Climate change: what we know and what not

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Summary. — There is ample scientific knowledge about climate change which is assessed at a frequency of about once every seven years by large, international groups of scientists in the comprehensive reports of the Intergovernmental Panel on Climate Change (IPCC). This presentation attempts a short and digestible summary of the certainties and uncertainties existing about the physics of climate change. For my summary, I strongly rely on the contribution of IPCC's working group 1 to the most recent IPCC assessment report that was published in 2021. To set the stage, I first present some basics about climate and climate modeling before summarizing the current state of knowledge and then providing a few personal conclusions.

1. – Introduction

"*It is unequivocal that human influence has warmed the atmosphere, ocean and land.*" This is the first sentence of the Summary for Policy Makers of the Working Group 1 contribution to the Sixth Assessment Report published in September 2021 by the Intergovernmental Panel on Climate Change (IPCC). The IPCC is the United Nations' body responsible for assessing the status of climate science. Working group 1 (WG1) covers the physical science basis which is also the topic of this text. The assessment reports are major documents issued by the IPCC at a frequency of about every 7 years. The latest WG1 report [1] has more than 2000 pages, more than 230 scientists were involved as lead authors, and about 5 times as many as contributing authors. They had to respond to almost 10^5 reviewer comments. Anyone who wants to get an exhaustive overview of “what we know and what not” about the physical basis of climate change science is referred to this report. A less comprehensive version of the assessment is provided by the “Technical Summary” [2], and an even shorter summary which is more accessible for the general public by the “Summary for Policy Makers” [3].

This presentation provides my personal, very incomprehensive view on the matter which is, nevertheless, strongly influenced by the IPCC reports. The title and the content are prompted by reactions to a number of presentations on climate science I have given over the years to a variety of audiences. Often, I sensed surprise about how many details on our changing climate are still unknown. Possibly, I sometimes fall into the trap of talking too much about things we do not know, which are, of course, to a scientist much more attractive than things which are known. Therefore, I think it is important to emphasize from the start that there is exhaustive knowledge on climate change, but at the same time not to brush over the unknowns.

The first sentence of the “Summary for Policy Makers” cited above characterizes knowledge about anthropogenic global warming as “unequivocal”. To my knowledge, such a strong statement is made for the first time in an assessment report. The recent IPCC reports use a calibrated language to qualify the certainty or uncertainty of findings (see Box 1.1, [4]). Confidence in evidence is expressed using five levels between “very low” and “very high”, the assessed likelihood of an outcome or result is characterized by terms as “very likely”, for a probability larger than 90%, or “more likely than not” for a probability larger than 50%. The title of this presentation could be challenged epistemologically. Is knowledge, is certainty about understanding possible at all? As much as possible, I will use IPCC terminology in this presentation to qualify the degree of certainty instead of using absolute statements like “We know . . . ”. I interpret the use of the term “unequivocal” by the IPCC in the sense that there is as much confidence in the existence of anthropogenic global warming as one can have. Uncertainties, however, still exist in particular concerning the magnitude of warming that can be expected in the future, and what global warming means on the regional scale, or, to put it in the words of Marotzke *et al.* [5], “how weather will change with climate”.

As confidence in findings is difficult to justify without sound understanding of underlying processes I introduce some climate basics in sect. **2**. Section **3** provides an overview of the current state of climate research in terms of observations, attribution of observed changes, and climate model projections. Some concluding remarks are made in sect. **4**.

2. – Climate basics

2·1. *What is climate? –* “*Climate is what you expect; weather is what you get.*” The American science fiction author Robert Heinlein is often quoted with this aphorism, but variants of it have been discovered in other, earlier works. Funny as it may sound, it contains the essential characteristic of climate being the statistics of weather “*over a long period of time*” [6]. How complex the interactions in the Earth system are that produce the climate has been noted already by Alexander von Humboldt in the 19th century: “*The*

