Report on the 7th Heidelberg Laureate Forum's
Hot Topic session

Climate crisis: facts and actions

The science of climate change and what we can do to tackle the problem

Heidelberg, September 24, 2019, 13:00–16:45

*Report written by the Hot Topic coordinator and moderator **Michele Catanzaro**, PhD in Physics and freelance science journalist.*

"Every bit of warming matters, every year matters, every choice matters."
(IPCC, Special Report "Global Warming of 1.5 °C")

Climate change is increasingly being called "climate crisis" or "climate emergency." The reasons are that it is already showing its effects and that we are being too slow in tackling it. Climate has always changed, but the current rate is faster than anything human history has previously known.

The Earth is already 1.1 degree above the pre-industrial period. The last five years (2015–2019) have been the warmest five-year period on record, according to the United in Science Report. The effects of global warming are hitting harder and sooner than expected, the report states.

In 2018, there were deadly heatwaves in Canada and Japan and a large heatwave and drought in Northern Europe, which led to devastating fires in Sweden. The concomitant occurrence of these heatwaves across the Northern Hemisphere would have been extremely unlikely without climate change, research found. In 2019 certain areas of France reached 46 degrees and cyclone Dorian, the strongest storm ever recorded near the Bahamas, discharged immense precipitation in the region because of its slow-moving pace. Although tropical cyclones are not becoming more frequent, the associated precipitation is becoming more intense, due to warmer air taking up more moisture. Sea level is also rising fast, causing erosion and life-threatening storm surge, due to warming of the oceans and the influx of fresh water in the Atlantic Ocean coming from the melting of polar regions and the Greenland ice sheet.

The world is getting closer and closer to the 1.5 °C warming limit that is considered a threshold above which more intense and maybe incontrollable consequences may occur. How catastrophic the scenario would be above this threshold is not fully known. But no one would take a plane if the probability that it would crash is even as low as 10 or 20%.

The threshold has already been reached on land, in fact. The global average is still lower, because the oceans are warming more slowly. But the planet will reach an average 1.5 °C warming between 2030 and 2050, if nothing changes.

If we want to avoid that, a radical and very quick change is needed in how we deal with CO_2 emissions, that is, the main cause of global warming. It is estimated that we have already used more than 2/3 of the CO_2 budget available to keep temperatures below the 1.5 °C threshold.

In order to reach that target with high probability, CO_2 emissions should stop their increasing trend immediately and start decreasing within 2020. In 2030, emissions should be half of those of 2010, and there should be net zero emissions in 2040.

Moreover, in the next few decades, we should find a way to produce "negative emissions," that is, to remove CO_2 from the atmosphere. Reforestation is not enough, because it competes with cropland, it increases forest fires, and it can even contribute to warming in certain locations. Technologies to capture CO_2 from the atmosphere are being developed, but technologies to store it are not yet well-established at large scale.

Unfortunately, many of the actions necessary to reduce emissions are not taking place. CO_2 emissions grew by 2% in 2018, reaching a record height of 37 B tonnes, and there is no signal that they will peak anytime soon. Policies' effort should be fivefold higher in order to achieve the 1.5 °C objective.

Why are we failing? We have faced and solved similar complicated problems in the past: for example, lead in gasoline and the hole in the ozone layer. We are making advances with other complex problems in the present: for example, the global tobacco addiction.

But none of these problems is so multivariable as climate change, nor so embedded in the basic workings of our society. It's a "super wicked problem." However, scholars can do a lot to tackle this issue, both as researchers and as citizens. The Hot Topic session at the 7th Heidelberg Laureate Forum explored the frontiers of research on climate change and the societal aspects of the problem in which scientists can play a role.

This is how the current world looks like, at 1.1 °C of global temperature above the pre-industrial level.

First part: Facts

1. The mathematics of climate change

A hierarchy of climate models, all feeding into each other, combined with the input of data, produces reliable forecasts (within their margins of uncertainty), as confirmed by the models' capacity to understand the past.

Chris Budd
Professor at Gresham College, professor of mathematics and director of the Institute for Mathematical Innovation at the University of Bath

The bedrock of the science of climate change is modelling. For example, the Intergovernmental Panel of Climate Change (IPCC) bases its predictions on the future evolution of climate on models, and all of them predict significant increases in temperature.

