propose that winter ice thickening by wind-powered pumps be considered and assessed as part of a multipronged strategy for restoring sea ice and arresting the strongest feedbacks in the climate system.

1. Introduction

1.1. The Urgent Need to Deal With Climate Change

The climate is warming, and the rate of change is highest in the Arctic, where summer ice is vanishing at an accelerating rate. According to the 2013 Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the warming of the atmosphere and ocean system is unequivocal. From 1880 to 2012 the globally averaged combined land and ocean surface temperatures increased 0.85 ± 0.20°C, with the last three decades warmer than the previous one and warmer than any others since 1850. The increase in temperatures has been even higher in the Arctic region, with dramatic effects. On 30 December 2015, temperatures on a buoy 300 km from the North Pole shot up 29°C due to an influx of warm air from Storm Frank, and some data suggested the temperatures topped the freezing point at the North Pole in the dead of winter, an exceedingly rare event (http://www.telegraph.co.uk/news/weather/12075282/North-Pole-temperatures-spike-above-freezing-as-Storm-Frank-sends-warm-air-north.html, 10 Jul. 2016).

It can be stated with "high confidence" (see AR5 for a definition of this and similar terms) that the Greenland and Antarctic ice sheets have been losing mass and glaciers have been shrinking worldwide. Arctic sea-ice extent (area covered by at least 15% ice) decreased from 1979 (when satellite measurements began) to 2012, at a rate "very likely" in the range of 3.5%–4.1% per decade. The pace of decrease is apparently accelerating: for the baseline 1978–1999, the rate was 3% per decade [*Johannessen et al.*, 1999]. The loss of Arctic sea ice in the summer of 2007 was much greater than expected and attracted the attention of the scientific community and the public [*Kerr*, 2007; *Revkin*, 2007]; but the extent of sea ice in 2012 was even lower, and through July 2016, the sea ice extent was lower than ever recorded in the spring, more than 2 standard deviations below the 1981–2010 average. Figure 1 illustrates the alarming and accelerating loss of ice in the Arctic Ocean.

The loss of Arctic sea ice is due to anthropogenic effects and is therefore likely to continue to accelerate. According to the IPCC AR5 Report, the increase in global temperatures is very similar to that predicted from the cumulative anthropogenic CO_2 emissions of 2040 ± 310 Gt between 1750 and 2011. It is "extremely likely" that most of the global temperature increases are due to anthropogenic forcings. Anthropogenic

Source: Frieler et al. Delaying future sea-level rise by storing water in Antarctica (2016) / Desch et al. Arctic ice management (2017)

