

Impact of climate change in astronomy

Weather: State of (lower) atmosphere daily, localized

Climate: Long term trends (~30 years), global / synoptic scales



Faustine CANTALLOUBE, LAM

Julien MILLI, ESO/IPAG Grenoble

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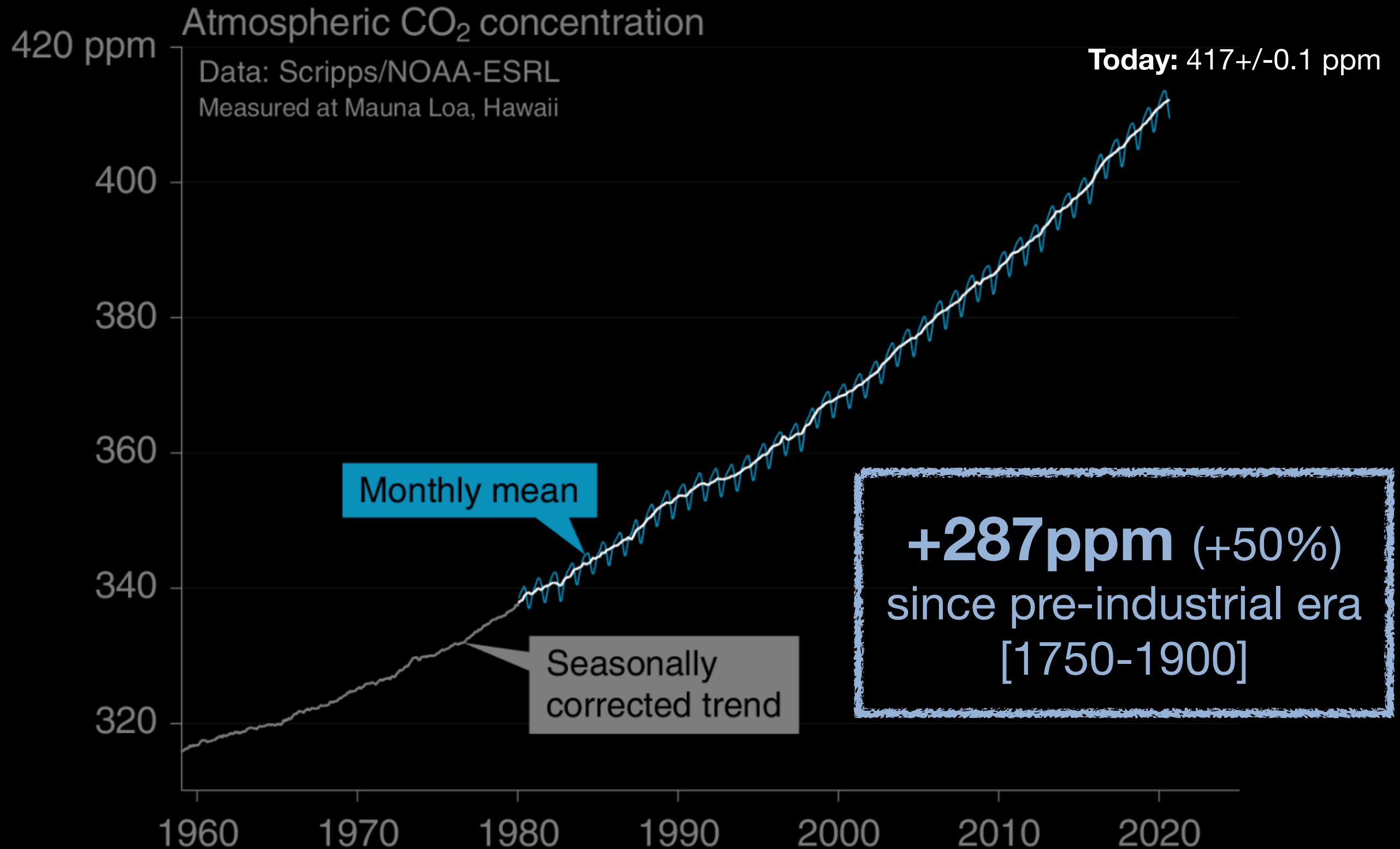
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Susanne CREWELL, Institute for Meteorology and Geophysics (IMGW)

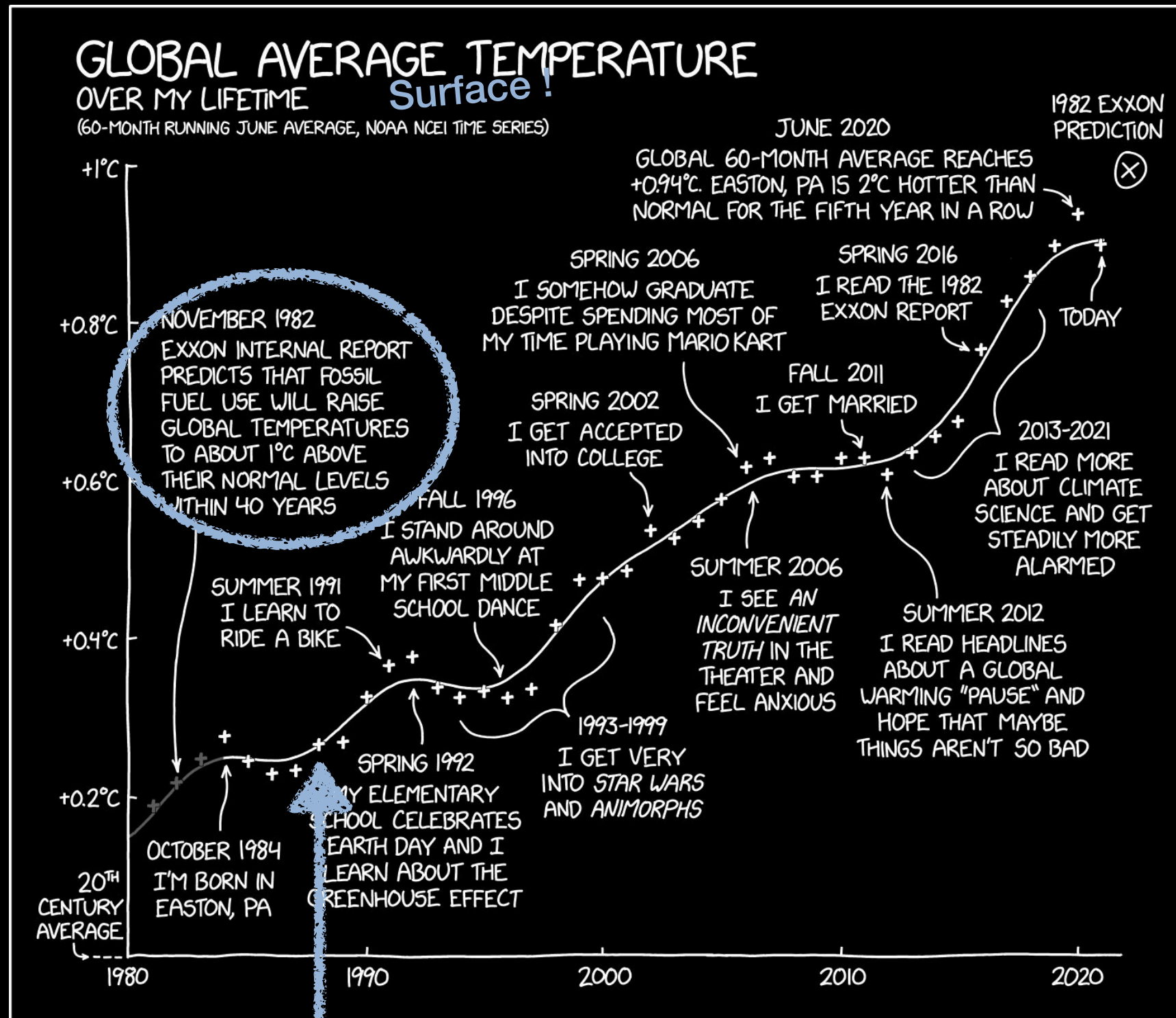
Stefanie Fiedler, Institute for Meteorology and Geophysics (IMGW)

et al.

Climate: where we stand ?



Climate: where we stand ?



Today:
1.1 +/- 0.1°C

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IPCC is founded !
(and I'm born)

IPCC - AR6 report from WG1

The physical science basis

ipcc

intergovernmental panel on climate change

IPCC (GIEC): Intergovernmental Panel on Climate Change

AR6: Assessment Report 6, 2015-2023 (AR5 published in 2014)

Summary for Policymakers

WGs: WG1- *The Physical Science Basis* (7/08/2021)
WG2- *Impacts, Adaptation and Vulnerability* (for 2022)
WG3- *Mitigation of Climate Change* (for 2022)

WG1: **234** volunteer scientists from **66** countries
Reviewed **14,000** papers and wrote **4000** page summary report
Received **78,000** comments

Rational: The past, present and future of climate,
to inform the society, industries and policy makers

WGI

Working Group I contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change



Summary for Policy Makers, 42 pages
<https://www.ipcc.ch/report/ar6/wg1/#SPM>

IPCC - AR6 report from WG1

A. The Current State of the Climate

A.1 Human influence has warmed atmosphere, oceans and lands

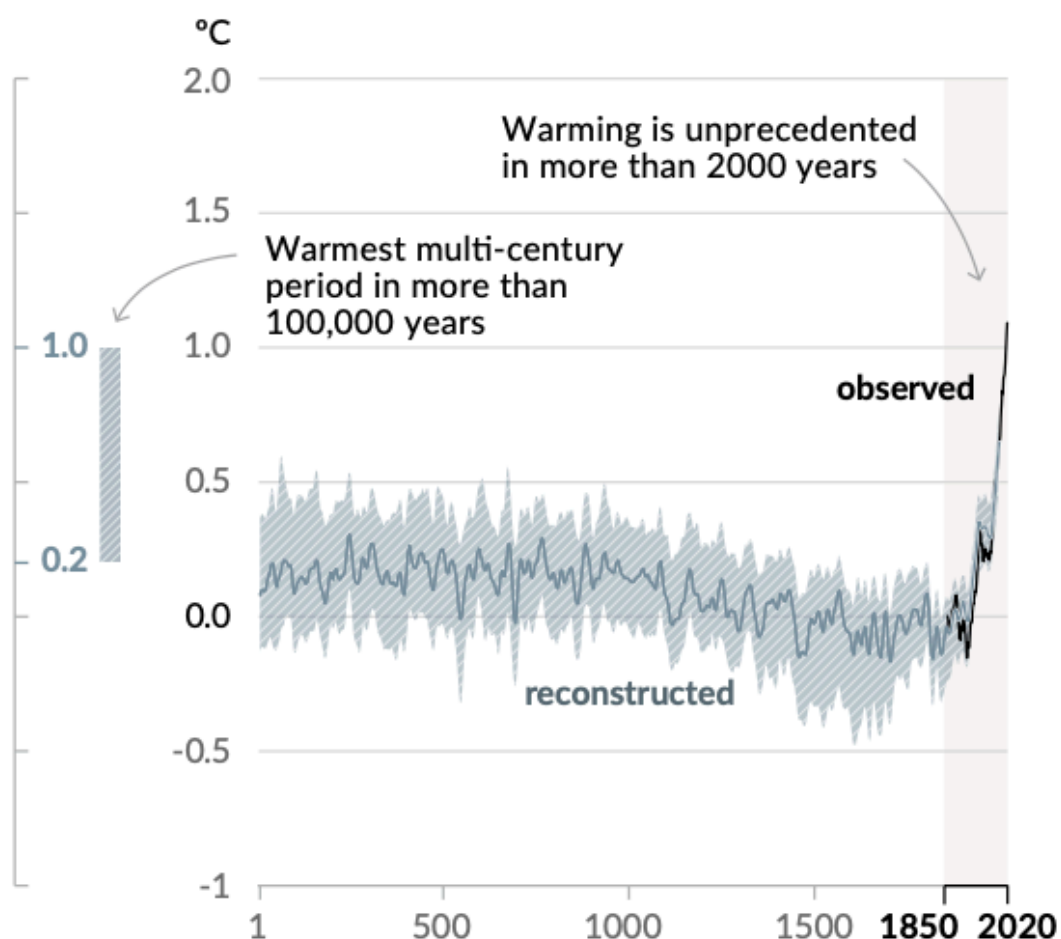
A.2 The scale of recent changes is unprecedented over 100-1000 years

A.3 It already affects weather & climate extremes everywhere

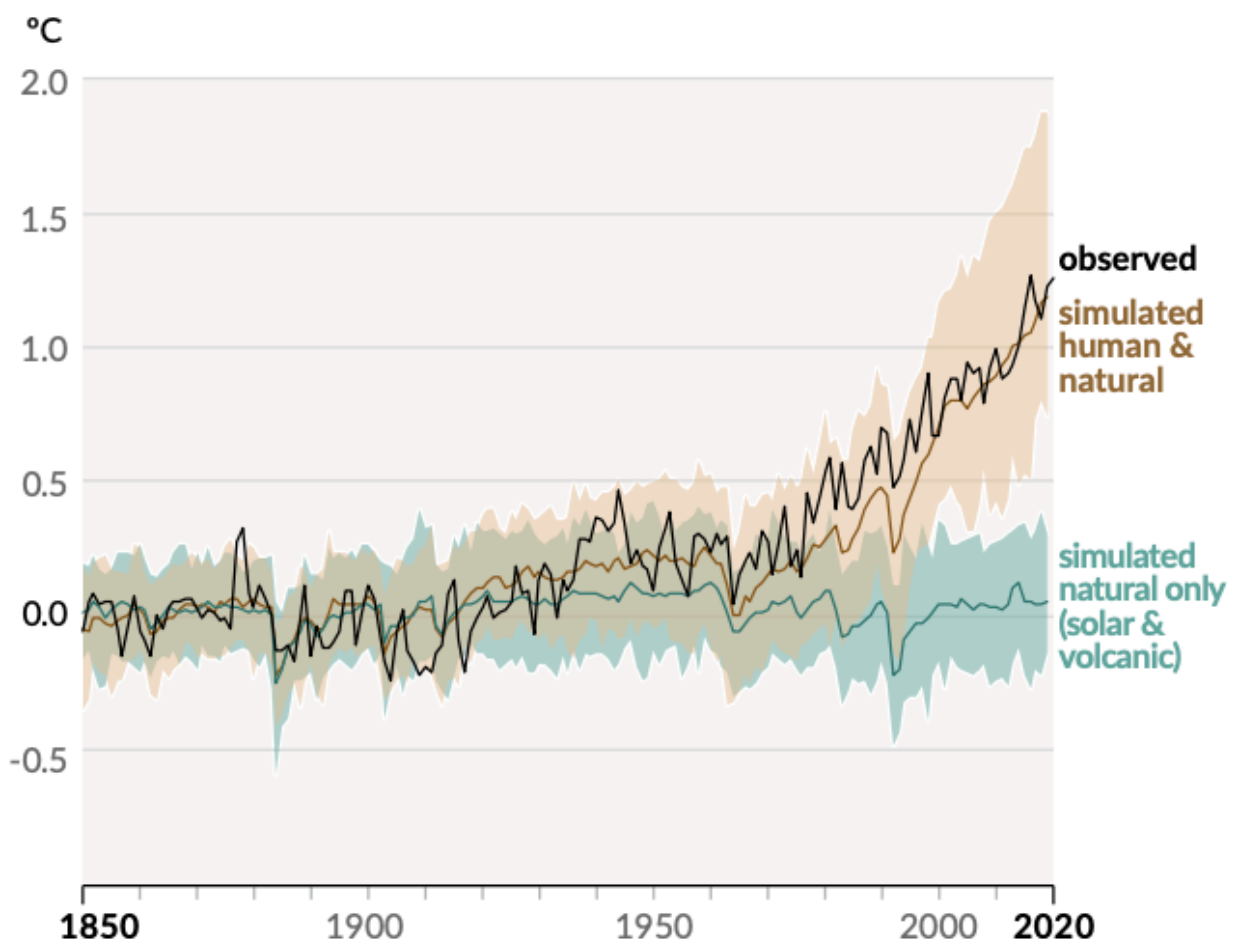
A.4 Improve knowledge on processes makes us understand better radiative forcing