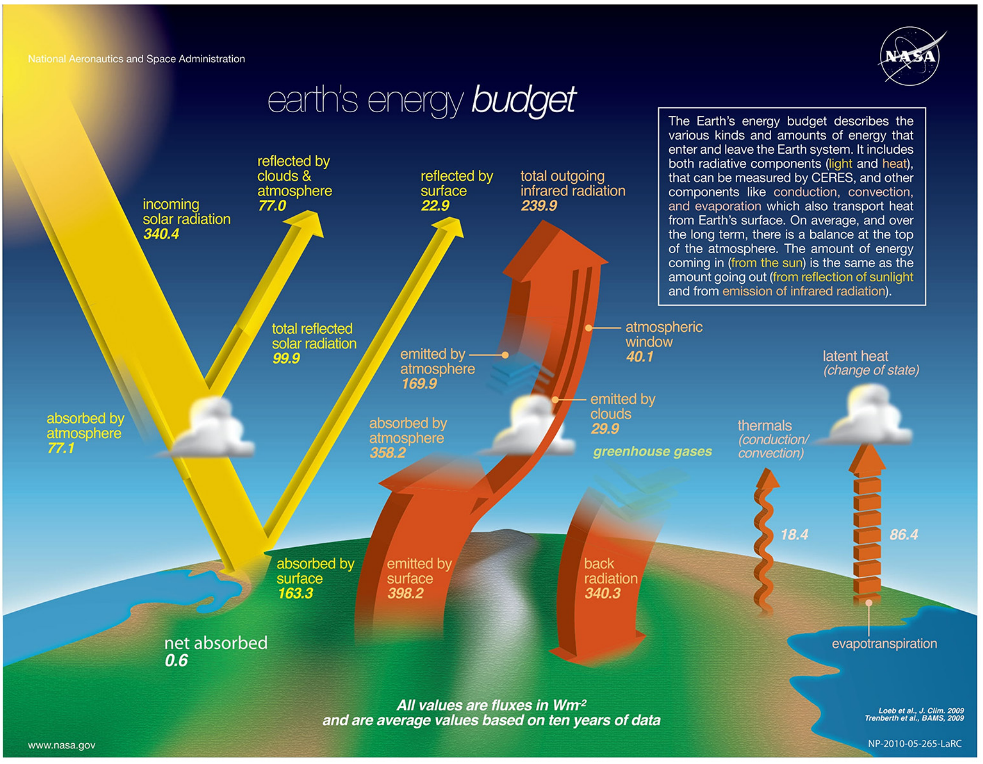

Fig. 1. – Earth's energy budget. (Figure from NASA [9].)

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." [7] (personal translation from German original). This complexity is what makes understanding and predicting Earth's climate complicated.

2˙2. *Earth's energy budget.* – However, central elements of the behaviour of the climate of planet Earth (and more generally of planets with an atmosphere) can be understood from a one-dimensional view on the energy budget of the Earth's atmosphere as presented in fig. 1. On average, the Earth receives about $340\,\mathrm{W/m^2}$ solar radiation. About 30% of it (Earth's albedo) is reflected back to space directly (mostly by the atmosphere and in particular clouds, but partly also by the surface), a bit more than 20% is absorbed by the atmosphere, and almost half of it absorbed at the surface. The surface emits energy in the form of infrared radiation following the temperature dependence of the Stefan-Boltzmann law, but also transfers energy to the atmosphere in the form of latent and sensible heat, *i.e.* basically by evapotranspiration and heat conduction, respectively. Only a small fraction of the emitted infrared radiation reaches space directly. The largest part is absorbed by greenhouse gases (H_2O, CO_2, and others) and clouds in the atmosphere, reemitted in all directions, and partly absorbed at the surface, again. This greenhouse effect is why the Earth is much warmer than one could expect from a planet without an atmosphere absorbing in the infrared. It is also intuitive why changes in greenhouse gas concentrations would change the energy balance, and that clouds are important for it. They do both, cool the surface by preventing solar radiation to reach it, and warm it by preventing terrestrial, infrared radiation to exit the atmosphere. The net effect is a cooling (of about $20\,\mathrm{W/m^2}$), but the effect of individual clouds depends on their environmental conditions defined in particular by their altitude, geographical position, and time of occurrence. For a more comprehensive presentation of the energy budget, see, *e.g.*, Trenberth *et al.* [8].