Images: LTB Spezial 26

Image: LTB Spezial 26

Geoengineering

Climate Engineering … or Intervention

Solar Radiation Management

Solar Reflection Management

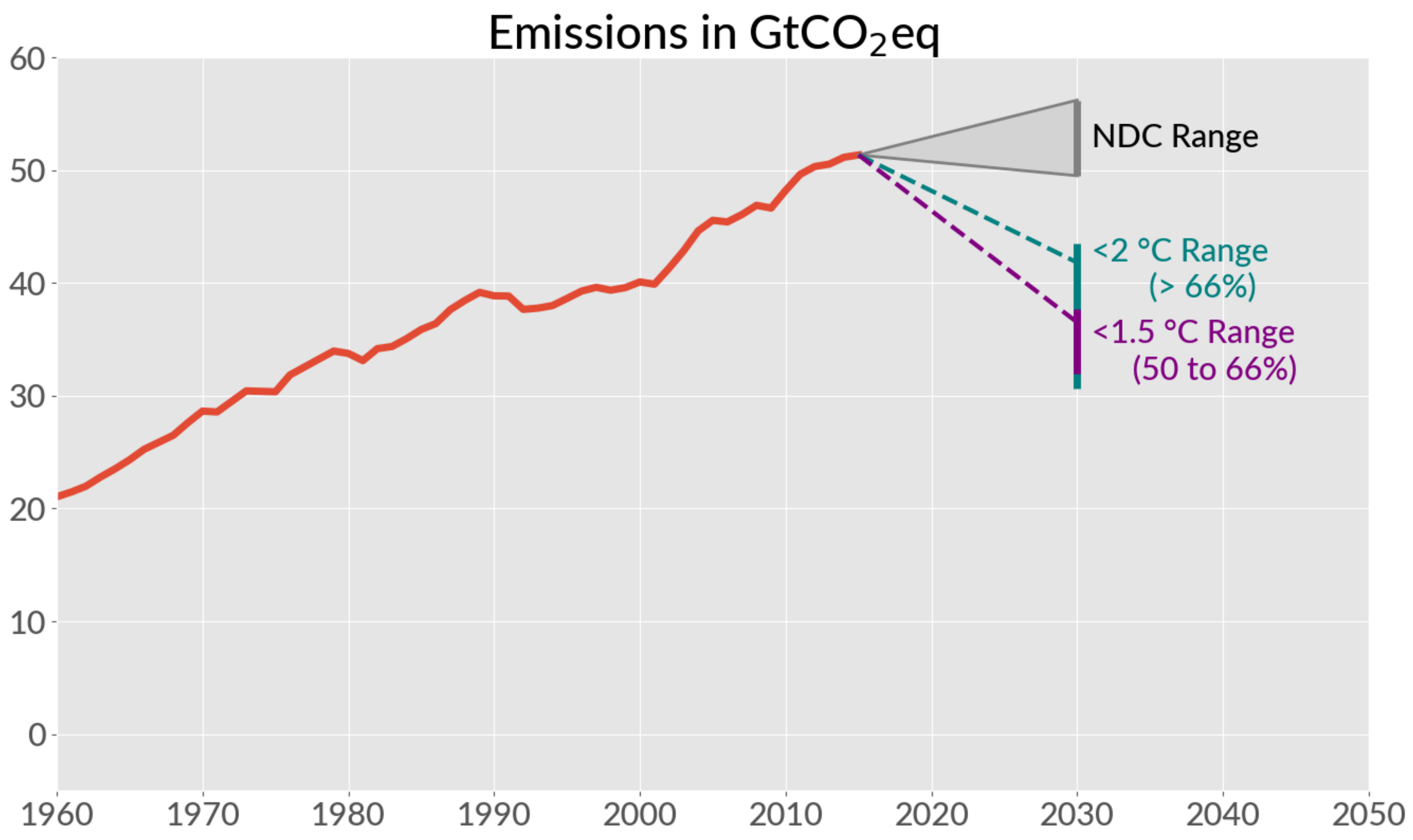
Albedo Modification … or Hacking

Cocktail Geoengineering