Changes in global surface temperature relative to 1850-1900

a) Change in global surface temperature (decadal average) as **reconstructed** (1-2000) and **observed** (1850-2020)



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



IPCC - AR6 report from WG1

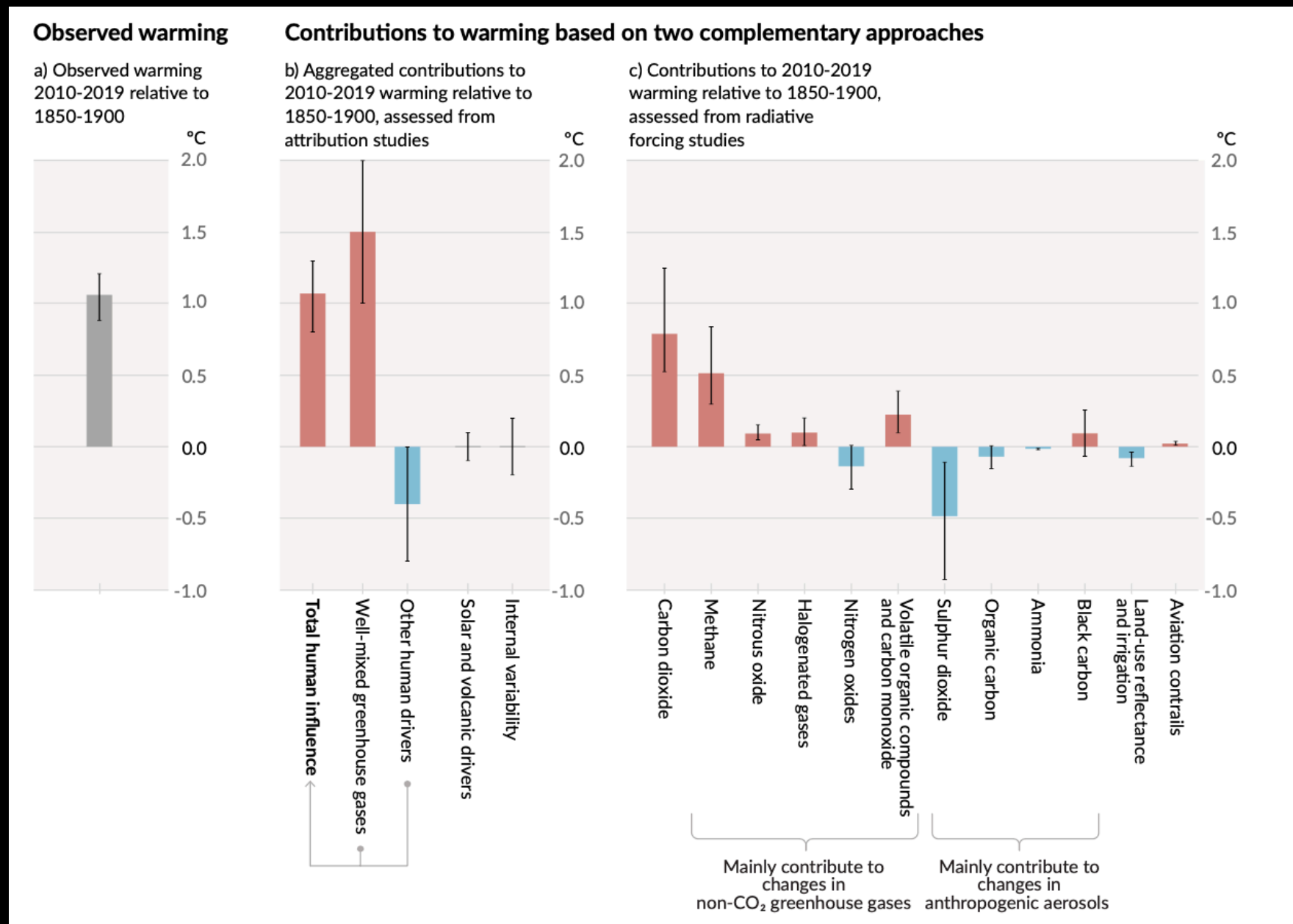
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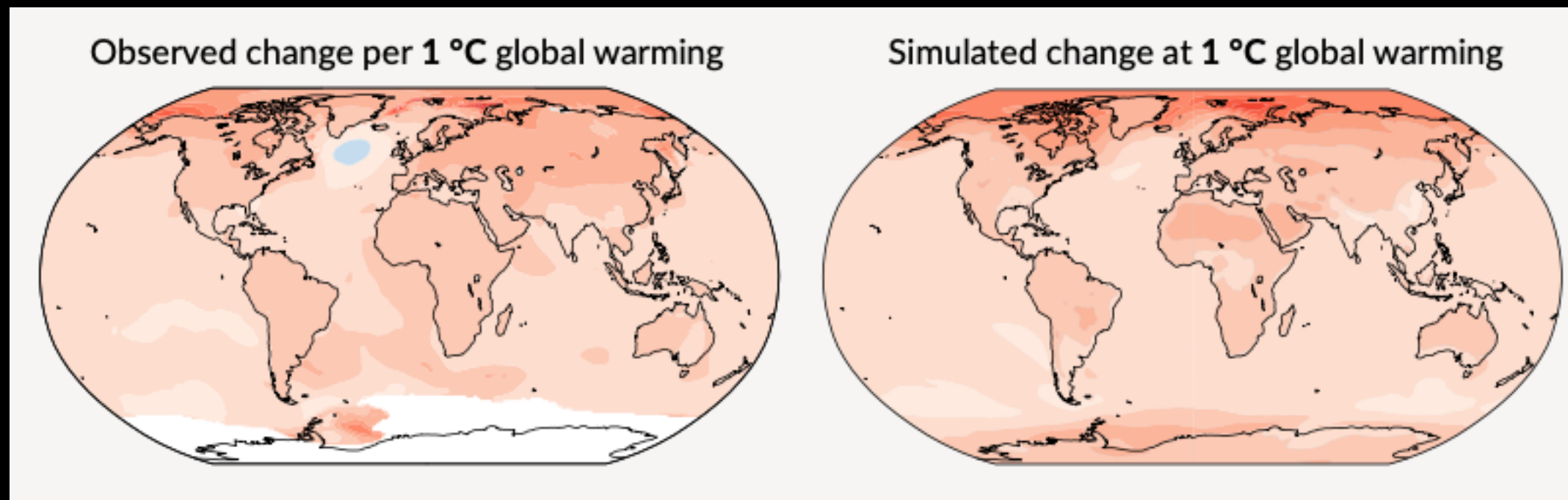
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B. Possible Climate Futures

- B.1 Temperature will continue rising until at least 2050 - 2°C will be exceeded
- B.2 Many changes become larger (e.g. intensity and frequency of extreme weather events, ice loss...)
- B.3 It affects water cycle (intensification variability, wet & dry, monsoon...)
- B.4 As atmospheric CO₂ increases, the carbon sinks (lands and oceans) are less efficient
- B.5 Most changes are irreversible for centuries or millennia



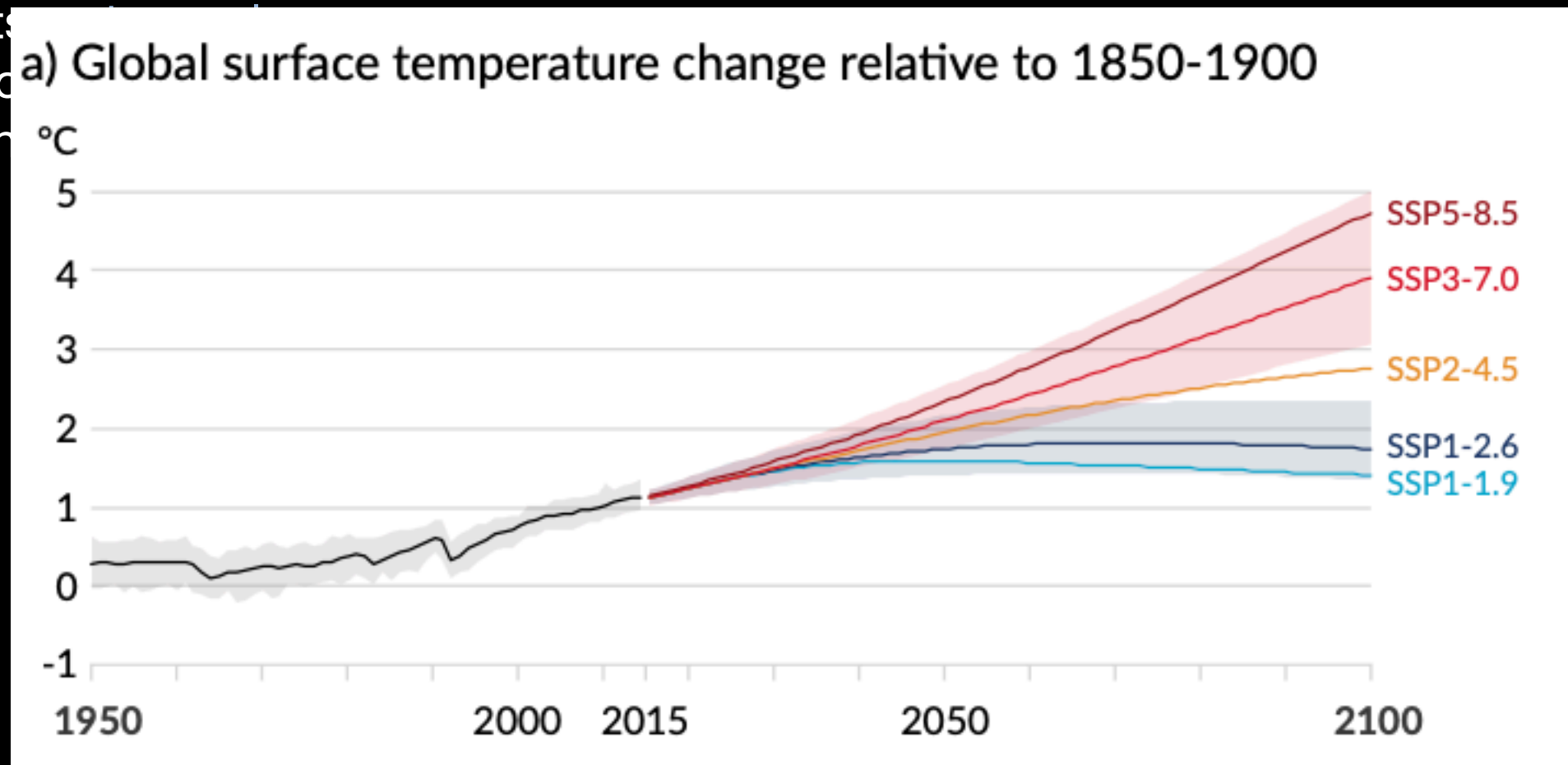
IPCC - AR6 report from WG1

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C. Climate Information for Risk Assessment and Regional Adaptation

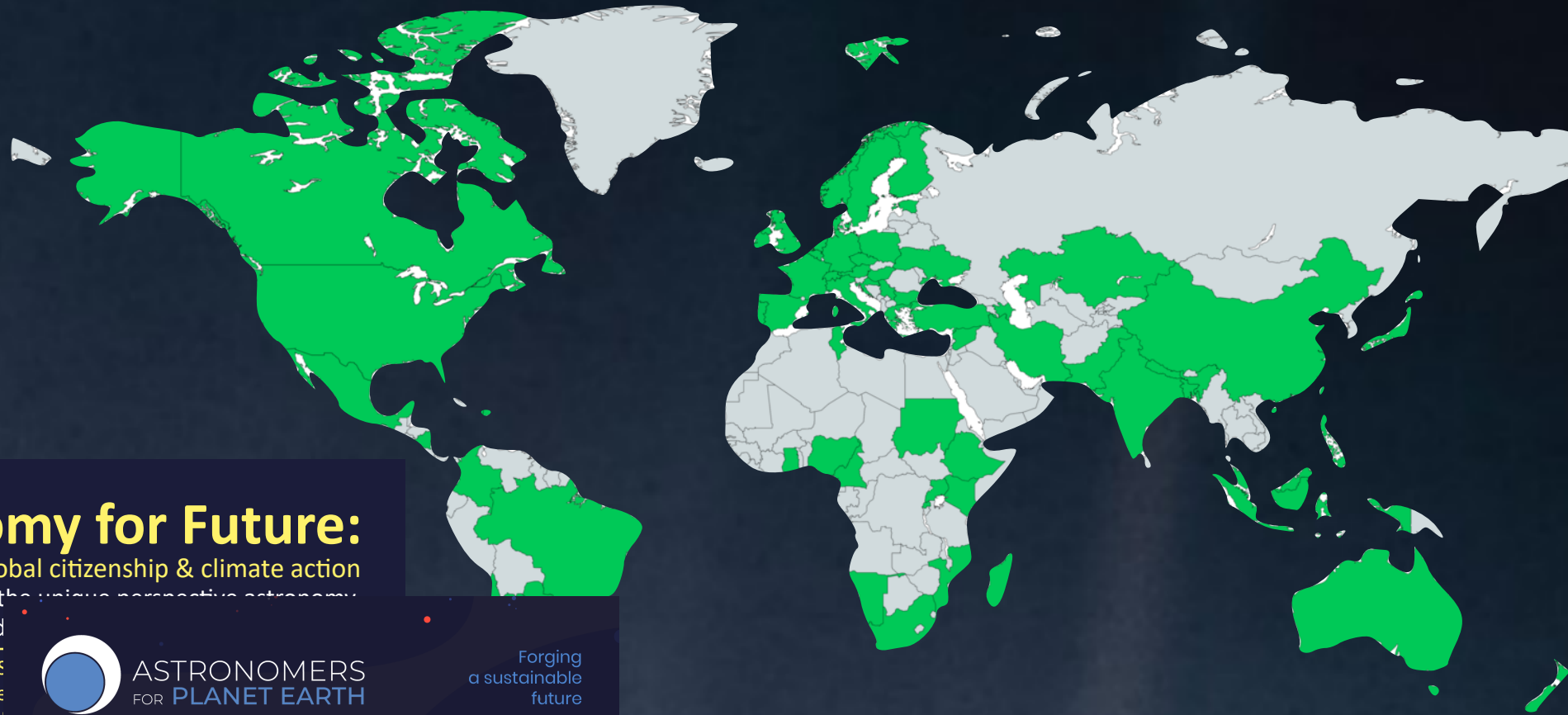
- C.1 Modulation by natural drivers & internal variability can affect significantly, amplify or attenuate
- C.2 Higher warming means wider spread in Climate Impact Drivers changes
- C.3 Tipping point cannot be ruled out !