Models allow us to make forecasts, but they also allow to quantify the uncertainty of these predictions, and to understand sensitivity, i.e. how an increase in the mean temperature can lead to increase in extreme events. Moreover, they also "predict the past," that is, they allow to understand the drivers of past climate changes.

A very frequent question on this point is: if weather forecasts fail in predicting next week's weather, how can one trust climate models that forecast much further in the future? The reason why they can be trusted is that the latter don't aim at predicting the weather of one specific day in the future, in a specific spot in space. On the contrary, they provide statistical properties of the future weather, that is, averages done over several years, and for a volume of space with an edge of 100 kilometres.

Another question is: how can we test those models, given that one cannot make experiments with climate to check them? The way of doing that is seeing how well they predict past climate. For example, models that don't factor in human CO_2 production underestimate the past evolution of the global temperature. Models that include it, but don't factor in the role of El Niño and of volcanoes, are not good neither.

Only when both human and natural factors affecting temperatures are included in the models, then their output and actual past observations align very well over the last 150 years. This is probably one of the best ways of visualizing that global warming is influenced by human emissions, beyond natural drivers.

The simpler climate models are Energy Balance Models (EBM). While they are very basic, they have the advantage of making predictions for longer times. Their starting point is that the energy coming from the Sun to the Earth is equal to the energy radiating back from the Earth. Several energy balances between Earth's surface and the atmosphere (modelled as 2-points with absorptions and emissions) combined with estimates of the energy coming from the Sun and the transparency of the atmosphere to infra-red radiation, allow predictions to me made of the average temperature of the Earth and the atmosphere.

With these simple tools one can make reasonable predictions of Earth temperature and see the effect of CO_2: it decreases the transparency of the atmosphere to the outgoing, long-wave radiation, which increases the temperature.

More sophisticated (intermediate complexity) mathematical models allow to go back in time and study the changes in the climate over millions of years, for example they help us to understand the ice ages.

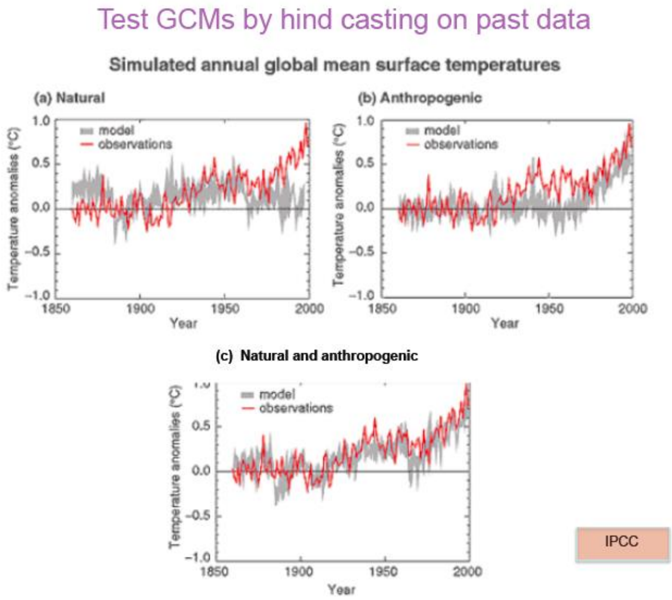
Finally, the most complex models are the “Global Climate Models” (GCMs), which include many variables and are used by the IPCC to make predictions of the changes in climate over the next 100 years or so. While more realistic, they have a shorter prediction time than the simpler models and are difficult to analyse and understand intuitively, because of their convoluted nature.

In advising policy makers GCMS are part of highly complex “Earth System Models” (ESMs) that study the impact of climate variations, on agriculture, energy production, human settlements etc.

All of the above models start from the law of physics expressed in the form of partial differential equations. Then, the models are informed with as much data as possible - from measurements of moisture to the effects of the Sun and the complex chemistry of the atmosphere. Uncertainty is built into the models from the beginning. All of the models are then solved numerically, typically on a super computer.

The uncertainty in the predictions of climate models come from a series of sources, They rely on a lot of data that are difficult to measure in themselves (for example, data on polar regions); they have billions of variables with sometimes unclear cause-effect relationships; they are nonlinear, which can lead to chaotic effects (which however is more important in weather forecasts than in climate forecasts because the latter are statistical averages.)

In summary, a hierarchy of different models, all feeding into each other, combined with the input of data, produce reliable forecasts (within their margins of uncertainty), as confirmed by the models’ capacity to understand the past.