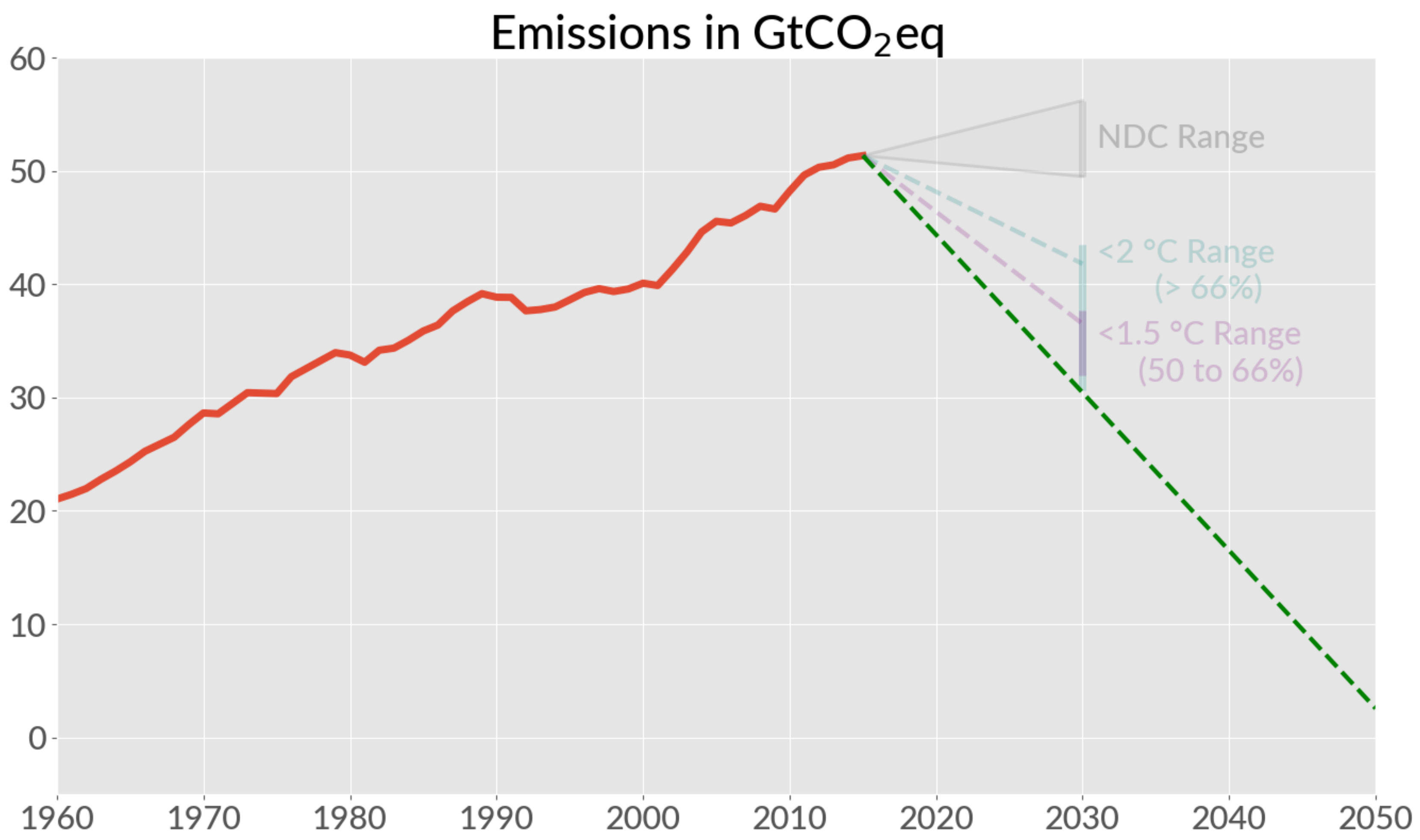
Carbon Dioxide Removal

Negative Emissions

Image: LTB Spezial 26



Source: PRIMAP-hist / Global Carbon Budget (2017) / UNEP Gap Report (2017)



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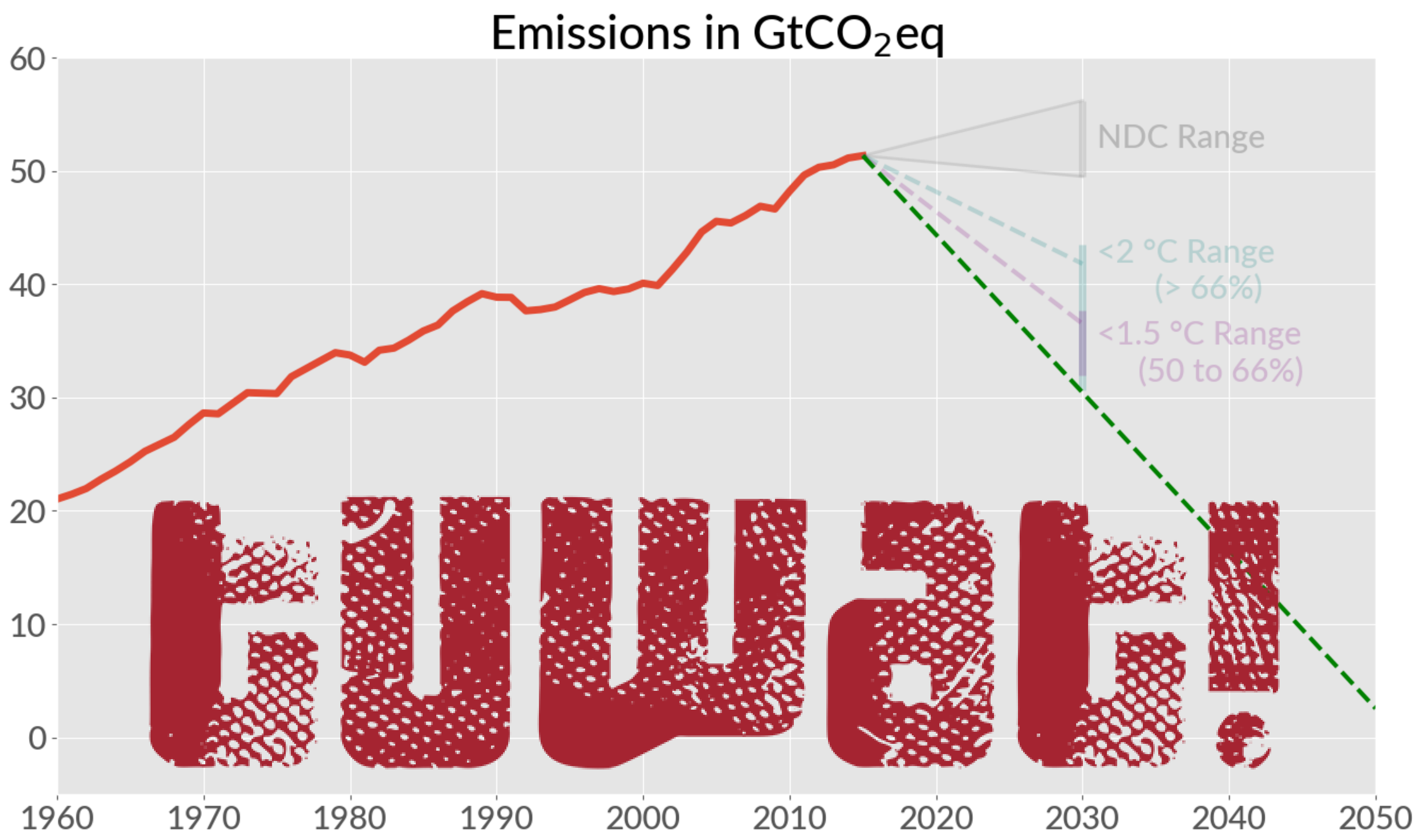