D. Limiting Future Climate Change

- D.1 Strong, rapid and sustained reduction of GHG is needed + we need to reach net-zero CO₂
- D.2 Whatever the scenario, within 20-years, temperature trends will be above natural variability

Astronomers for Planet Earth

ASTRONOMERS
FOR PLANET EARTH



Astronomy for Future:

Development, global citizenship & climate action

Join us to discuss the unique perspective astronomy provides on our own Planet Earth

Mon 29 June - Special Session
Tues 30 June - Lunch Session
European Astronomical Society



ASTRONOMERS
FOR PLANET EARTH

Forging
a sustainable
future

Join us to discuss the unique perspective astronomy provides on our own Planet Earth

Invited speakers

- Didier Barret (Institut de Recherche Astrophysique et Planétologie)
- Sandra Benitez Herrera (Instituto Astrofísica de Canarias)
- Luis Calçada (European Southern Observatory)
- Faustine Cantalloube (Max Planck Institute for Astronomy)
- Jaime E. Forero-Romero (Universidad de los Andes)
- Stefania Giodini (Red Cross Data Center)
- Rachel Grange (ETH Zürich)
- James Hansen (Columbia University)

Thu, 1 July

Special Session (SS30)

eas.unige.ch

Fri, 2 July

Lunch Session (SS30)

European Astronomical Society
Annual Meeting 2021, Leiden

Invited speakers

- Allison Anderson (University of Plymouth)
- Clarisse Aujoux (Sorbonne Université, Paris)
- Lewis Ball (SKAO)
- Xavier Barcons (ESO)
- Olivier Berné (IRAP, Toulouse)
- Claudia Cicone (University of Oslo)
- Hannah Dalgleish (University of Oxford)
- Debra Fisher (Yale University)
- Sara Lucatello (INAF, Padova)
- Michael Mann (Penn State)
- Robert Massey (Royal Astronomical Society)
- Vanessa Moss (CSIRO)
- Kimberly Nicholas (Lund University)
- Karen Olson (Steward Observatory, Arizona)
- Matthias Steinmetz (AIP Potsdam)
- Sarah White (Rhodes University)
- Andy Williams (ESO)

PANEL DISCUSSION

"The future of the EAS annual meeting"

- Sara Lucatello (INAF Padova; EAS Vice President)
- Johan Knappan (IAC Tenerife; member of the EAS meeting board)
- Vanessa Moss (CSIRO)
- Huib Röttgering (Leiden Observatory; chair of the EAS hosting committee 2020/2021)
- Joop Schaya (Leiden Observatory; chair of the EAS SOC 2020/2021)
- Sarah White (Rhodes University; EAS inclusion committee)



Scientific organisers

Chairs: Michelle Willebrands, Leo Burtscher, Abijit Borkar, Andreas Burkert, Keir Vanessa McBride, George Miley, Dav



Scientific organisers

Leo Burtscher (co-chair), Hannah Dalgleish (co-chair), Tobias Beuchert, Faustine Cantalloube, Victoria Grinberg, Natasha Hurley-Walker, Matthieu Isidoro, Knud Jahnke, Michelle Willebrands



This, is our home

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<https://astronomersforplanet.earth/open-letter>

Nature Astronomy, 'Climate Issue' 2020

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The ecological impact of high-performance computing in astrophysics

Computer use in astronomy continues to increase, and so also its impact on the environment. To minimize the effects, astronomers should avoid interpreted scripting languages such as Python, and favour the optimal use of energy-efficient workstations.

Simon Portegies Zwart

The third pillar of science, simulation and modelling, already had a solid foothold in fourth-century astronomy, but this discipline flourished with the introduction of digital computers. One of its challenges is the carbon emission resulting from this increased popularity. Generally unrecognized, the magnitude of the carbon footprint of computing in astrophysics should be emphasized. One purpose of this Comment is to raise this awareness, and present best practices for super-computer usage and choice of programming language.

Carbon footprint of computing In Fig. 1, we compare the average human production of CO₂ (red line) with astronomical activities, such as telescope operation, the emission of an average astronomer* and finishing a (four-year) PhD (green points). While large observing facilities are cutting down on carbon footprints by relying remote operation, the increased speed of computing resources can hardly be compensated by their increased efficiency. This also is demonstrated in Fig. 1, where we compare measurements for several popular astronomical computing activities (red square points). These measurements are generated using the Astrophysical Multipurpose Software Environment, in which most of the work is done in optimized and compiled code. We include simulations of the Sun's evolution from birth to the asymptotic giant branch using a Henyey solver* and parametrized Population synthesis.

We also present in Fig. 1 timings for comparing the evolution of a self-gravitating system of a million equal mass point particles in a virialized Plummer sphere (10 dynamical times) and a 'N-body' system. These calculations are performed by direct integration (with the fourth-order Hermite algorithm) and using a hierarchical tree-code (with leapfrog algorithm). Both calculations are performed on a CPU as well as with a graphics processing unit (GPU). Not surprisingly, the tree-code running a single GPU (second turquoise point from the left) is about a million times faster than a right-most turquoise point; one factor

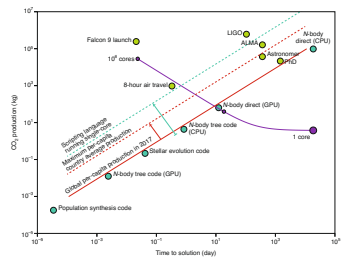


Fig. 1 Carbon production of a number of common activities among astronomers. CO₂ production as a function of the time to solution for a variety of popular computational techniques employed in astrophysics (various data points), and other activities common among astronomers* (green data points). The solid red curve gives the individual world-average production in 2017, whereas the dotted red curve gives the maximum per-capita country average. The Laser Interferometer Gravitational-Wave Observatory (LIGO) carbon production is taken over its first 306-day run (using ~180 kW), and for the Atacama Large Millimeter/submillimeter Array (ALMA) a 1-year average*. A Falcon 9 launch lists about 22 minutes during which ~10,000 litres of highly refined kerosene is burned. The tree-code running on a GPU was performed using $N = 2^8$ particles. The direct N-body code on a CPU (right-most turquoise data point) was run with $N = 2^8$ particles* and the other codes with $N = 2^8$ particles. All performance results were scaled to $N = 2^8$ particles. The calculations were performed on a single core. The energy consumption was computed using the scaling relations of ref. 1* and converted from kWh to CO₂ using 0.283 kWh/kg. The turquoise dotted curve shows the estimated carbon emission when these calculations would have been implemented in Python running on a single core. The burgundy curve shows the human and carbon production changes while increasing the number of compute cores from 1 to 10¹⁰ (out of a total of 2.29 × 10¹⁷ of the world's fastest computer, left-most point) using the performance model of ref. 1*. Figures created with Matplotlib*.

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An astronomical institute's perspective on meeting the challenges of the climate crisis

Analysing greenhouse gas emissions of an astronomical institute is a first step to reducing its environmental impact. Here, we break down the emissions of the Max Planck Institute for Astronomy in Heidelberg and propose measures for reductions.

Knud Jahnik, Christian Fendt, Morgan Fousneau, Iskren Georgiev, Tom Herbst, Melanie Kaasinen, Diana Kossakowski, Jan Rybizki, Martin Schlegler, Gregor Seidel, Thomas Henning, Laura Kreidberg and Hans-Walter Rix

Humanity's production of greenhouse gas (GHG) emissions is threatening our physical and mental health, and the chances of long-term survival of human society as we know it*. The GHGs emitted as we burn fossil fuels for energy have already resulted in a mean surface temperature rise of more than 1 °C since the late nineteenth century. To further limit the temperature rise to less than 1.5 °C (as per the Paris Agreement) requires all sections of human society to reduce their GHG emissions to net zero by 2050. The scientific profession is not exempt. It is our responsibility to analyse the origin of our work-related emissions, to identify solutions for reducing emissions, and to determine the responsibility on a personal, institute, community and society-wide level for implementing the necessary changes.

Astronomers of the Max Planck Institute for Astronomy (MPIA) in Heidelberg, Germany, we have assessed our work-related GHG emissions. The MPIA is a well-funded, international astronomy research institute with ~150 researchers and ~320 employees in total. A wide range of research is conducted at the institute, including the development of astronomical instrumentation, analysis of observational data, and theoretical modelling of astrophysical phenomena with computing facilities. The institute is a well-connected body within Europe and international, which, in combination with the broad range of research disciplines that these values are normalized to the GHG impact of CO₂. In particular, the numbers in this table account for flight emissions at altitude (for example, soil, nitrates, nitrogen oxides, a complement of clouds from contrails), as well as methane emissions from meat farming. The MPIA total GHG emissions for 2018 amount to 18.1 tCO₂e per researcher. Alternatively, the contribution per referred science publication, of which there were

MPIA GHG emissions We assessed the MPIA GHG emissions in seven categories: business flights, commuting, electricity, heating, computer purchases, paper use, and cafeteria meat consumption. These categories were selected either because they were likely to have a large contribution or because we had no prior gauge of their significance. To further limit the temperature rise to less than 1.5 °C (as per the Paris Agreement) requires all sections of human society to reduce their GHG emissions to net zero by 2050. The scientific profession is not exempt. It is our responsibility to analyse the origin of our work-related emissions, to identify solutions for reducing emissions, and to determine the responsibility on a personal, institute, community and society-wide level for implementing the necessary changes.

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583 either authored or coauthored by MPIA astronomers in 2018, is 4.6 tCO₂e. However, regardless of the chosen denominator, these metrics have caveats in attribution. For example a substantial part of the institute's emissions results from instrumentation projects that will lead to future publications, but at the same time, we do not account for the emissions associated with the construction of observing facilities used in the 2018 papers; in addition, simulations can take months to years.

The MPIA astronomy-related GHG emissions per researcher in 2018 were alarmingly around three times higher than the German target for 2030 (which is in line with the Paris Agreement), and more than twice as high as the average German resident, whose annual 2018 GHG emissions (by consumption) were 11.6 tCO₂e (ref. 1*). GHG emissions by consumption per adult resident were 14.0 tCO₂e (ref. 2*). Of course, these numbers just compare the work-related contributions of MPIA researchers to the Paris target and German average, neglecting the additional emissions associated with non-research-related 'private' emissions by MPIA researchers, such as, for example, housing, commuting, private mobility, or food. Few comparisons exist in the astronomical context. We therefore compare the MPIA emissions to the recent assessment by the Australian astronomical community*. The MPIA per researcher emissions are approximately half that of an Australian astronomer, which amounts to 42 tCO₂e per capita (see Fig. 1). Note that we calculated flight emissions using the model by atmospheric*, which estimates approximately double the emissions of the Qantas calculator* used for the original Australian assessment. Adjusting the reported Australian number by this factor, the MPIA flight emissions are similar or

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Measuring carbon emissions at the Canada-France-Hawaii Telescope

Measuring the carbon emissions of the CFHT in 2019 reveals that the per employee emissions are 16.5 tCO₂e, six times above the recommendation of the Paris Agreement, with -63% due to the electricity consumption of the summit facility and -25% to out-of-state air travel. Concerted efforts are underway to reduce this figure.

Nicolas Flagey, Kahea Thomas, Andreea Petric, Kanao Withington and M. Johannes Seidel

Astronomers may not be the main contributors to climate change or the first to be affected by its consequences: we are not directly burning fossil fuels, and global warming and its associated catastrophes have not substantially impacted observations at ground-based telescopes yet. However, the way of life in the world of astronomy is emblematic of the negative impact of humankind on the climate. We travel to attend meetings all over the world or to capture telescope observations in visitor mode. Our observatories on the ground require a tremendous amount of power to operate. While we look for habitable planets in the Universe, we should not forget that Earth is the only one known so far to harbour life, and thus the only one we should be invested in keeping habitable.

Astronomy and society-wide level for implementing the necessary changes. Astronomers of the Max Planck Institute for Astronomy (MPIA) in Heidelberg, Germany, we have assessed our work-related GHG emissions. The MPIA is a well-funded, international astronomy research institute with ~150 researchers and ~320 employees in total. A wide range of research is conducted at the institute, including the development of astronomical instrumentation, analysis of observational data, and theoretical modelling of astrophysical phenomena with computing facilities. The institute is a well-connected body within Europe and international, which, in combination with the broad range of research disciplines that these values are normalized to the GHG impact of CO₂. In particular, the numbers in this table account for flight emissions at altitude (for example, soil, nitrates, nitrogen oxides, a complement of clouds from contrails), as well as methane emissions from meat farming. The MPIA total GHG emissions for 2018 amount to 18.1 tCO₂e per researcher. Alternatively, the contribution per referred science publication, of which there were

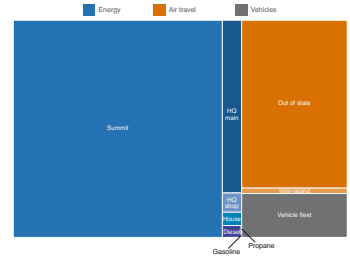


Fig. 1 Visual breakdown of the carbon emissions at CFHT in 2019. The area covered by each block represents its contribution to the total (16.5 tCO₂e). Energy-related emissions are in blue, air-travel emissions are in orange, vehicle-fuel emissions are in grey.