2˙3. *Climate modeling.* – Numerical climate models are used by scientists to study the complex interactions of climate processes and are the only tool that enable detailed projections of future climates. Today's models are the result of more than half a decade of development efforts which are, of course, ongoing. In the 1960s, attempts were made to represent Earth's energy budget as presented above in numerical models known as one-dimensional radiative convective equilibrium (RCE) models. Earth's troposphere is considered to be in RCE as the energy transfer happens either via radiation or, the mostly upward transfer of latent and sensible heat, via convection. The latter does not play a role in the stratosphere which is to first order in pure radiative equilibrium. A ground-breaking study was published by Manabe and Wetherald [10] who calculated with such a 1D-RCE model that the surface temperature would increase by 2.7 K in a new equilibrium established as a response to the doubling of the atmospheric CO_2 concentration. This quantity is known today as equilibrium climate sensitivity (ECS) and its prediction by Manabe and Wetherald has turned out remarkably robust. Kluft *et al.* [11] repeated their calculation with much higher vertical resolution and a state-of-the-art radiative transfer model and arrived at a warming of 2.8 K. Of course, such models can only be informative about global average climate and neglect a lot of details of the climate system. Manabe and Wetherald, for instance, ignored clouds. However, the ECS predicted by them is in the range of today's observation-based estimates for present-day Earth and also values predicted by today's state-of-the-art climate models (see below). In 2021, Syukuro Manabe was co-awarded the Nobel prize in physics for his contributions to understanding climate change. 1D-RCE models are still used today in particular to better understand dependencies of ECS and aid our analysis of more complex models.

One may argue that 3D climate modeling started in the 1950s with a study by Philips [12] who built on ongoing work for short-term numerical weather predictions. He studied the flow patterns evolving in a global 2-level quasi-geostrophic model with 17×16 horizontal grid points that was started with an atmosphere at rest and simulated a period of about 30 days. Since then, numerical climate models have basically evolved in two directions. Scientists have, on the one hand, added complexity and on the other, increased resolution [13]. Over time, the atmospheric general circulation models have been enhanced by coupling them to land surface processes and to models representing the circulation of the oceans. Since 1995, these coupled atmosphere ocean general circulation models from a variety of climate research centers around the world are being compared in the Coupled Model Intercomparison Project (CMIP). With all models, a set of well-defined numerical simulation experiments is performed that now include, *e.g.*, a long equilibrium run for preindustrial conditions, a simulation of the recent past since 1850, projections of the future following specified emission scenarios, and more idealized experiments, like an instantaneous doubling of the CO_2 concentration. Results of the current phase (CMIP6; [14]) have provided important input for the Sixth Assessment Report (AR6) as the earlier project phases have for earlier IPCC reports. In the fifth phase of the project (CMIP5), for the first time, several models included an interactive representation of the carbon cycle, and since then also the number of models with complex representations of atmospheric chemistry is increasing. Typically, the models of CMIP6 represent the global atmosphere with horizontal mesh sizes of about 100 km. This means that a large number of processes that occur on sub-grid scales cannot be resolved adequately in the simulation and thus need to be accounted for by additional assumptions made in so-called parameterizations. However, with the advent of exascale computing looming, climate modeling is attempting the step change to so-called storm-resolving simulations with mesh sizes of a few kilometers horizontally [15]. A rationale is that at such resolution we can get rid of some of the parameterizations, for instance of atmospheric convection, to base crucial processes like vertical atmospheric energy transport (see above) on laws of physics instead, and thereby increase the fidelity of the simulations further.

3. – The current status of climate research

3˙1. *Observations.* – Earth's atmospheric volume fraction of carbon dioxide has increased from a pre-industrial value of about 280 ppm ("parts per million", *i.e.* 280 of one million air molecules were CO_2) to an average of about 416 ppm in 2021 (measured at Mauna Loa, Hawaii). The concentrations of other, largely anthropogenic greenhouse gases like methane have increased, too.