Models including only natural causes of warming (a) don't explain the observed increase of global temperatures. Models including only anthropogenic causes (b) provide a better fit, but the best one is obtained by including both natural and anthropogenic causes.

2. How to speed up climate research?

Current climate models are slow in providing prediction, don't take into account many of the complex feedbacks between physical and social systems, and fail to predict extremes and local variability. Machine learning can help with these issues.

Sonia Seneviratne
Professor at ETH Zurich (Swiss Federal Institute of Technology Zurich) and IPCC (Intergovernmental Panel on Climate Change) coordinating lead author

A new era for climate science is urgently needed. In a time of climate crisis, decision-making must be informed by science. But we are working against the clock, so decision-making needs near real-time information. Currently, the IPCC updates its predictions with a cycle of six years, which is far too slow.

Moreover, decision-making needs knowledge well beyond that provided by climate models. A better coordination is needed between climate scientists, impact scientists, and mitigation scientists. The IPCC report called "Global Warming at 1.5 ˚C" was a first essential step to trigger more interactions between scientists with different backgrounds.

Currently, scholars are carrying out three different steps of simulation. In the first place, they study scenarios: changes in population, possible mitigation actions in agriculture, economy, use of energy, carbon capture and storage. These are studied through Integrated Assessment Models.

The results of these scenarios are the input of climate models, or Earth System Models. These produce projections of changes in temperature, precipitation, the carbon cycle, vegetation, ocean currents, droughts, and other physical and biogeochemical changes of the climate system at both global and regional scales.

These projections are used as input to compute impacts: on agriculture, ecosystems, economy, health, water. These impacts in turn may affect the realism of society development and climate mitigation scenarios assumed at the first step of simulation, in Integrated Assessment Models.

For example, an initial scenario in which a lot more cropland is planted in many land regions (either for food production or biofuels) needs to consider the potential risk of droughts and other extreme events that could affect crop production under an even warmer climate. Or an initial scenario with a lot of trees planted in Russia must face the fact that, beyond offsetting carbon, trees may contribute to net warming instead of cooling in such regions because of changes in albedo (because the trees would make the surface darker when there is snow cover). In addition, extensive reforestation would require a lot of time to be effective and would not constitute a long-term sink for carbon, as forests can be affected by fire, in particular under higher global warming. Ultimately, such analyses may question some of the considered mitigation scenarios, and it is thus essential to assess which would be most resilient under a warming climate.

The whole development of new research regarding emissions scenarios compatible a stabilisation of global warming at a given level, their exact implications for impact, and the assessment of their realism under the warmer climate conditions requires a ca. 6-8 years cycle in the context of IPCC reports. This window is, however, too long for policy needs.

The critical link in this chain are Integrated Assessment Models, which are economic and geographical models simulating society development under different constraints in terms of greenhouse gas emissions. As mentioned, they don't take into account all the possible feedbacks from other levels of modelling and this challenges how realistic the derived scenarios are.