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The carbon footprint of large astronomy meetings

The annual meeting of the European Astronomical Society took place in Lyon, France, in 2019, but in 2020 it was held online only due to the COVID-19 pandemic. The carbon footprint of the virtual meeting was roughly 3,000 times smaller than the face-to-face one, providing encouragement for more ecologically minded conferencing.

Leonard Burtcher, Didier Barret, Abhijeet P. Borkar, Victoria Grinberg, Knud Jahnik, Sarah Kendrew, Gina Maffey and Mark J. McCaughey

The scientific evidence that we live in a climate emergency calls for urgent action*. As a society, we are collectively failing to live within our environmental boundaries* with possibly catastrophic consequences for human civilization. The time to address these issues is now*. The United Nations Emissions Gap Report for 2019 states that each year a global reduction of emissions of 7.6% is required to limit the average global temperature rise to 1.5 °C (ref. 1*) — the target that was outlined in the Paris Agreement in 2016. At the current rate of emissions, we will exceed the carbon budget* to meet this goal within the next eight years*. While ultimately systemic change is required to solve the climate crisis, it is also the responsibility of individuals to reduce our emissions. This applies in particular to astronomers who rely heavily on computing fuel energy for, for example, computation, telescope operation and travel*. To future-proof astronomy, we must recognize impending environmental change, financial uncertainties and the need for moral introspection, which threaten to hinder the continuation of the discipline. At the same time, the advancement and sharing of knowledge in general (and particularly with the public) is becoming even more vital as we face a global threat.

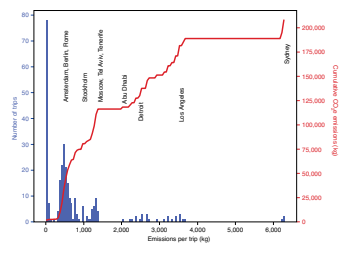


Fig. 1 Histogram of CO₂ emissions per trip. The blue histogram corresponds to the left axis, and cumulative emissions are shown with the red line and the right axis. Some example destinations are indicated for reference. Note that these numbers refer to respondents only (~22% of all participants).

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The impact of climate change on astronomical observations

Climate change is affecting and will increasingly affect astronomical observations, particularly in terms of dome seeing, surface layer turbulence, atmospheric water vapour content and the wind-driven halo effect in exoplanet direct imaging.

Faustine Cantalloube, Julien Milli, Christoph Böhm, Susanne Crewell, Julio Navarrete, Kira Rehfeld, Marc Sarazin and Anna Sommani

Astronomers are entering an era in which they will change the way they work, with the arrival of the 30–80 m class ground-based telescopes and large international observational projects sparking new ways of communicating and collaborating. These scientific challenges come together with societal ones, such as the role astronomers play in communicating and undertaking actions to significantly reduce the environmental footprint of astronomical research. More generally, and in order that astronomy through their unique perspective on the Universe, communicate about and act on climate change consequences and in this context, we have investigated the role some key weather parameters play in the quality of astronomical observations and analysed their long-term (longer than 30 years) trends in order to grasp the impact of climate change on future observations. In what follows we give four examples of how climate change already presents or could potentially affect the operations of an astronomical observatory. This preliminary study is conducted with data from the Very Large Telescope (VLT), operated by the European Southern Observatory (ESO), located at Cerro Paranal in the Atacama Desert, Chile, which is one of the driest places on Earth. For the analysis presented below, we used the various sensors installed at Paranal Observatory but also, to show a longer time span (from 1980 to the present), we used the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate, ERA5*, with a spatial resolution of 31 km, which we interpolated at the Paranal Observatory location. To investigate longer timescale evolution (times 1980 to 2018), we used the National Centers for Environmental Prediction (NCEP) reanalysis (2000 to 2018) at a spatial resolution (130 km) that averages the global topography and may blend the ocean–continent interface, we use in some cases the ERA20C reanalysis data*. In addition, we

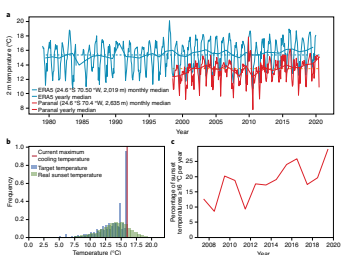


Fig. 1 Temperature in the region around Paranal Observatory. a, Monthly averaged daily mean temperature over the Paranal Observatory as a function of time, retrieved from the ERA5 reanalysis data (blue) and as measured at the Paranal Observatory (red), with the corresponding yearly average (black line) and median (dashed line). b, Occurrence of the rain (grey) and snow (black) temperature (limited to 16 °C, solid red line) of the US DOE cooling system, from 2006 to 2020. c, Frequency of the sunset temperature minimum at Paranal to be below the 10 °C threshold, as a function of time, from the ERA20C reanalysis data (green) with its global median (green dotted line), and from the CMIP5 climate projection using the SSP5-8.5 scenario (Beijing Climate Centre, BCC-CSM2-MR model ensemble), adjusted to the ERA20C mean (orange).

nature astronomy PERSPECTIVE <https://doi.org/10.1038/s41550-020-1160-1> [Check for updates](#)

The imperative to reduce carbon emissions in astronomy

Adam R. H. Stevens^{1,2,3}, Sabine Bellstedt⁴, Pascal J. Elahi^{1,2,4} and Michael T. Murphy⁵

For astronomers to make a significant contribution to the reduction of climate change-inducing greenhouse gas emissions, we first must quantify the sources of our emissions and review the most effective approaches for reducing them. Here we estimate that Australian astronomers' total greenhouse gas emissions from their regular per capita activities are 2.25 tCO₂e yr⁻¹ (equivalent kilometres of carbon dioxide per year). This can be broken into -15 tCO₂e yr⁻¹ from supercomputer usage, -4.2 tCO₂e yr⁻¹ from flights (where individual flight emissions correlate with seniority), > 3.3 tCO₂e yr⁻¹ from the operation of observatories, and 2.6 ± 0.4 tCO₂e yr⁻¹ from powering office buildings. Split across faculty scientists, postdoctoral researchers and PhD students, this averages to > 37 tCO₂e yr⁻¹ per astronomer, more than 40% greater than the average Australian non-dependant's emissions in total, and equivalent to around five times the global average. To combat these environmentally unsustainable practices, we suggest that astronomers should strongly preference the use of supercomputers, observatories and office spaces that are predominantly powered by renewable energy sources. Where current facilities do not meet this requirement, their funders should be lobbied to invest in renewables, such as solar or wind farms. Air travel should also be reduced wherever possible, replaced primarily by video conferencing, which should also promote inclusivity.

Climate change is widely regarded as the biggest ongoing issue facing the planet's inhabitants right now. So much so that over 11,000 scientists from 153 countries recently signed a proper warning of global climate catastrophe. Humanity's continuing emission of greenhouse gases—driven predominantly by the burning of fossil fuels as a source of energy—has already led to the mean global surface temperature of ~1 °C relative to pre-industrial levels*. For global heating to be limited to 1.5–2 °C over the Paris Agreement's target, we require a rapid and effective anthropogenic emissions in the next few decades*. Even then, it is expected that there will be long-lasting (timescales of 2 × 10⁴ yr) temperature perturbations at the end of the March 2019 quarter according to the Australian Bureau of Statistics—of which 18.7% are dependants under the age of 15—the country's emissions rate equates to 26.2 tCO₂e yr⁻¹ per capita on average. This is in stark contrast to the 2018 global average of 7.3 ± 0.7 tCO₂e yr⁻¹ per non-dependant (based on total emissions from the Global Carbon Budget 2019* and the global population from Worldometers, taking the range of the 2017 and 2019 values as the uncertainty on the latter) and makes Australia one of the highest-emitting countries per person in the world. Countries that have comparable per-capita emissions rates to Australia include the United States and Canada*. Perhaps it is no coincidence then that members of the astronomical community from these countries have written white papers on this same topic, which include several practical, sensible suggestions for mitigation strategies*. This is clearly an issue that astronomers worldwide are cognisant of; the Canadian paper* was one of the five most widely discussed papers for its month of release, with members from 43 astronomy institutes up-voting it on the Visceral website. In Australia, an open letter has been written to the federal government, highlighting the urgent need to reduce greenhouse gas emissions, which has been signed by over 80 Laureate Fellows—the most

these leads to action that will result in a decrease in the community's emissions. For to be aware of a problem but choose not to act is practically no different than to deny the problem's existence, especially when one is demonstrably contributing to said problem. We all have an ethical obligation here that must not be ignored. Climate change action is particularly important for Australia-based astronomers (and Australians in general), as Australia's record of greenhouse gas emissions is particularly poor in the global context. Australia's total emissions (including international flights and shipping) for the year ending March 2019 were 538.9 million equivalent tonnes of CO₂ (MtCO₂e) (ref. 1*). With a population of 25.287 million people at the end of the March 2019 quarter according to the Australian Bureau of Statistics—of which 18.7% are dependants under the age of 15—the country's emissions rate equates to 26.2 tCO₂e yr⁻¹ per capita on average. This is in stark contrast to the 2018 global average of 7.3 ± 0.7 tCO₂e yr⁻¹ per non-dependant (based on total emissions from the Global Carbon Budget 2019* and the global population from Worldometers, taking the range of the 2017 and 2019 values as the uncertainty on the latter) and makes Australia one of the highest-emitting countries per person in the world. Countries that have comparable per-capita emissions rates to Australia include the United States and Canada*. Perhaps it is no coincidence then that members of the astronomical community from these countries have written white papers on this same topic, which include several practical, sensible suggestions for mitigation strategies*. This is clearly an issue that astronomers worldwide are cognisant of; the Canadian paper* was one of the five most widely discussed papers for its month of release, with members from 43 astronomy institutes up-voting it on the Visceral website. In Australia, an open letter has been written to the federal government, highlighting the urgent need to reduce greenhouse gas emissions, which has been signed by over 80 Laureate Fellows—the most

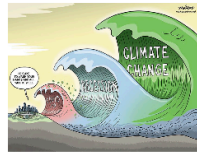
International Centre for Radio Astronomy Research, The University of Western Australia, Crawley, Western Australia, Australia. *Australian Research Council Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D). †Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Hawthorn, Victoria, Australia. ‡Perseus Supercomputing Centre, Kensington, Western Australia, Australia. *E-mail: adam.stevens@uwa.edu.au

Nature Astronomy, 'Climate Issue' 2021

Climate change continues to be an issue

As the world recovers from one global crisis, it must steel itself for the coming of a far greater one: the climate crisis. Astronomers and planetary scientists have roles to play as trusted scientific experts, but should seek partnerships with domain experts when venturing outside their areas of knowledge.

The COVID-19 pandemic has been a stark reminder of humanity's close links to the 'natural' world. Despite advanced knowledge of virology, immunology, medicine and crisis response techniques, the human species has experienced more than 4 million deaths following infection by a virus that arose naturally (according to best current knowledge). The situation could have been worse, however, and governments around the world did act to mitigate the impact on lives. These measures set an important precedent for action from civil authorities and international cooperation in the future. It is now clear that another global disaster is heading our way and already making its effects felt: the climate crisis. It is inevitable that global temperatures will rise as a consequence of human pollution of the planet over the last two and a half centuries, and particularly over the last 50 years. "Nature does not bargain and you cannot compromise with the laws of physics," warns climate activist Greta Thunberg.



Credit: Graeme MacKay

While the initial efforts of some astrophysicists to model the COVID-19 outbreak were criticized in some quarters, the climates of terrestrial planets is a domain where astronomers and planetary scientists have extensive knowledge and expertise. This provides astronomers with a unique viewpoint on Earth's climate crisis, and we should certainly communicate our understanding of this topic to the wider public, especially given our abundant opportunities to engage in public outreach, appear in the media, and teach hundreds of thousands of students every year.

It should be stated quite clearly that there is no way to 'fix' the climate crisis. It is unavoidable that the planet will warm, and there will be environmental consequences of that warming: heatwaves, heavy precipitation, droughts, coastal flooding and tropical cyclones. Last month the Intergovernmental Panel on Climate Change released their latest report, which made it clear that there are opportunities to limit the extent of environmental impact if action is taken immediately, though, and future outcomes will depend on the degree of action taken. The report focuses on limiting global cumulative CO₂ emissions, reaching at least net zero, and ideally also reducing emissions of other greenhouse gases such as CH₄. But it does not explain how to limit CO₂ emissions; that will be for governments and intergovernmental organizations to decide. In November this year hundreds of thousands of students and world

NATO policy advisor Andrew Williams has distilled his experience in this area into a **Comment** in this issue. Again, the advice is to work with the experts.

Exactly a year ago we dedicated our September 2020 issue to presenting the quantitative impact of astronomy as a profession on the environment. Some of the numbers presented in the various articles were surprising: attending a large European astronomy conference generates as much CO₂ per capita as a year of everyday life in a developing country; the average Australian astronomer, just through their professional activities, generates 40% more CO₂ than a typical Australian, with senior astronomers being the biggest contributors and the footprint of European astronomers is not much smaller. These articles and some of the others in the issue raised awareness within the community of astronomy's carbon footprint, and the topic was discussed widely in journal clubs and departmental and board meetings. The Astronomers for Planet Earth group, which was formed off the back of the large European astronomy conference mentioned above, has been keeping the momentum going, engaging in a number of activities detailed in another **Comment** in the current issue. Organizations such as the European Southern Observatory and the Square Kilometre Array Observatory have been putting forth their sustainability plans. Professional astronomy can exist in a low-carbon future, but changes must be made, from removing the dependence of our observatories and summer committees

editorial



comment



Forging a sustainable future for astronomy

The climate crisis is no longer a prediction for the future, it is happening here and now. Astronomers have realized that they need to become part of the solution and are working towards reducing their own carbon footprint as well as communicating an astronomical perspective.

Leonard Bartscher, Hannah Dalgleish, Didier Barret, Tobias Beuchert, Abhijeet Borkar, Faustine Cantalloube, Abigail Frost, Victoria Grinberg, Natasha Hurley-Walker, Violette Impellizzeri, Mathieu Isidro, Knud Jahnke and Michelle Willebrands

The climate crisis is real and humans are causing it: the urgency of these scientific facts is becoming increasingly clear. Developing nations such as low-lying Bangladesh have experienced the impacts of climate change with devastating floods in recent years, while richer nations in the global north suffer record wildfires, heatwaves and floods. Indeed, a study conducted earlier this year by the Yale Program on Climate Change Communication found that internationally, a large majority of people have understood that everyone is vulnerable in a deteriorating climate, and encourages immediate and significant action. And yet, current climate action is too little and too slow to reduce emissions quickly enough to keep within 1.5 °C of global heating, the goal of the 2015 Paris Agreement. More awareness, and more action, is essential. Fundamentally it is governments and corporations that must act, but actions by individuals and groups have power too, especially when they come from wealthy people whose contributions to greenhouse gas emissions are disproportionately large (Fig. 1).