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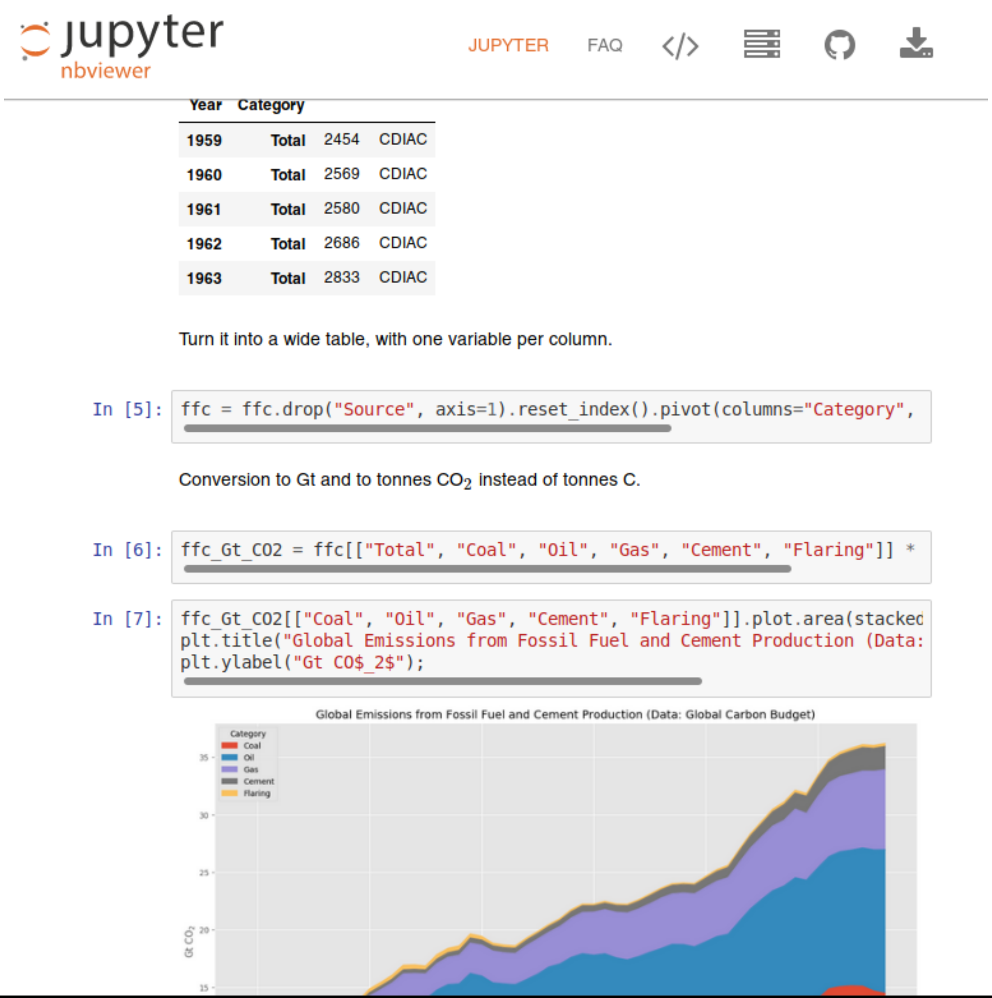