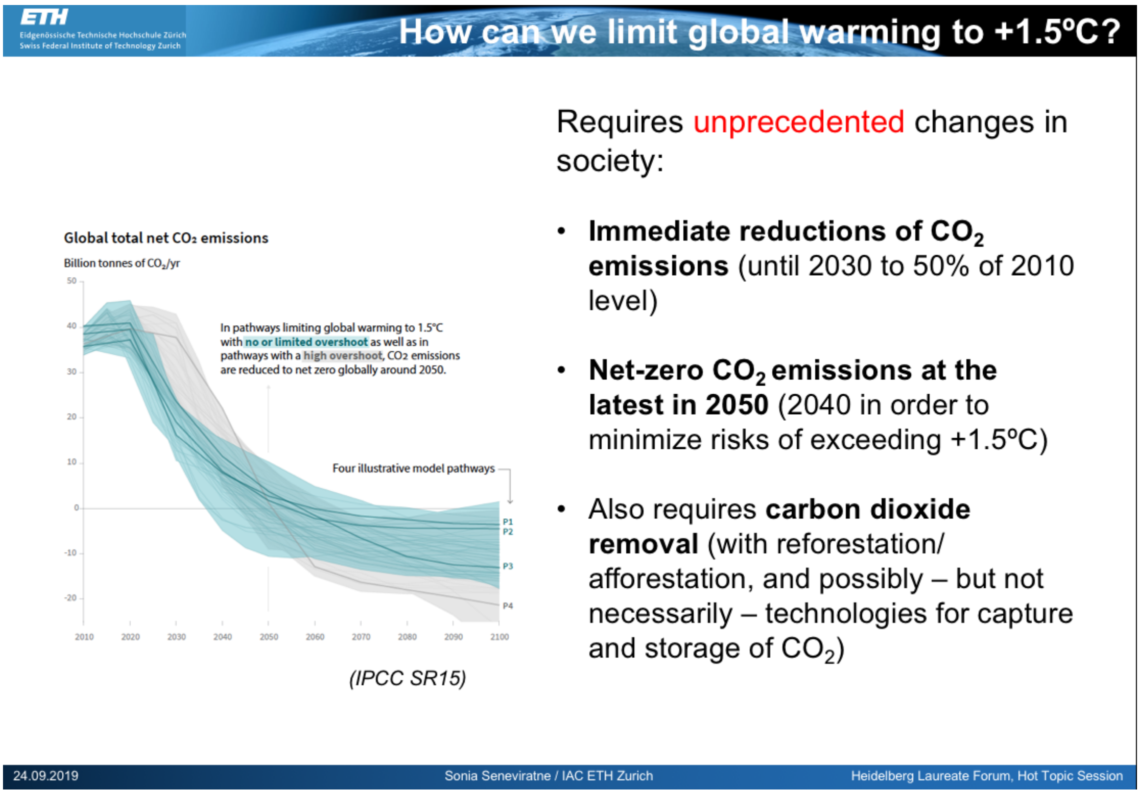
A key problem is that this modelling approach only considers global-scale statistics in climate under higher warming levels as input, and does not integrate regional features and extreme events. However, these regional changes can be large. For example, a 2 degrees global warming can produce regional increases of up to 6 degrees in Central Europe.

Extremes affect people, because they make certain locations less habitable, triggering migration, instability, and conflicts. Extremes also affect energy: for example, heatwaves affect the cooling of power plants: more energy is needed to cool them precisely at the times in which there is less possibility to use it.

How can science make progress in the face of these limitations? One way forward in overcoming the current decoupling between Integrated Assessment Models and Earth

System Models (ESM) is the development of ESM emulators, though data science. That is, using data science and machine learning to build an emulator for ESMs that includes regional variability and extremes. This is a promising pathway to overcome the present decoupling between Integrated Assessment Models and Earth System Models.

First results show that simple data science approaches can yield very efficient Earth System Model emulators that can represent the temporal and spatial variability of temperature at different levels of global warming with realism. The expertise of machine learning scientists and the improvement of algorithms and hardware would allow to further develop emulators allowing to simulate the complex interactions within the climate system at lower computational cost, thus substantially speeding up research in climate science. This is highly needed given that new society development pathways consistent with a reduction by half of greenhouse gas emissions and fossil fuel industry need to be achieved under a 10 year time frame if we are to keep a chance at stabilizing global warming at around 1.5 °C.



Keeping global warming well below 2 °C requires an unprecedented effort.

3. Supercomputation in Climate Change: Four ways to make more accurate climate predictions

> *In order to overcome limitations of climate models and make them more useful for decision-making, we must move towards stochastic modelling, use machine learning, and increase massively computation power through a joint international effort.*

Tim Palmer
Royal Society Research professor in climate Physics at the University of Oxford

Climate models are much more than a subject of scientific curiosity. They are used to make short term climate predictions (for example, whether El Niño will happen in the next six months or later); to understand how climate would change if certain processes were removed (for example, human emissions); to inform decisions on decarbonization (like the Paris Agreement); to guide investment in infrastructures aimed at making society resilient; and to evaluate the consequences of geoengineering projects (for example, could spraying aerosol in the stratosphere to reflect sunlight back to space have unforeseen consequences?).

Although there is an amount of scientific consensus on climate change, there are also major uncertainties in models, when projecting future climate change. For example, the most likely value of warming according to models is around 2 to 2.5 degrees above pre-industrial times.

However, there is a probability distribution around these values. This distribution has a long tail that goes above 4 degrees, a temperature range in which certain areas of the world would become inhabitable, because the body would lose its ability to perspire in them. Given this distribution, saying that climate change will be a hoax, or a catastrophe, or lukewarm, is inconsistent with current knowledge.

The uncertainty in climate models comes from the fact that their results are obtained by trying to solve numerically the Navier-Stokes equations. Representing them with simplified models and truncating them give rise to uncertainties.