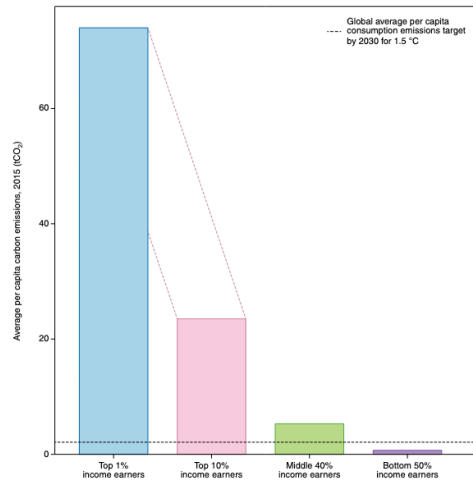


Fig. 1 | Who is responsible for carbon emissions world-wide? The richest 1% (income >US\$109,000) of the population produce 15% of emissions and the 10% richest (>US\$38,000) produce 48% of emissions. This shows that our lifestyle has the highest impact on our planet; wealthy people therefore have the highest imperative to change behaviour. Data taken from ref. 18.

The carbon footprint of astronomers is substantial, too. For instance, the average emissions associated with visiting a single in-person conference are similar to the annual per capita emissions of developing countries¹. And yet astronomers can contribute to solving the climate crisis in two key ways. Firstly, by demonstrating how global collaboration is possible without burning fossil fuels, and secondly, through communicating the climate crisis from an astronomical perspective²⁻⁴.

Discussing, and reducing, our own emissions as astronomers is vital for a number of reasons. The most fundamental is the moral argument: we know that our emissions are causing harm, so reducing them is the ethical choice. But we also need to reduce emissions for our own discipline's sake⁵ (Fig. 2). Countries signing up to net-zero targets necessitate the need to perform carbon-neutral research; the sooner

we prepare, the better we will manage the transition for our own discipline. Finally, we need to reduce emissions in order to make ourselves credible actors in the much larger societal fight against the climate crisis. How can we convincingly tell the general public and policy makers that 'there is no planet B' while hopping onto the next intercontinental flight for a conference at a fancy location?

To support both climate action within astronomy and to help astronomers communicate the climate crisis, the grass-roots organization **Astronomers for Planet Earth (APE)** was founded in 2019. In two years, APE has rapidly grown to a global organization connecting more than 1,100 research astronomers, astronomy educators, and students⁶. APE members

comment



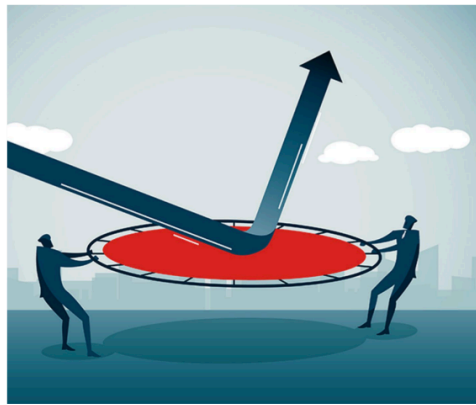
The need for political advocacy in astronomy

Astronomers are used to advocating for (financial) support for their future endeavours, but how should they go about lobbying for support for issues such as the climate emergency? Join forces with those experienced in effecting policy change.

Andrew Williams

In the modern era, astronomy seems far removed from politics, in part due to its focus on the discovery of fundamental knowledge and its universal truths, but also due to its relatively uncontroversial findings and unobtrusive nature of observation. The areas in which astronomers do engage politically, or at least 'get political', generally concern advocating for funding, science policy issues affecting the field such as open access, conditions in academia or satellite constellations, and more recently, dealing with societal issues such as institutional racism, diversity and decolonization. Yet what should the astronomy community do for crises that transcend national politics or self-protection? The most pressing crisis of our time is the climate emergency, which will generate a range of drastic and negative societal impacts in a relatively short timescale unless governments and industries around the world take strong and concerted actions. The recently released report by the Intergovernmental Panel on Climate Change⁷ (IPCC) further underscores the dire need for action.

The astronomy community has begun to grapple with reducing the climate impact of its own internal practices, from understanding the impact of professional conferences, to improving the environmental sustainability of observatories and computing facilities^{8,9}. The recently formed **Astronomers for Planet Earth** group seeks to provide resources, support education about climate change and corral the community's efforts to reduce its overall carbon footprint. These internally focused actions are noteworthy for a relatively small scientific field representing a tiny sliver of global carbon output, yet what role can astronomers and the astronomy community play to address the key drivers of climate change and promote solutions? Should astronomers engage with politicians, governments and corporations, particularly in a domain already saturated with a huge range of interest groups and advocacy coalitions? There are two reasons why I think astronomers should engage.



Credit: Erhui1979 / DigitalVision Vectors / Getty

First, scientists are citizens and there is a moral imperative to engage given the dire consequences of inaction¹⁰. This imperative is even greater for scientists equipped with the capacity to understand the science and the impacts. As scientists, astronomers can immediately take action in a number of ways, from taking personal steps to reduce their carbon footprint, protesting, writing letters to politicians, government leaders and media, to addressing their own funding agencies and organizations. At an individual level, these uncoordinated actions are the bedrock of activism that keeps policy issues high on government agendas and on the radars of large corporations, yet astronomers can go further.

The second reason for engagement is that the astronomy community can add value

to the climate policy domain through its unique perspective and authoritative and credible message. In addition to relatively unstructured and distributed activism, groups such as **Astronomers for Planet Earth** could take a coordinated approach to political advocacy. This approach requires developing an appreciation for how policy change happens and understanding the system complexity in the climate policy domain. The 70-year-old discipline of policy science shows that policy change is mainly and often frustratingly incremental due to the inertia associated with large systems, but with occasional 'punctuations' of rapid change. How this change happens depends hugely on the context, the nature of public opinion, political processes and timelines, the actions

Five steps for astronomers to communicate climate change effectively

Astronomers are trusted voices in the communication of science; our community should resist inundating people with facts and figures but use its advantage to encourage the public to listen to climate change experts and encourage the need for urgent cross-sectoral systemic change.

Alison Anderson and Gina Maffey

Climate change is one of the most serious challenges facing our planet and we are increasingly experiencing its dire effects with soaring temperatures, wildfires, floods and droughts. Within astronomy there is growing recognition of the urgency of the situation, the professions impact on it and the need to communicate outside the academy¹¹. Scientists are highly trusted by the public and tend to be seen as independent and non-controversial¹². Astronomers are particularly well placed to communicate on climate change, given that the exciting nature of their subject often provides them with a platform in the media and the ability to reach out to very large numbers of people through a variety of public outreach events around the globe. Astronomy offers many entry points to talking about climate change, from the climate history of the terrestrial planets to the notion that there is no alternative planet for humans to live on: there is no 'Planet B'. We argue that there is a real window of opportunity for astronomers to engage with the topic and weave climate change into their public engagement activities. There is a large body of research in science and environmental communication that can inform practice in the astronomy community and here we summarize the key findings.

Tell a story
Effective climate change communication requires two-way dialogue and strong narratives. Telling stories enables audiences to make sense of complex issues and human-interest narratives tend to be more memorable than numbers or graphs¹³. Best-practice guides on climate change communication recommend emphasizing scientific consensus while carefully explaining how a degree of uncertainty is present in all scientific work¹⁴. Metaphors can influence people's attitudes to climate change, while strong visual images and analogies should be relatable and, where possible, include people¹⁵. When crafting

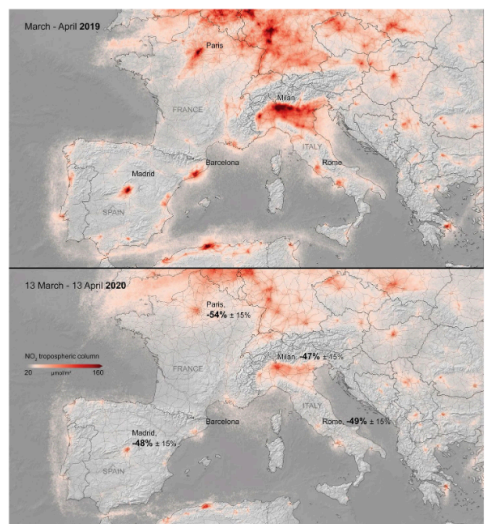


Fig. 1 | Nitrogen dioxide concentrations over Europe. These images use data from the Copernicus Sentinel-5P satellite to compare polluting nitrogen dioxide concentrations in March–April 2019 with the same period a year later, when pandemic restrictions were keeping many Europeans at home. Credit: Contains modified Copernicus Sentinel data (2019–20), processed by KNMI/ESA.

stories, however, it should be considered that the language and terminology used by scientists may not be shared by the public and can add to confusion about the issues¹⁶. As Somerville and Hassol point

out: "Scientists typically fail to craft simple clear messages and repeat them often. They commonly overdo the level of detail, and people can have difficulty in sorting out what is important... Many words that

The impact of climate change on astronomical observations

Climate change is affecting and will increasingly affect astronomical observations, particularly in terms of dome seeing, surface layer turbulence, atmospheric water vapour content and the wind-driven halo effect in exoplanet direct imaging.

Faustine Cantalloube, Julien Milli, Christoph Böhm, Susanne Crewell, Julio Navarrete, Kira Rehfeld, Marc Sarazin and Anna Sommani

Astronomers are entering an era in which they will change the way they work, with the arrival of the 30–40 m class ground-based telescopes and large international observational projects sparking new ways of communicating and collaborating. These scientific challenges come together with societal ones, such as the role astronomers play in communicating and undertaking actions to significantly reduce the environmental footprint of astronomical research. More generally, it is urgent that astronomers, through their unique perspective on the Universe, communicate about and act on climate change consequences at any level. In this context, we have investigated the role some key weather parameters play in the quality of astronomical observations and analysed their long-term (longer than 30 years) trends in order to grasp the impact of climate change on future observations. In what follows we give four examples of how climate change already affects or could potentially affect the operations of an astronomical observatory. This preliminary study is conducted with data from the Very Large Telescope (VLT), operated by the European Southern Observatory (ESO), located at Cerro Paranal in the Atacama Desert, Chile, which is one of the driest places on Earth. For the analyses presented below, we used the various sensors installed at Paranal Observatory but also, to show a longer time span (from 1980 to the present), we used the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate, ERA5¹, with a spatial resolution of 31 km, which we interpolated at the Paranal Observatory location. To investigate longer timescale evolution (from 1900 to 2010), at a cost of a coarser spatial resolution (130 km) that averages the actual orography and may blend the ocean–continent interfaces, we in some cases used the ERA20C reanalysis data². In addition, we

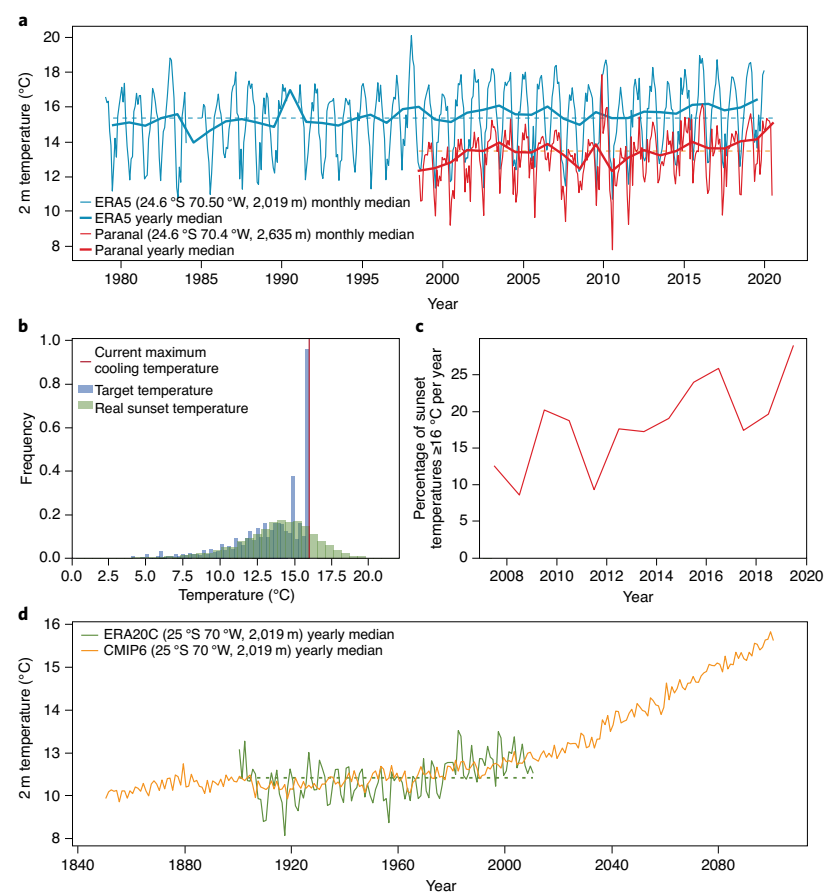


Fig. 1 | Temperature in the region around Paranal Observatory. **a**, Monthly averaged daily mean temperature over the Paranal Observatory as a function of time, retrieved from the ERA5 reanalysis data (blue) and as measured at the Paranal Observatory (red), with the corresponding yearly average (thick lines) and median (dashed lines). **b**, Occurrence of the real (green) and target (blue) temperature (limited to 16 °C, solid red line) of the UTs dome cooling system, from 2006 to 2020. **c**, Frequency of the sunset temperature measured at Paranal to be above the 16 °C limit of the current cooling system, as a function of time. **d**, Yearly median near surface air temperature as a function of time, from the ERA20C reanalysis data (green) with its global median (green dotted line), and from the CMIP6 climate projection using the SSP5-8.5 scenario (Beijing Climate Centre, BCC-CSM2-MR model ensemble), adjusted to the ERA20C mean (orange).

We witness the problem

We are part of the problem

We undergo the problem

Technology is indeed improving

BUT

we are also doing finer science

Paranal Observatory (Chile)

24°37'38"S 70°24'15"W



*Very Large Telescope
(2635m)*

Paranal Observatory (Chile)



Paranal Observatory (Chile)



Paranal Observatory (Chile)

Data: -> suitable for climate studies !

- We collected ~30 years of ambient meteorological data
- Re-analysis data are available (ECMWF, GMAO, NCEP/NCAR)
- Weather balloon (twice daily at Antofagasta)
- Projection for next century (IPCC-defined SSPs: CMIP)



Questions:

- Do we see the climate change in our observatory data ?
- How does it compare with external data ?
- Does it affect the quality of the observations ?
- What's gonna happen in ~20 years (ELT, SKA, ATC, AtLAST...)