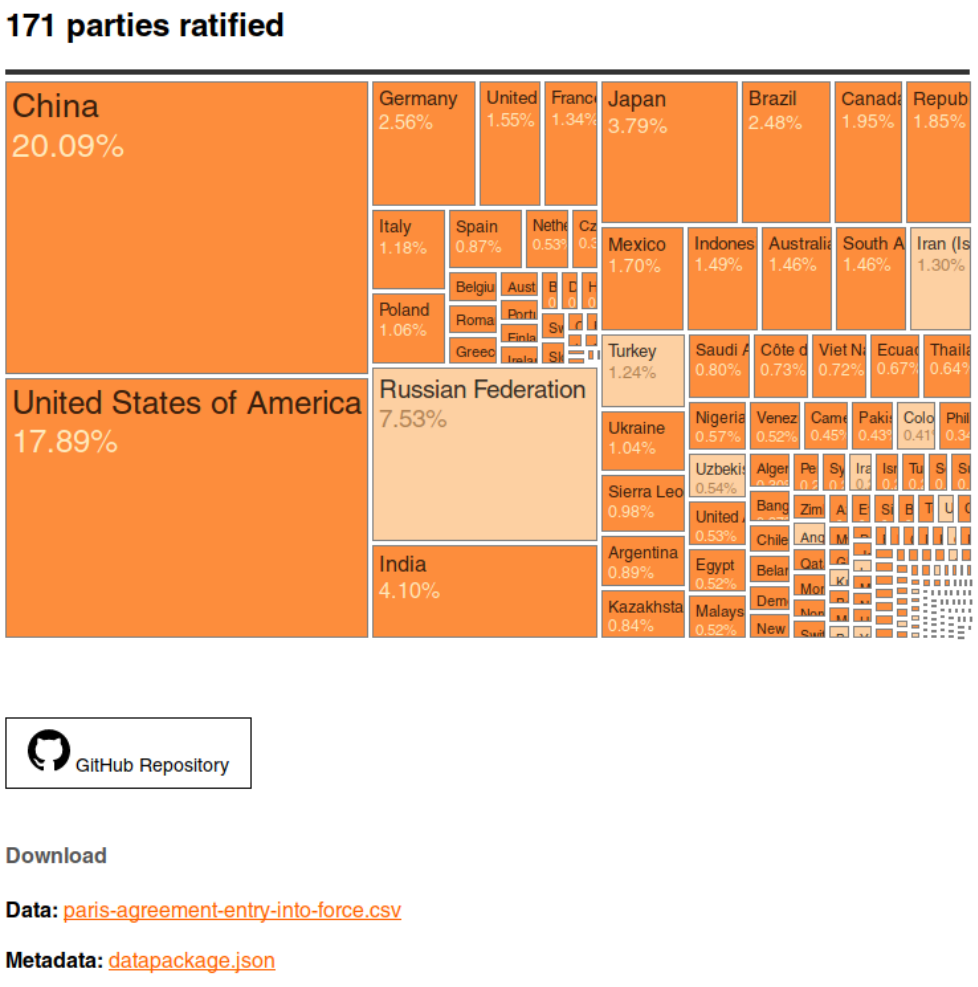

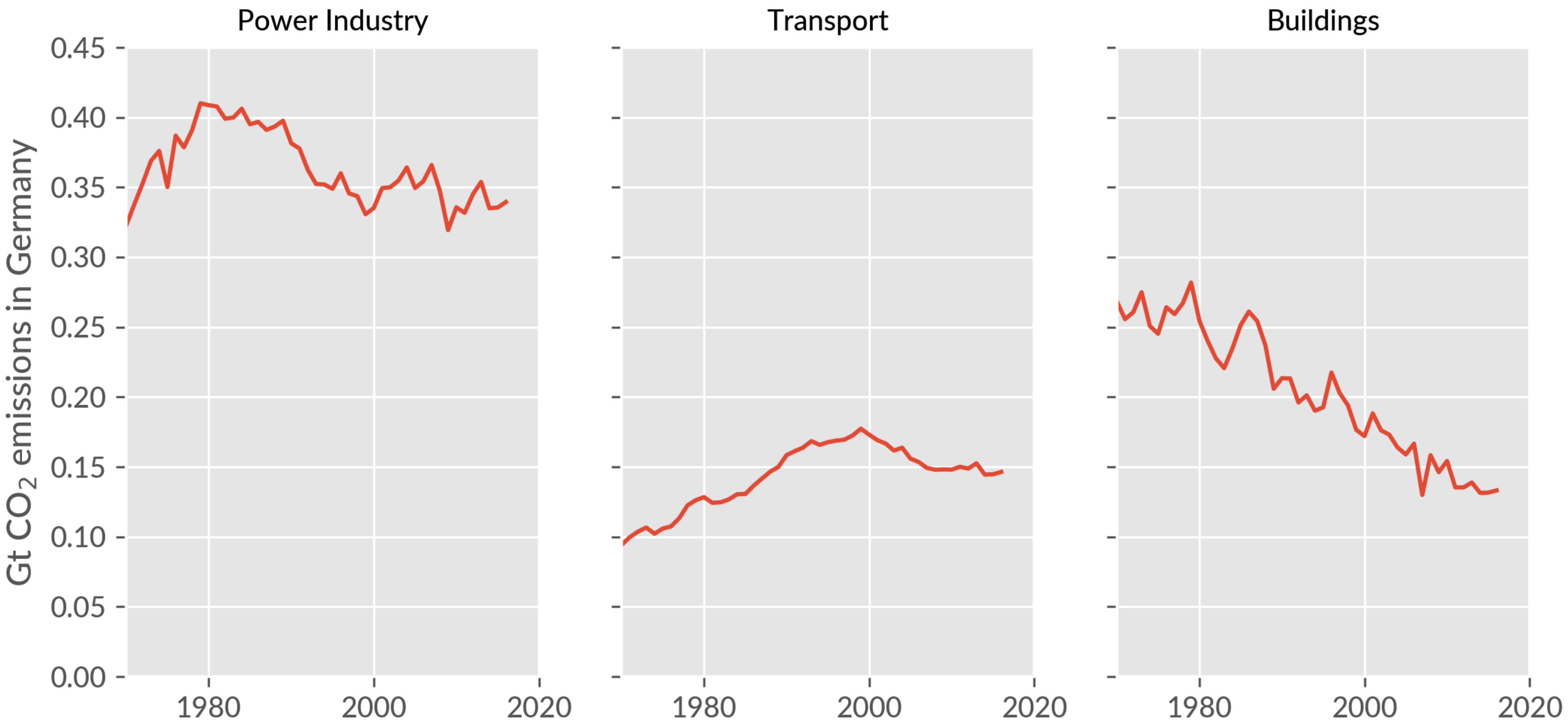