To solve them, they are projected into a finite grid with a 100 km scale. Below this scale, there are many things that remain unresolved: cloud systems, the flow over small-scale mountains, fluxes of heat from the ocean to the atmosphere, radiative fluxes into space, the reflection of sunlight by clouds, the ocean dynamics that shapes the Gulf Stream, etc.

How can we improve from the current situation? A first approach is adding noise to the system: paradoxically, more noisy systems can be more accurate. In practice, this means moving towards stochastic climate models that respect the scaling symmetry of the Navier-Stokes equations better than the deterministic ones, because they blur the boundary between the dynamics and the parametrization. By producing ensemble realizations, these models have an in-built way to represent uncertainty.

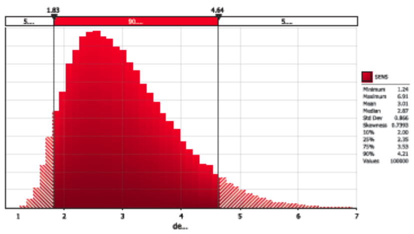
Moreover, they could even help to save energy in computation. Current models are bit-reproducible, that is, they are completely deterministic: this consumes a lot of energy in supercomputers. That energy (which anyway could be obtained by renewable sources, by placing computing infrastructures in places where they are abundant) could be invested in a better way.

A second approach to improve modelling is using Artificial Intelligence to downscale the core scales of climate modelling. This may be implemented by replacing the parametrization with neural networks: given that parametrization usually takes half of the computation time, making it more computationally efficient would be very useful. It may even be implemented by learning new types of parametrization through data: but learning from past samples may not necessarily extrapolate to the future. Finally, it may be implemented by replacing the Navier-Stokes altogether with neural networks: this idea generates a lot of scepticism.

A third approach to improve modelling is ramping up ambitions. In order to move from a blurry to a sharper picture, we need more computing power that would allow us to solve the laws of physics much more accurately. We need to treat this with the same level of ambition Europe put in the Large Hadron Collider. In other words, we need something similar to a CERN to do at the international level what we cannot do at the national level.

Beyond these strategies, there is a fourth point that is crucial. Human resources are dearly needed. Climate science must be able to attract and retain people bringing knowledge from other fields.

The Scientific Consensus about Climate Change



Equilibrium warming from a doubling of CO_2

- The scientific consensus about climate change refers to agreement about the distribution of climate sensitivity.
- Claiming that climate change **will be** something definite (either "hoax, lukewarm or catastrophe") is inconsistent with current scientific understanding.
- Uncertainties are even larger on regional scales and for other variables (such as precipitation).

There is great consensus on climate change predictions, but science needs to improve to reduce uncertainties.

4. Some reflections on CC impacts, vulnerability, adaptation, and mitigation

In order to tackle climate change, hard scientists and social scientists must work together. The problem will not be solved unless we take into account the social context of climate change, and tackle the poverty and development issues in which it is embedded.

Opha Pauline Dube
Researcher at the University of Botswana and IPCC special report, 1.5 ˚C global warming coordinating lead author

One drawback in addressing the climate change problem is the gap between hard scientists and social scientists. Climate change models need to consider the socio-economic context of climate change, i.e. what drives climate change and vulnerability. Why despite the destructive climate related disasters, reducing emissions remains elusive to the global community?

Climate change signals some of the negative effects of globalisation, the extensive human influence on the functioning of natural systems, unsustainable development and resulting widespread inequality and poverty. For example, youth are protesting throughout the world against fossil fuels, but in certain regions they are doing so amidst power cuts associated with lacking development and unmanaged globalization. This brings to the fore the notion of “decarbonizing poverty,” i.e. the possibility to address climate change without tackling global inequality, which will be deeply flawed.

Computer scientists can have a significant role in highlighting this broader approach, for instance, by approaching the youth through computer games and applications that help them develop better understanding of global connectivity, to identify meaningful interventions, i.e. behavioural changes that can have a global impact. For example, a decision by the global youth to reduce pieces of clothing to what is absolutely necessary could go a long way in curbing overuse of resources and pollution, while also saving Africa from being a dumping ground for second hand clothes from developed countries.

Impacts of climate change affect both human and natural systems and are a function of exposure and vulnerability. For instance, coastal areas and small islands are exposed to sea level rise and are likely to be hit by tropical cyclones by virtue of their geographical location. But despite the exposure, vulnerability will vary within these areas depending on susceptibility to harm and capacity to cope and adapt, which is linked to socio-economic factors.