Four examples of climate change indicators

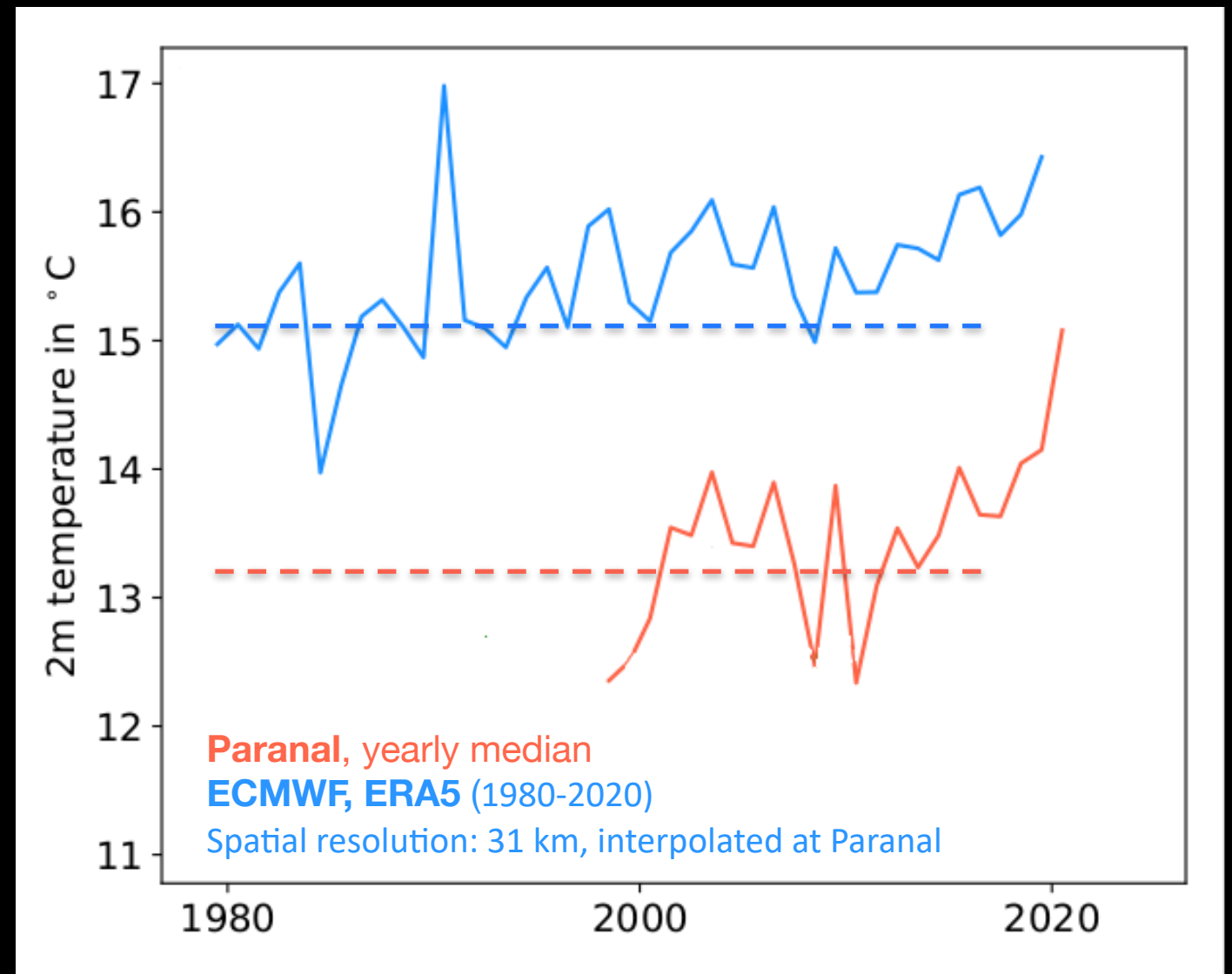
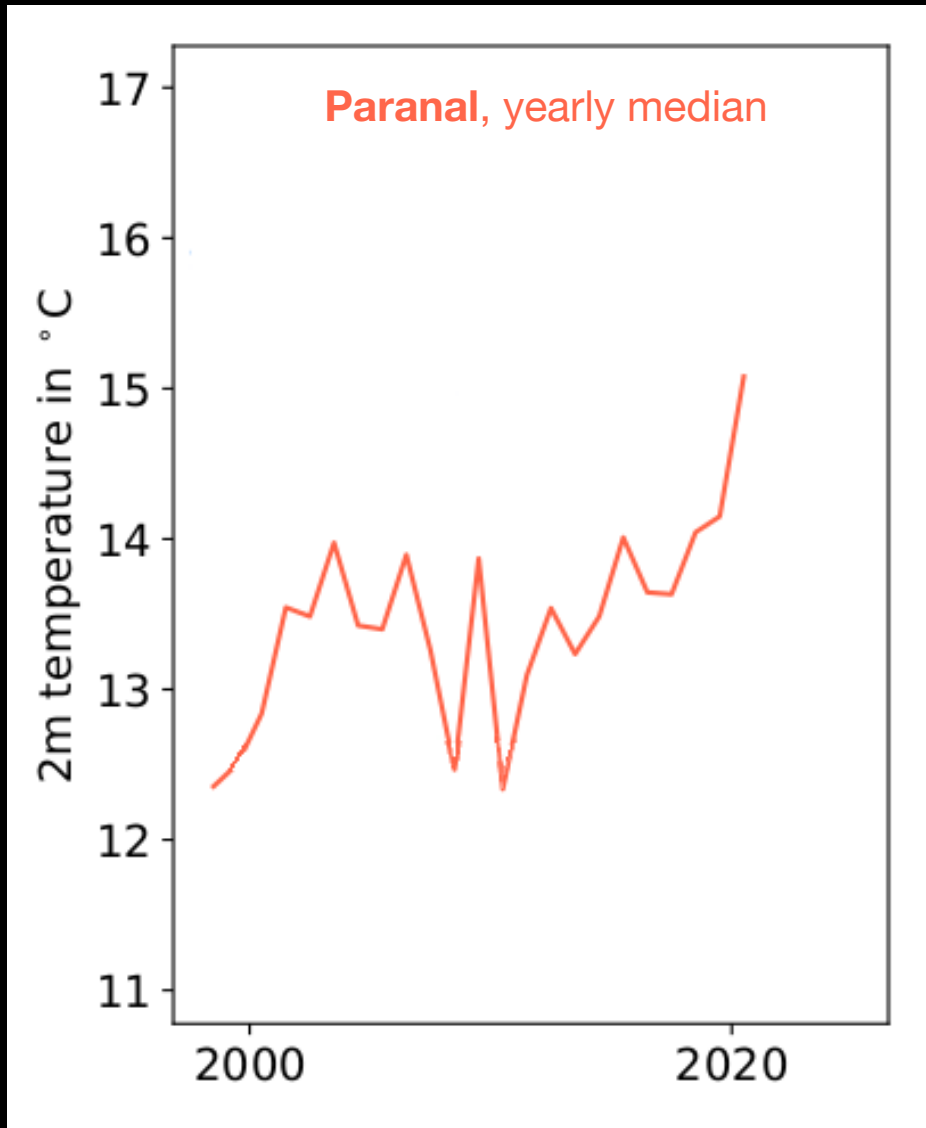
At Cerro Paranal observatory



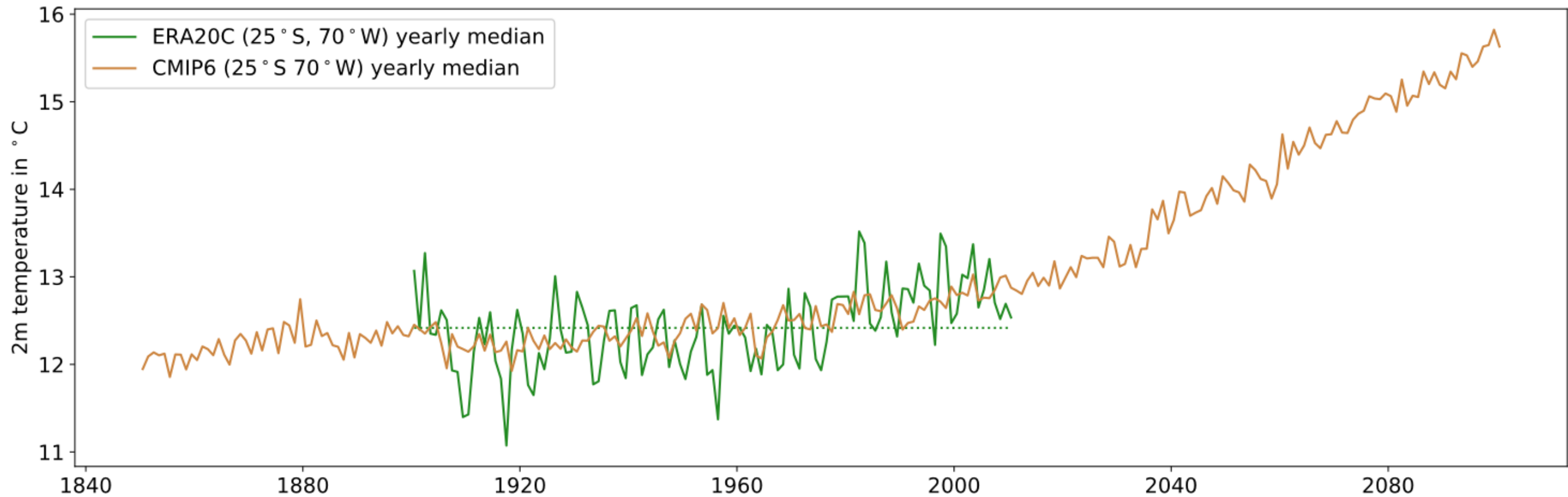
MASS-DIMM (1998)

1. Temperature
2. Seeing
3. Jet stream wind speed
4. Humidity

1. Temperature: observations



1. Temperature: projection



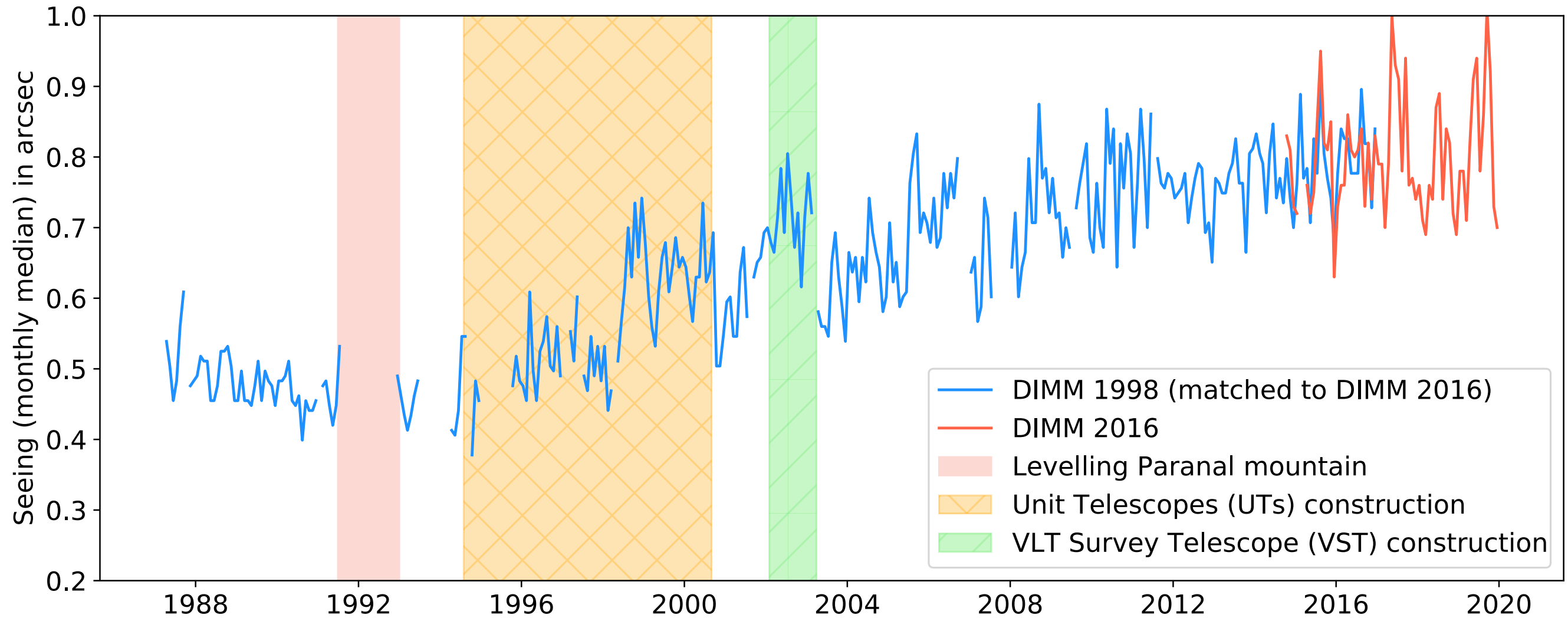
CMIP6

Climate projection using the SSP5-8.5 scenario
Beijing Climate Centre, BCC-CSM2-MR model ensemble

ECMWF

Reanalysis data ERA20C (1900-2010)
Spatial resolution: 130 km, 'interpolated' at Paranal