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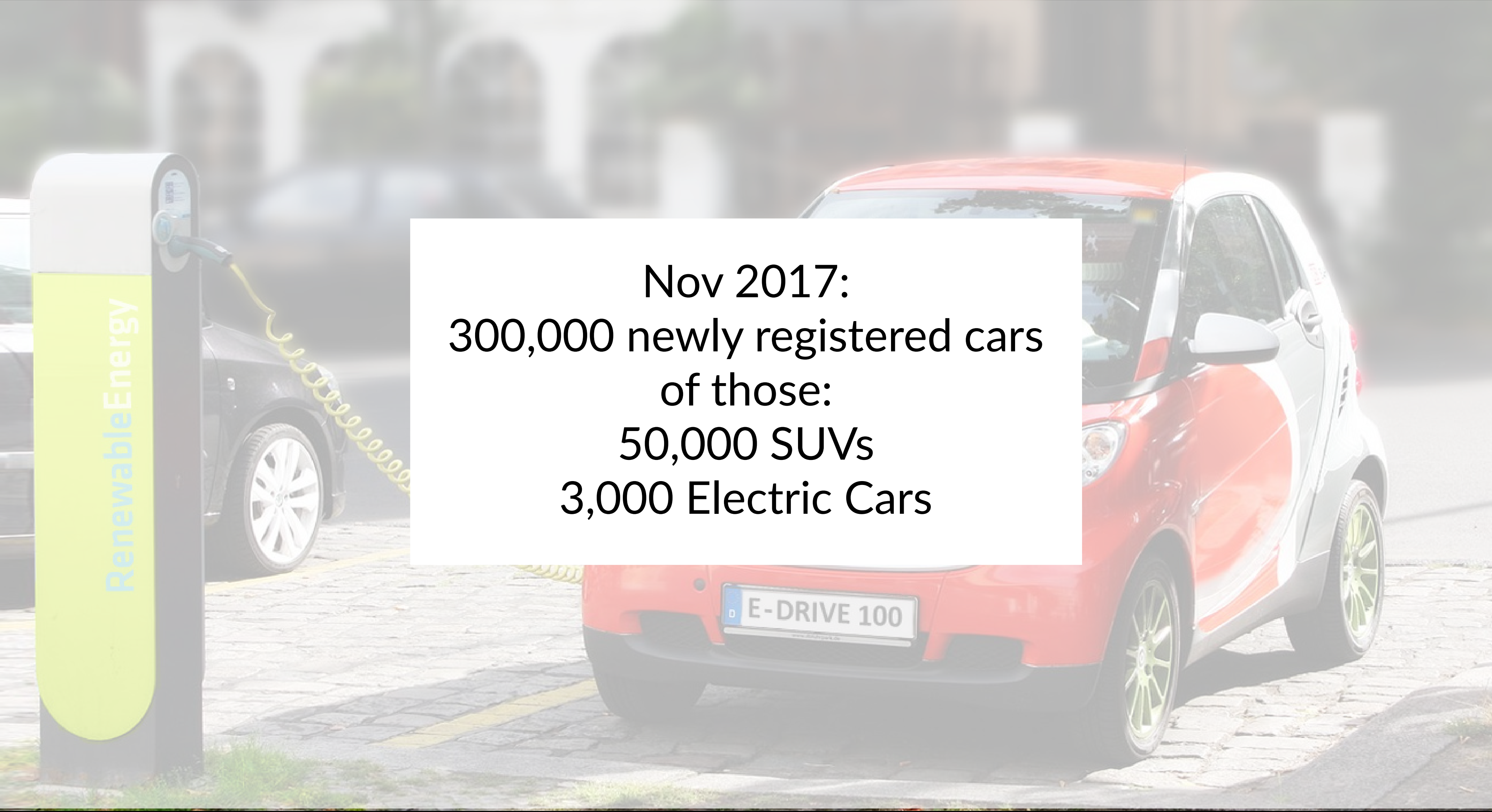
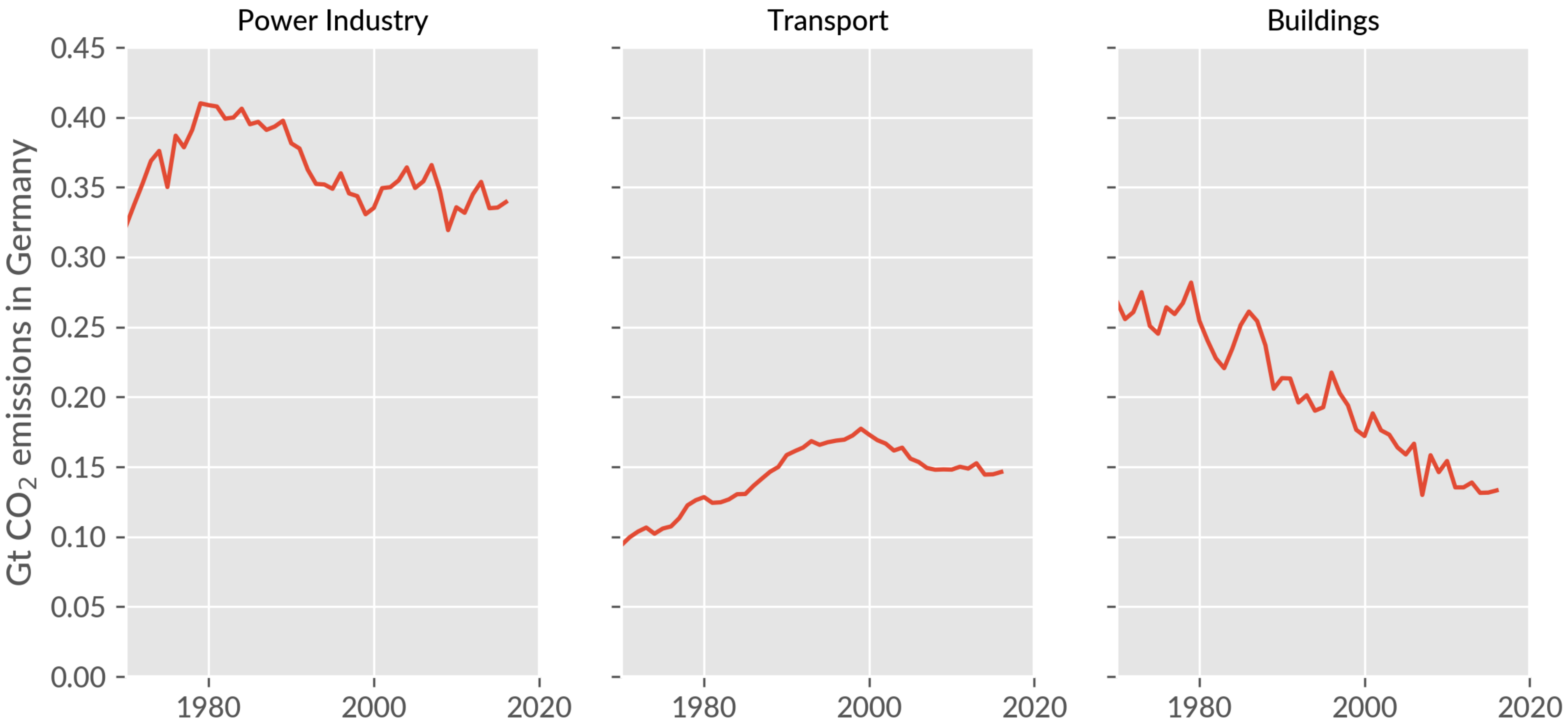