Earth's globally averaged surface temperature has already warmed by about 1.1 °C when comparing the average over the years 2011–2020 with a preindustrial reference (1850–1900) [3]. Of course, there is no direct measurement of this quantity but it is derived from the large number of available surface observations which are, however, inhomogeneously distributed. Nevertheless, the different institutions providing independent analyses arrive at very similar trends. Figure 2 shows the time evolution of global annual mean surface temperatures analyzed by the US National Oceanic and Atmospheric Administration (NOAA). Averaged over all land areas the temperature has increased by approximately 1.6 °C, *i.e.* about twice as much as averaged over all ocean areas [3]. A larger warming over continents is not only due to the thermal inertia of the oceans, but would also be expected in a hypothetical warmer equilibrium, which can be explained to

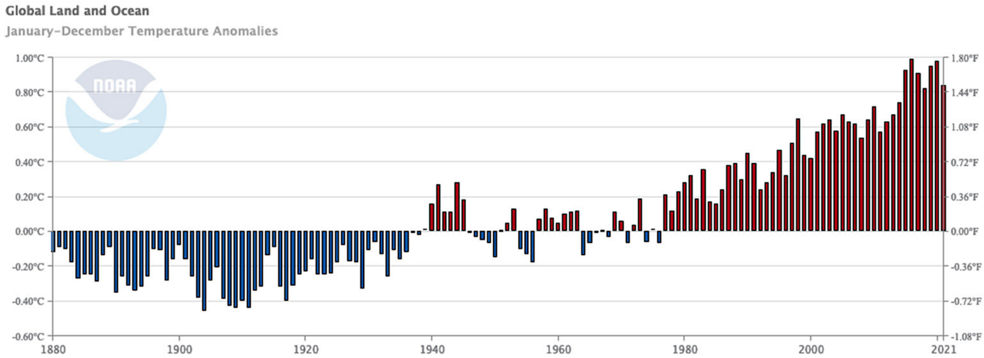

Fig. 2. – Annual and global mean surface temperature relative to the 20th century average as calculated by the US National Oceanic and Atmospheric Administration (NOAA). (Figure from NOAA [18].)

first order by energy budget considerations over land and ocean [16]. Due to the limited water availability over land, evaporation can contribute less to the cooling of the surface and a new equilibrium would require higher temperatures than over oceans. It is also relatively well understood from largely thermodynamical considerations of feedbacks to warming that high (and in particular Arctic) latitudes warm more than lower latitudes. Pithan and Mauritsen [17] argue that dominant contributions to these feedback differences are related to a larger increase of black-body emissions for unit warming at higher temperatures and the different vertical structures of the warming (causing differences in the so-called lapse-rate feedback) at high and low latitudes. Of course, also the frequently mentioned ice-albedo feedback at high latitudes, *i.e.* less reflection of sunlight by a surface with less ice and snow cover, contributes to the effect.

Besides surface temperature, changes in a large number of other climate parameters are reported in AR6, *e.g.*: Global mean sea level increased by 0.20 m ("very likely" range: 0.15 to 0.25 m) between 1901 and 2018. The average rate of sea level rise has increased over time and reached, with "high confidence", 3.7 (3.2 to 4.2) mm/year between 2006 and 2018. Precipitation averaged of all global land masses has "likely" increased since 1950, with a faster rate of increase since the 1980s. The storm tracks of the mid-latitudes have "likely" shifted poleward in both hemispheres since the 1980s. The Arctic sea ice area in September, *i.e.* when the seasonal minimum occurs, has decreased by about 40% between 1979–1988 and 2010–2019. It is not surprising that with rising mean temperatures it is "virtually certain" that since the 1950s, hot extremes have become more frequent and more intense over most land regions, while cold extremes have become less frequent and less severe. There is "high confidence" that, also since the 1950s, and at least for most land regions with sufficient data availability, the frequency and intensity of heavy precipitation events have increased. The limitation of these statements to sometimes relatively short periods does not necessarily mean that there were no changes earlier, but it could also be that the availability of observations is insufficient to detect trends.