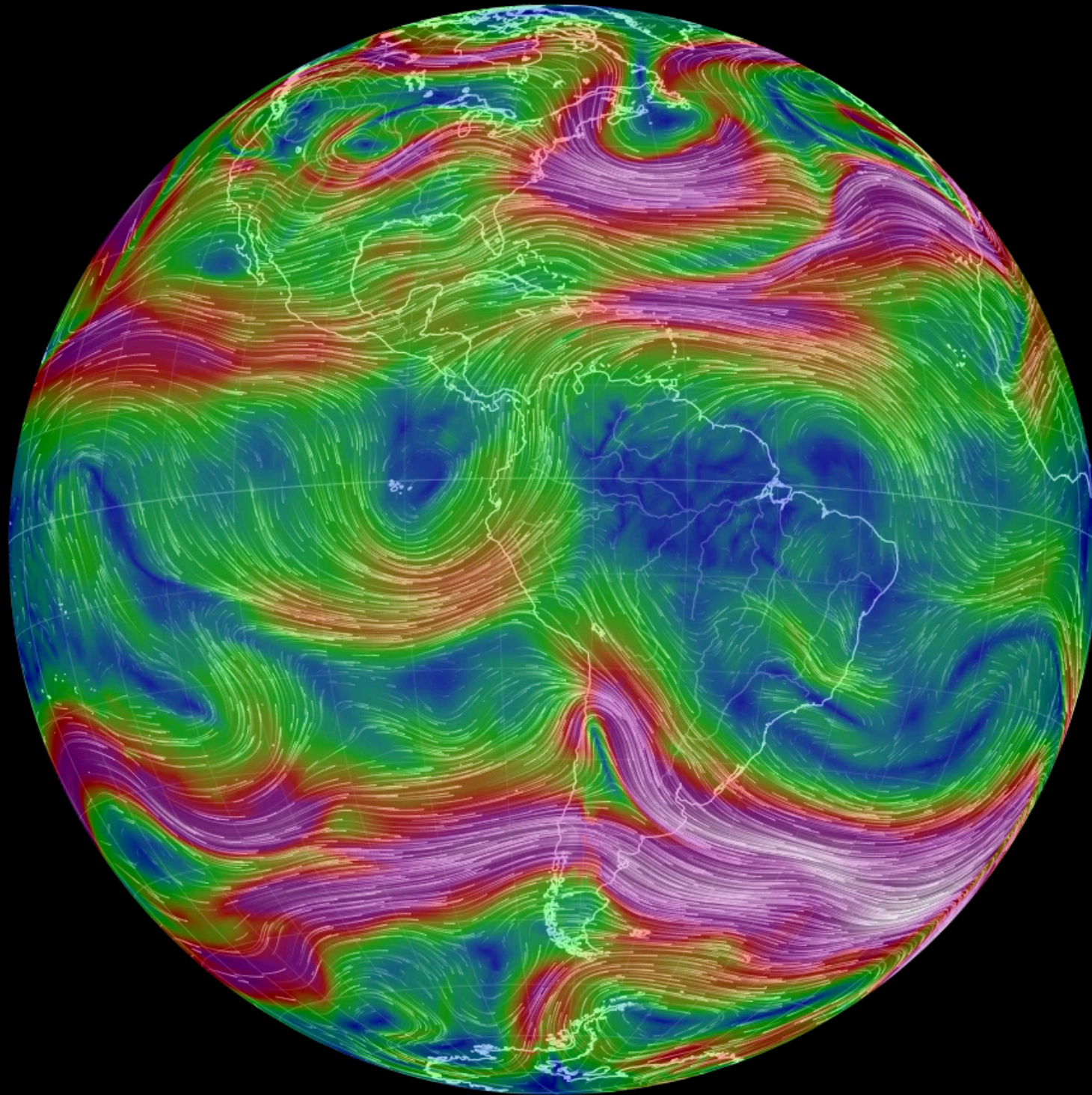
2. Surface Layer Seeing: observations



Two hypothesis:

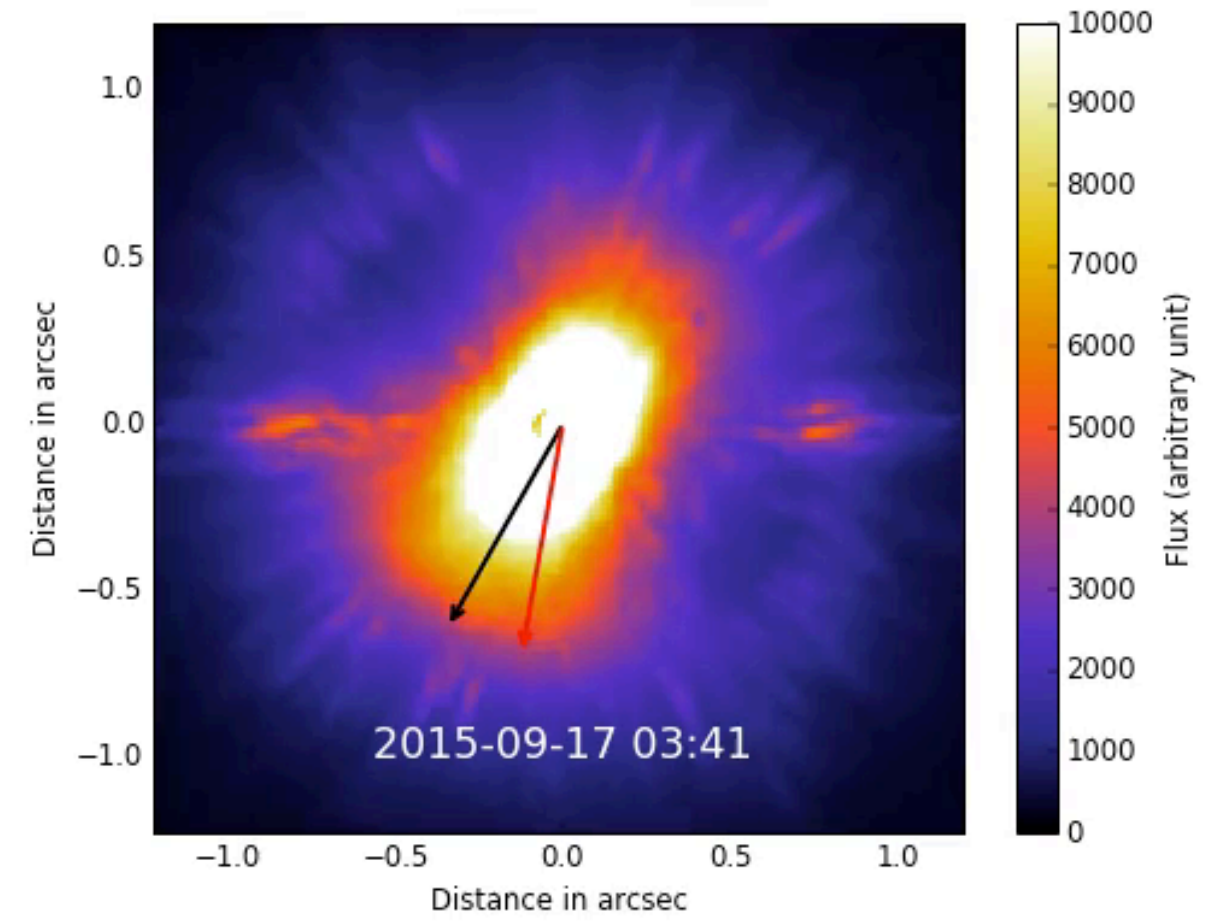
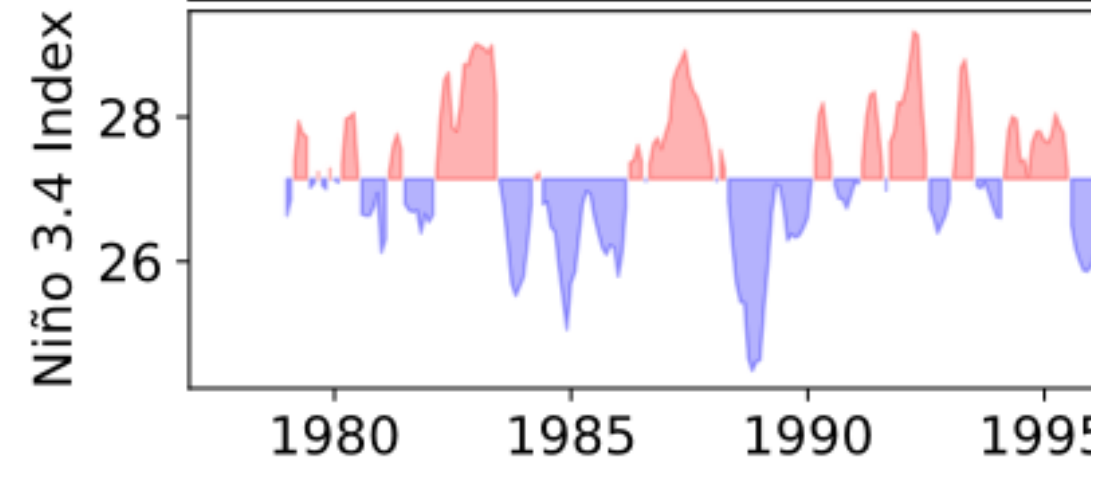
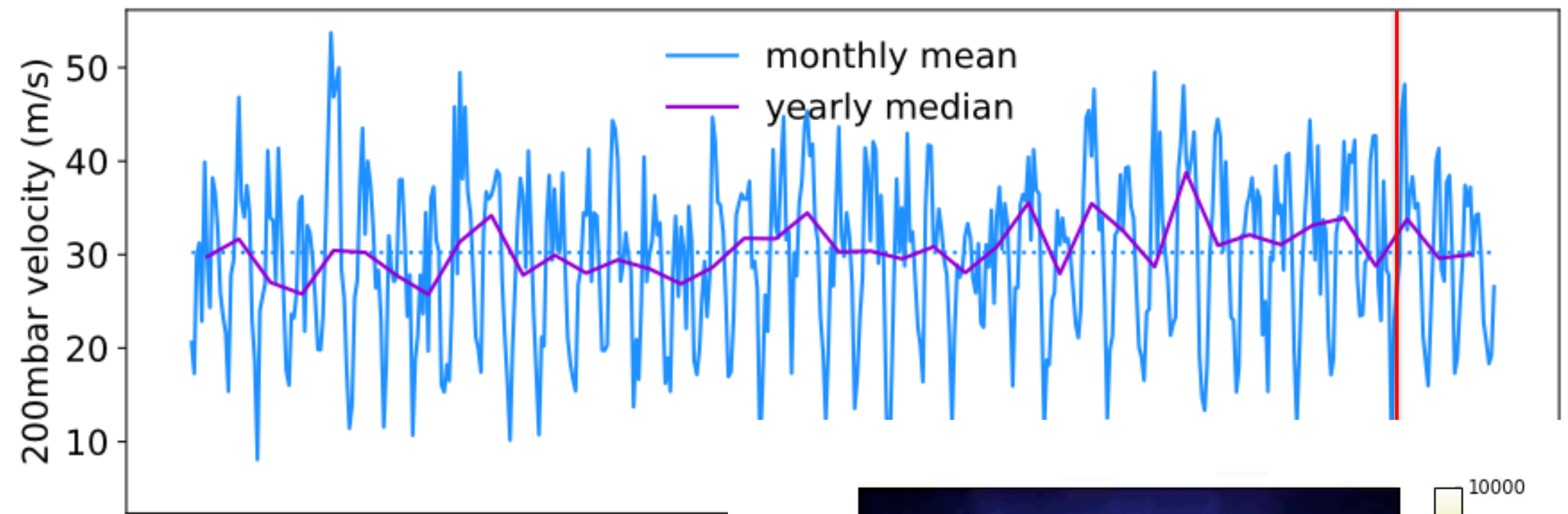
- (1) levelling of the mountain and the numerous changes of configuration of the DIMM
- (2) the local changes due to global atmospheric circulation transition

3. Jet stream wind-speed: definition



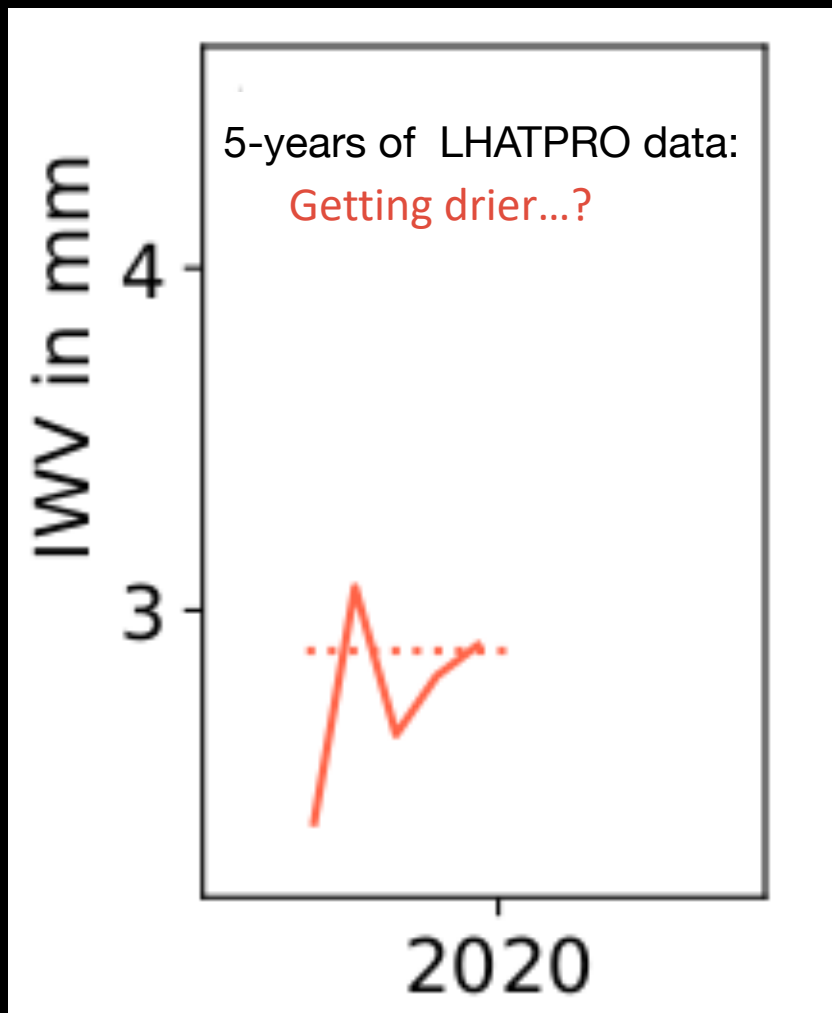
Subtropical jet stream layer: 12+/-1 km, 20 to 60m/s

3. Jet stream wind-speed: observations



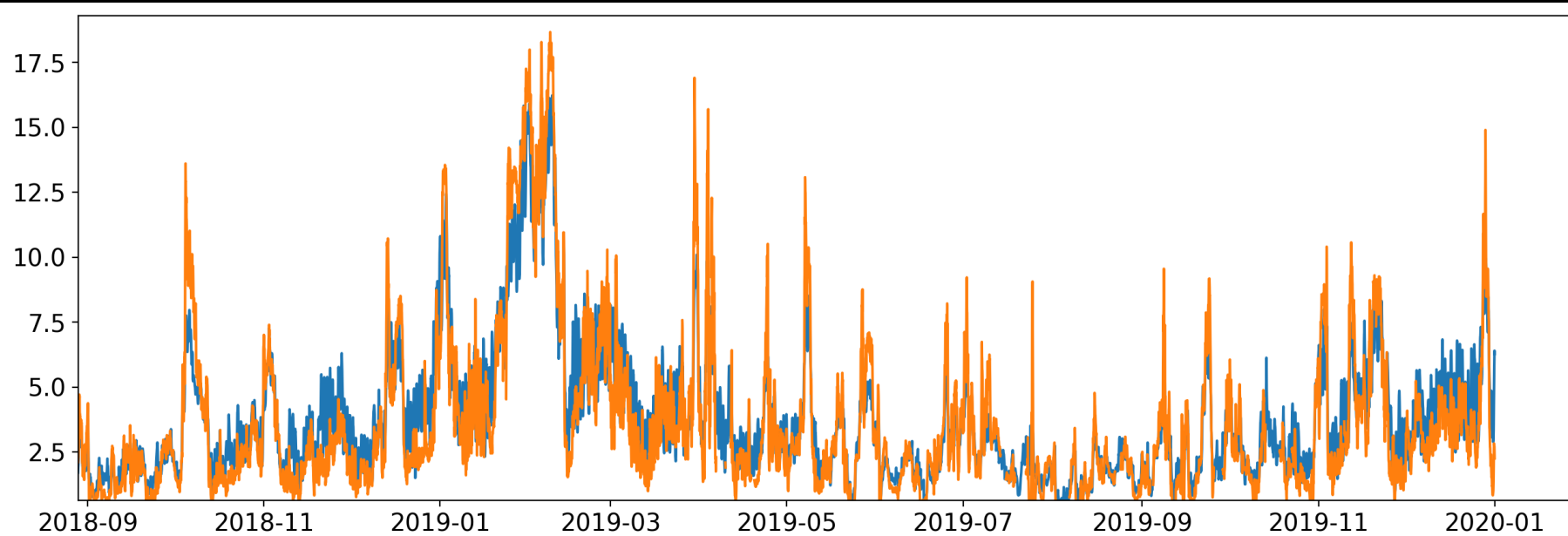
+2-3 m/s since 2015 ...