Nov 2017:
300,000 newly registered cars
of those:
50,000 SUVs
3,000 Electric Cars

Source: Kraftfahrt-Bundesamt



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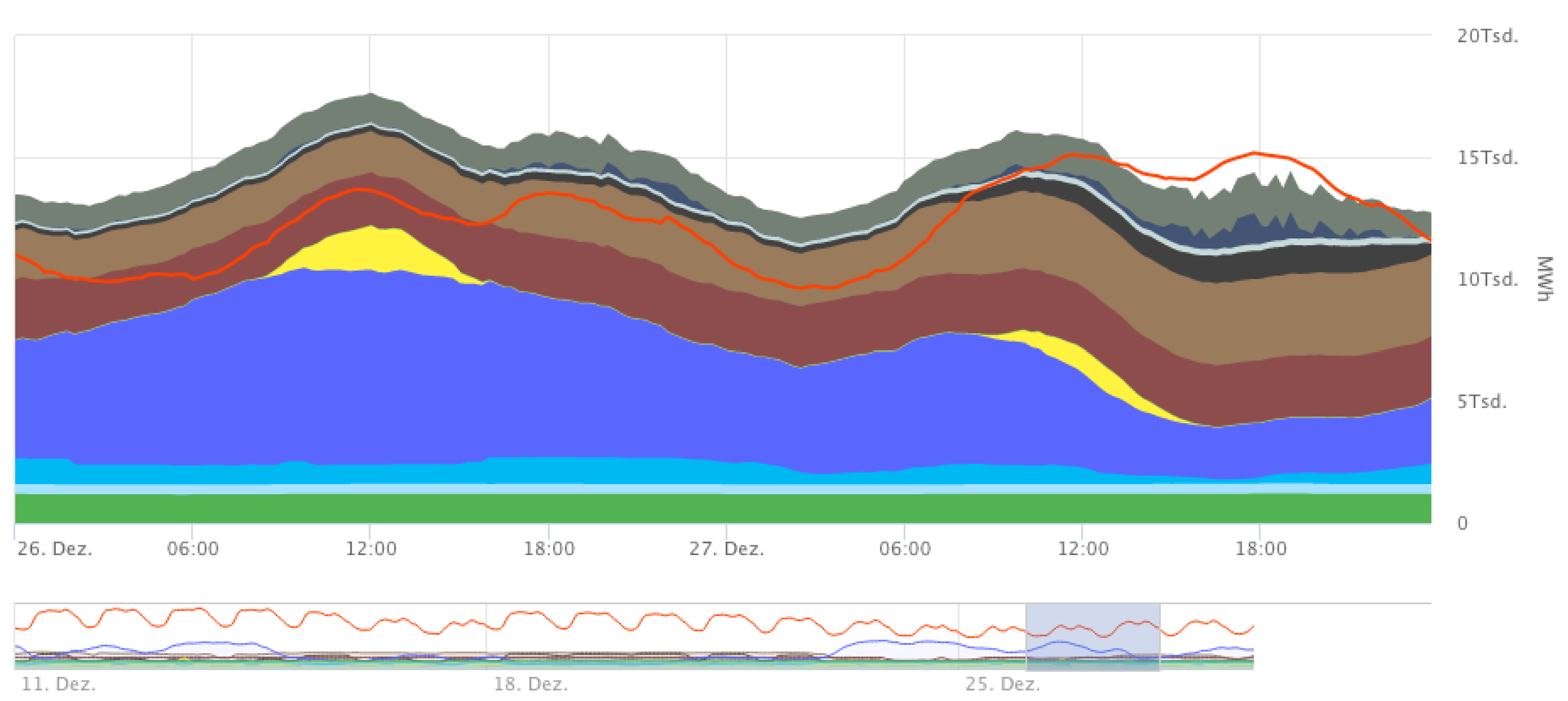

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We don’t know everything,
but we know enough to act.