3˙2. *Causes of climate change.* – The previous section provides examples for changes in a variety of climate parameters that have been clearly detected according to the IPCC AR6. Many of these changes can be attributed to the anthropogenic increase of greenhouse gases [3]. The attribution of climate change was arguably pioneered by another co-recipient of the 2021 Nobel prize in physics, Klaus Hasselmann, who used the so-called fingerprint method to identify the anthropogenic signal in global mean temperature on the background of the noise introduced by natural variability in the 1990s [19-21]. As many other attribution techniques that have been developed and used since then, this method involves the numerical simulation of factual and counter-factual climate states, *i.e.* states with and without a specific forcing, in this case with and without the anthropogenic increase of atmospheric greenhouse gases. Attribution techniques are today not only used to identify causes for observed trends, but also to estimate how much more or less likely specific extreme events may have become due to anthropogenic forcing. A good starting point for more information on attribution is the AR6 "Cross-Working Group Box: Attribution" [4] which states that "attribution often builds on the understanding of the mechanisms behind the observed changes". Personally, I would emphasise the importance of understanding even more strongly. Today's complex global models, for instance, are used in attribution studies, and, of course, do simulate warming from increasing greenhouse gas concentrations, but they are often questioned due to their opaqueness. For the understanding of global warming, I hence consider the above-mentioned view in terms of the global energy budget as crucial. It may be argued that the 1D-RCE models that basically represent this view are too simple to cover the complexity of the system. My trust in the attribution of global warming to anthropogenic emissions comes from the understanding provided by simple tools and the fact that adding more complexity (three dimensions, many more processes) to models cannot stop them to warm for higher greenhouse concentrations.

However, the magnitude of the warming is still somewhat uncertain. A key parameter frequently used to characterize it is the so-called equilibrium climate sensitivity (ECS) which measures how global surface temperature would change in the long term if the atmospheric CO_2 concentration doubled. Arguably, the Swedish physicist and chemist Svante August Arrhenius was the first to investigate the change in surface temperature as a function of CO_2 concentration [22]. He estimated a warming of about 6 K for CO_2 doubling, but speculated that it might be overestimated. Based on only two climate models, the U.S. National Academy of Sciences estimated in 1979 an ECS of between 1.5 and 4.5 K [23]. Until recently, estimates of ECS and its uncertainty range had changed only slightly, illustrating that this is an aspect of climate science where there was little progress over the last decades. The same temperature range is also found in the IPCC's Fifth Assessment Report. A review by Sherwood *et al.* [24] was able to narrow this range based on historical and paleoclimate data and process understanding. In the current AR6, the "likely" range of climate sensitivity has narrowed to 2.5 to 4 K, with a best estimate of 3 K [3].

Thanks to ongoing model development and longer observation time series, AR6 states even more clearly than previous reports that humans are influencing many aspects of

Earth's climate. As mentioned initially, anthropogenic global warming is, for the first time, called "unequivocal". The "likely" range for the human contribution to the current warming of the Earth's surface since the preindustrial reference period (1850–1900) is given to be 0.8 to 1.3 °C, with a best estimate of 1.07 °C, *i.e.* virtually all of the observed warming is anthropogenic. Furthermore, it is now considered "likely" that humans have contributed to the observed change in precipitation patterns since the mid-20th century, and very likely that they are primarily responsible for the retreat of glaciers since the 1990s and for the decline in Arctic sea ice since 1979 [13]. Concerning extremes, it is now considered "virtually certain" that heat extremes have increased since 1950, and there is "high confidence" in a major human contribution. Some of the extreme heat events of the past decade would have been extremely unlikely without human influence. It is further assessed that the increase in extreme precipitation events over most land areas since the 1950s is "likely" primarily anthropogenic [25]. However, dividing Earth's land masses into 45 regions, 19 show an increase in heavy precipitation events, and none a decrease. But existing attribution studies allow only for two of the 19 regions to have at least "medium confidence" in the increase being anthropogenic [3]. Of course, this does not necessarily mean that the increase is not anthropogenic, but that evidence is limited, yet.

Of course, climate change can also occur due to natural, non-anthropogenic forcings. Large volcanic eruptions are known to cool the planet by injecting sulfur-rich gases into the stratosphere where they build aerosols that scatter sunlight away from the surface, another effect that can be understood to first order in a one-dimensional energy-budget view. The aerosols have a stratospheric lifetime of about a year. The most recent relatively large eruption, the one of Mt Pinatubo, Philippines, 1991, caused a peak global cooling of about 0.4 K. Variability of solar irradiance also has an impact. However, the well-known 11-year solar cycle causes irradiance variations of only about 0.1% and a variability of the global mean surface temperature of less than 0.1 K. On much longer, palaeo-timescales, in particular, orbital variability and atmospheric composition changes have influenced climate fundamentally.