4. Humidity: observations



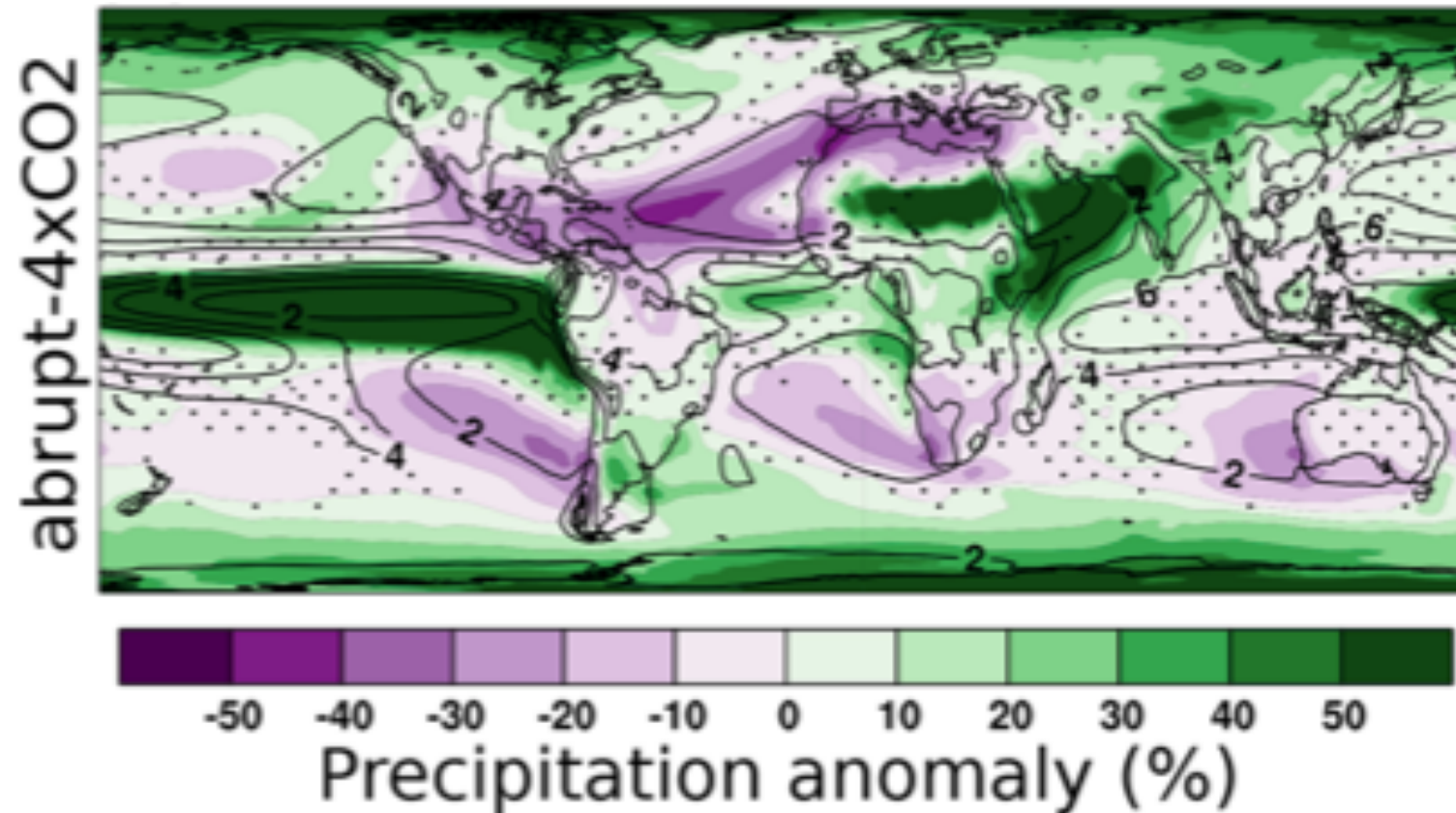
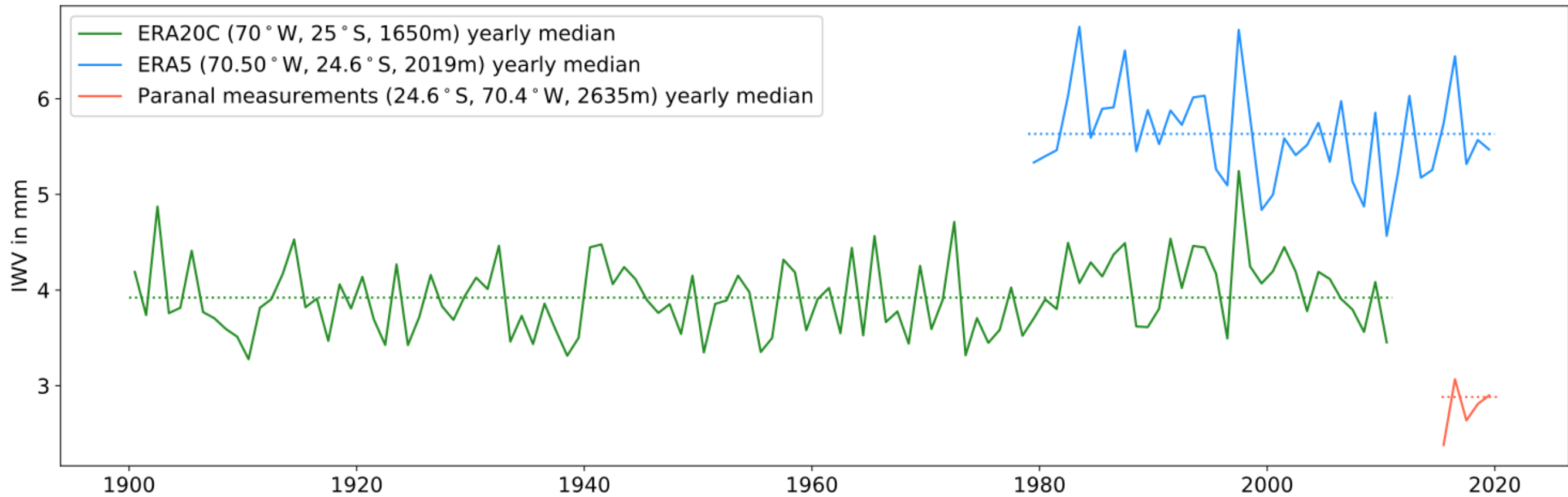
Low Humidity and Atmospheric Temperature PROfiling (LHATPRO)

Kerber, F. et al. Proc. SPIE (2012)



Comparison ERA5-scaled vs LHATPRO

4. Humidity: observations & projections



Impact of climate change...

the elephant in the room



Mont Stromlo (2003)

© Australian Capital Territory
Electricity and Water



Mont Graham (2006)

© Mount Graham International
Observatory



Mont Wilson (2020)

© Mount Wilson Observatory

*"In the future, under a warmer climate,
we expect more severe fire weather, more area burned,
more ignitions and a longer fire season."*

Flanningan et al., 2005,
Forest fires and climate change in the 21st century

Moritz et al., 2012
Climate change and disruptions to global fire activity

Impact of climate change...



Ressources



Light pollution bottom-up



5. INCLUDING BUILDINGS, STRUCTURES AND FACILITIES SHALL BE COMPATIBLE WITH THE LOCALITY AND SURROUNDING AREAS APPROPRIATE TO THE PHYSICAL CONDITIONS AND CAPABILITIES OF THE SPECIFIC PARCEL(S); AND

6. THE EXISTING PHYSICAL AND ENVIRONMENTAL ASPECTS OF THE LANDSUCH AS NATURAL BEAUTY AND OPEN SPACE CHARACTERISTICS WILL BE PRESERVED

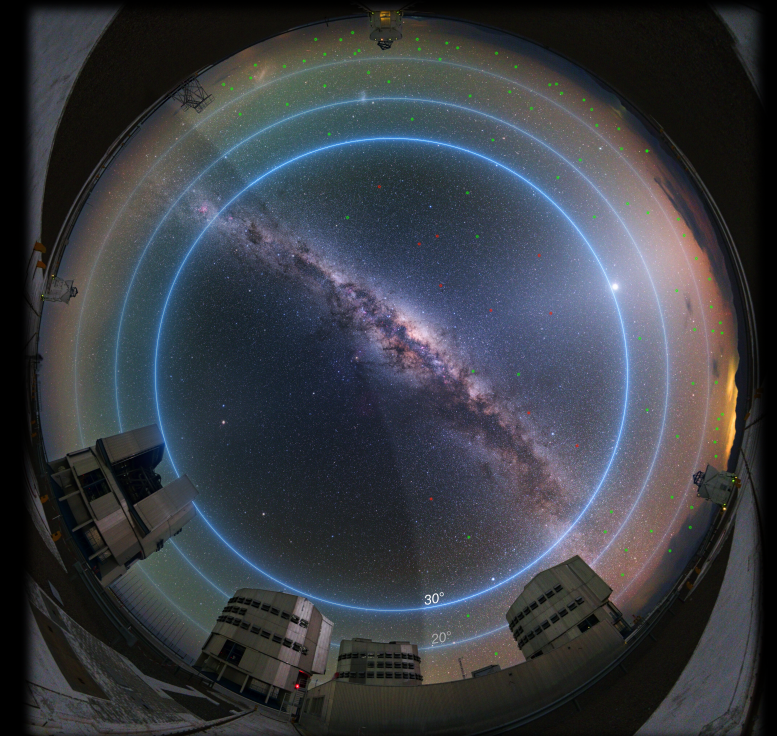
Local population



Energy



Commensality

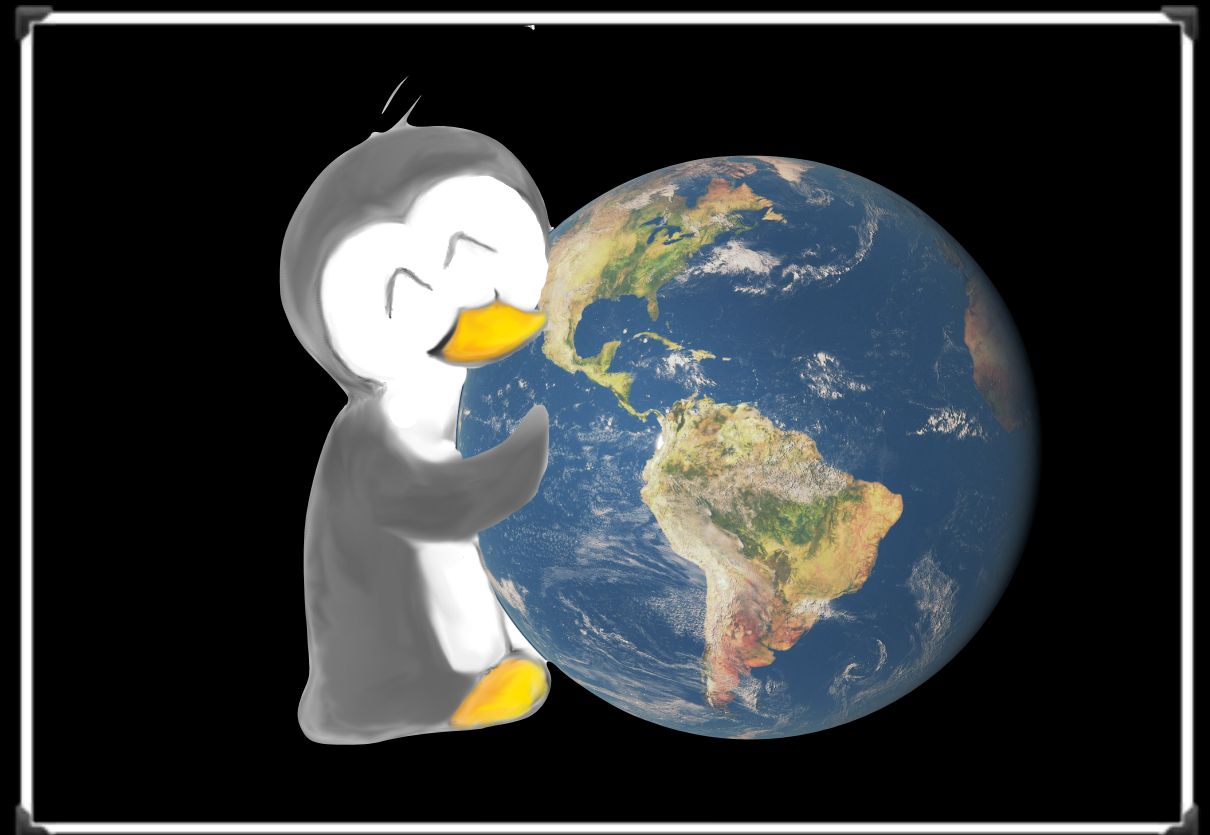


Light pollution top-down

Social stability is needed to run an observatory

Conclusions

- Yes, we see consequences of the anthropogenic global warming
- It starts to affect the quality of our observations
- Yet, it is difficult to firmly quantify / claim...
- And understand better large to small scale process !



Questions / comments / suggestions ?

Write me !

faustine.cantalloube@lam.fr

Perspectives

- List the other obvious impact for future astronomical obs.
- Extend the current study to more parameters (VLT & ELT sites)
- Compare with more models / measurements / predictions
- Other man-made alterations (e.g. aerosols, light pollution...)
- ... humidity ...