3˙3. *Projections of the future.* – For the CMIP6 simulations that informed AR6, a set of shared socioeconomic pathways, or "SSPs" for short, has been developed that describe different potential future trajectories of developments in global society [26]. In combination with different emission reduction targets, they map how societal decisions affect greenhouse gas emissions. Depending on the model and experiment, the concentrations or emissions of these scenarios enter simulations with complex global climate models which provide the climate projections.

Traditionally, in IPCC reports, the multi-model mean results of the simulations were communicated as most likely climate change resulting from a given scenario. However, as a number of CMIP6 models show very high ECS in comparison to the estimate from observations (see above), the estimate of future warming was determined in AR6 for the first time by combining the model simulations with some bias correction [27]. The spread of model results provides an indication for the uncertainty of the projections. For a very high-emission scenario SSP5-8.5, the increase in near-surface air temperature by the end of the century (2081–2100) relative to the pre-industrial reference period (1850–1900) is given in AR6 as 4.4 K. The "very likely" (5% to 95%) range is between 3.3 and 5.7 K. For the low-emission scenario SSP1-1.9, the corresponding range is 1.0–1.8 K. In the near term (2021–2040), it is "very likely" to exceed the 1.5 °C target from the Paris Climate Agreement in scenario SSP5-8.5, "likely" in scenarios assuming somewhat lower emissions (SSP2-4.5 and SSP3-7.0), and still "more likely than not" ($> 50\%$) in the low-emission scenarios SSP1-2.6 and SSP1-1.9. It should not be forgotten that, as discussed above for the observed warming, a stronger increase than the global mean is also expected in the future over the continental regions (see ref. [27] for all data in this paragraph).

The numbers presented above show that the global mean temperature projected for a given time in the future depends strongly on the emission scenario. However, due to the long lifetime of carbon dioxide and the inertia of the climate system, the warming of the Earth's surface on the time scales of decades to at least a century is determined largely by the total amount of carbon emitted, *i.e.* by cumulative historical emissions, such that very similar temperatures will be reached in different scenarios at the respective times of similar cumulative emissions [3]. Because of this relationship, remaining emission budgets for achieving specific warming targets can be determined. For example, it is estimated in AR6 that there is a 50% chance of reaching the 1.5 °C target or 2 °C target if 500 or 1350 billion tons of CO_2 ($GtCO_2$), respectively, will be emitted globally since the beginning of 2020. Currently, global emissions amount to about 40 $GtCO_2$ per year, meaning that emissions sufficient to cross the target of 1.5 °C will be reached in the early 2030s if global emissions stayed constant.

Hawkins and Sutton [28] argue that the projections of future climate are influenced by three sources of uncertainty: the assumptions made in the scenario, imperfections in the models, and the influence of internal variability. It is clear from the numbers presented above that the uncertainty of global mean temperature at, say, the end of this century, is strongly influenced by the scenario uncertainty. Hawkins and Sutton estimate its contribution on the time scale of a century to about 50%, while it contributes only about 10% for decadal projections. Internal variability is, by far, the largest source of uncertainty on this short time scale, but is less important on longer timescales. Model uncertainty, or one may say model imperfectness, contributes about 1/3 over all time scales, enough to think about how to improve the fidelity of current climate models.

The uncertainty is often larger for other climate parameters than temperature, and in general much larger for regional than global climate change, *i.e.* for changes on spatial scales that matter for people. One example for the inadequacy of present-day climate models and, more fundamentally, of our understanding of some global circulation features incorporated in these models is presented by Shepherd [29]. He presents results from four state-of-the-art climate models for the response of lower tropospheric zonal winds in the North Atlantic region in winter in a high-emission scenario for the end of this century. The results differ widely. Westerlies over the city of Hamburg, for instance, strongly increase in one model, moderately in another, remain almost unchanged in a third, and decrease in the fourth.

Stevens *et al.* [30] present simulations with also four different state-of the-art climate models in a very idealized setting usually called an aquaplanet, *i.e.* an Earth-like planet where the surface of the planet is covered fully by an ocean. Two simulations are performed which only differ by sea surface temperatures being prescribed globally 4 K warmer in one experiment than in the other. The four models produce responses of tropical precipitation to this global warming which can hardly be imagined more different. Of course, the "true" response to such an experiment is unknown, but the large difference of the simulated responses in such a simple setting creates doubts on the fidelity of projected changes in tropical precipitation simulated for more realistic, and more complicated settings. It is plausible that convection parameterizations, needed to represent vertical energy transport at scales smaller than those resolved by traditional climate models, are at the core of the problem, and that km-scale modeling, as mentioned in sect. **2**˙3 can alleviate it.

Sea level rise is a partly well understood phenomenon, in particular as almost half of the current increase comes from the thermal expansion of water with increasing temperature. For the high-emission scenario SSP5-8.5, models on average predict a global mean sea level rise until the end of this century of a bit less than 1 m compared to the preindustrial reference. However, according to a low-likelihood but high-impact storyline, the increase could also reach almost 2 m, and until 2300, even "sea level rise greater than 15 m cannot be ruled out with high emissions" [3]. The uncertainty in this quantity is to a large degree due to uncertainties related to the evolution of ice sheets and its simulation.

Relatively large uncertainties are also associated with future projections of some extreme weather events. This is partly due to the poor statistics existing for very extreme events which occur at very low frequency, but the modeling of some extremes, as tropical cyclones or floodings in specific valleys may also require very high model resolutions. Again, physical understanding may help to increase confidence in projections. This understanding creates, for instance, high confidence in the projection of a 7% intensification of extreme daily precipitation events on the global scale. Regionally this is often much less clear due to relatively large uncertainties in potential circulation changes as mentioned above for the example of Europe. It is, however, clear that every additional warming increases the intensity and frequency of hot extremes. For some regions, there is high confidence, that, *e.g.*, the temperature of the hottest days will increase 1.5 to 2-fold compared to global mean warming. AR6 also states high confidence in an increase of peak wind speeds of the most intense tropical cyclones (for all changes reported in this paragraph and other extremes, see [3]).

4. – Some concluding remarks

I've started this text citing the IPCC AR6 that anthropogenic global warming is "unequivocal", one may also say that this is something that we know, or at least, something of which the physical climate science is as certain as it can possibly be. As reported above, there are many other aspects of global warming of which scientists are more or less certain, and others with a higher degree of uncertainty. In general, one may say that features related to global thermodynamics are much better understood than possible changes of global circulation patterns. Personally, I think that none of the reported uncertainties justifies to postpone efforts to massively reduce the emission of greenhouse gases. Changes can turn out both less or more severe than best estimates. In the end, decisions cannot and should not be taken by scientists, but societies. The IPCC reports provide a very valuable basis for this decision making. Here, I've only tried to summarize parts of the physical basis of climate change, which is also the subject of the reports of IPCC's working group 1. This is certainly an insufficient input for decision making, as I have not said anything about the impacts of climate change and how to possibly react specifically. These topics are covered by the respective IPCC reports by the working groups 2 (Impacts, Adaptation and Vulnerability) and 3 (Mitigation of Climate Change).

While I do not think that uncertainties in projections provide a justification for postponing emission reduction efforts, they do limit our capacities to adapt to climate change. I find it disconcerting, that the "likely" range of global equilibrium climate sensitivity is still as large as reported (2.5 to 4 K), that we have fairly limited knowledge on how circulation systems in the North Atlantic region or tropical precipitation patterns may change under global warming, and that we cannot rule out extreme sea level rise. The job of scientists is to better understand these phenomena and reduce the uncertainty to enable societies to better prepare. In addition, while we know areas for which the uncertainties are large (the known unknows) it is entirely possible that there are limits to our understanding we are not yet aware of (the unknown unknowns). I think it is very likely that surprises will happen with continuing global warming. Although much warmer and colder periods have occurred on palaeo time scales, we simply have no empirical evidence of how a present-day world that is warmer by 2, 3, or 4 °C may look like. Improved scientific understanding can help to be better prepared for such surprises. As an example, the discovery of the springtime ozone hole over Antarctica in 1985 [31] came as a surprise, but humanity could react to it quickly thanks to global political consensus and a rapidly developed scientific explanation of the phenomenon that would have been unthinkable without the fundamental scientific knowledge about atmospheric ozone accumulated earlier.

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