Usually, developing countries are considered more vulnerable. But in fact developed economies have a more complex type of vulnerability to climate change linked to heavy investment on carbon economy that also controls the global economy. Added to this is that the carbon-based economy has already affected the climate system significantly and impacts will persist for the decades to come, even after emissions have been reduced.

In the light of this, adaptation to climate change becomes very important. Many different disciplines can play a role in defining optimum adaptation for different regions and sectors. Computer science plays a significant role in developing models, for example, integrating different information for different outcomes that could guide decision-makers.

Adaptation must not be narrowly defined, only in terms of its connection with climate change. It should be considered under the broader umbrella of sustainable development. Evidence points to an Earth System overwhelmed by human activities, to the extent that it could be argued than human influence is now of the level of a geological force and has culminated in a new geological era: the Anthropocene. If such changes are human driven this gives hope that humans have the ability if not to reverse, at least to reduce their impacts on the earth systems to sustainable levels. Hence it is important to determine what social system drives us into the Anthropocene? Because it is within that social system, that direction for change can be established.

Climate change is embedded in broader equality and development issue. It must be tackled taking into account these social components.

Second part: Actions

5. Super-Wicked. Climate knowledge and politics in historical perspective

The problem of climate change has been known for long. But action has been delayed, often on purpose, because our society is locked into infrastructural systems to which it has committed. This makes of climate change a super-wicked problem that needs to be reframed in order to be tackled.

Paul Edwards
Director of the Program on Science, Technology & Society at Stanford University

The biosphere takes 15000 TW of solar radiation every year and it converts it into 90 TW of biochemical energy. The technosphere takes 10 of these TW in the form of agriculture and forestry, 17 in the form of fossil fuels, etc. While before the XIX century the energy of the technosphere came totally from biomass, afterwards that source was replaced with coal, and later with oil and natural gas.

The potential problem with the energy sources of our current technosphere has been known for a very long time. In 1896 Arrhenius estimated that a doubling of carbon dioxide in the atmosphere would produce a 5-6 degree warming. In 1906, Angstrom rejected that, stating that water vapour absorbed energy in all the same frequencies as CO_2 (and there is much more water vapour in the atmosphere). However, in the 1920s and 30s, new measurements proved Angstrom wrong.

Since then, a lot of scientists have made estimates in the range from 2 to 5 degrees, consistent with the current ones. For example, in 1938 Callendar measured temperature variations in a remarkably good way, as checked by comparing with modern measures. In 1958, Keeling made his famous measures of atmospheric CO_2.

In 1972, the UN conference on the Human Environment used as an input a book called "Inadvertent Climate Modification." The same year, the famous report "The Limits to Growth" extrapolated Keeling's data and made predictions of how emissions would increase in the future. In the 1980s, the climate change field was already mature, with well-known and understood theories. Detailed predictions came in the 1990s, when IPCC pointed to a 2 to 5 °C warming for a doubling of CO_2 emissions. While the first reports could barely separate signal from noise, in 2013 IPCC was able to give an "extremely likely" assessment that human influence is the main driver of global warming since 1950, with levels of certainty in the 95% range.

How did we get to the current critical situation, given that the problem has been known for such a long time? One reason is in the infrastructure we have inherited. Our predecessors have invested in infrastructures for energy, transport, housing, agriculture and industry that make up the lifestyle we are born into. These infrastructures are akin to nature for us.

This generates a path dependence: once a society has set out on a path and realizes that it is suboptimal, it is difficult to go back. The investment in our infrastructures, the training carried out to use them, the network effects between those that live in them, generate a lock-in effect.

Infrastructures related to fossil fuels are enormous. Replacing them overnight would cost 10 trillion dollars, about one year of US' GDP. If we simply left it to wear out and never replaced it, emissions would drop to zero by 2060. This is in line with the models' requirement for avoiding the worst effects of climate change, but it's naive to think that it will happen.

Being locked into fossil fuel infrastructure is one of the so called "wicked problems." Other examples are the lack of education, poverty, public health, homelessness, water and food security, unemployment, high morbidity, and pollution. These are all complex, hard to formulate problems. There are many competing interests with different views of the problem. There are social and ideological dimension: behaviour, beliefs, and identity are wrapped up into our infrastructure. Think, for example, of the sort of commitment our society has to cars.

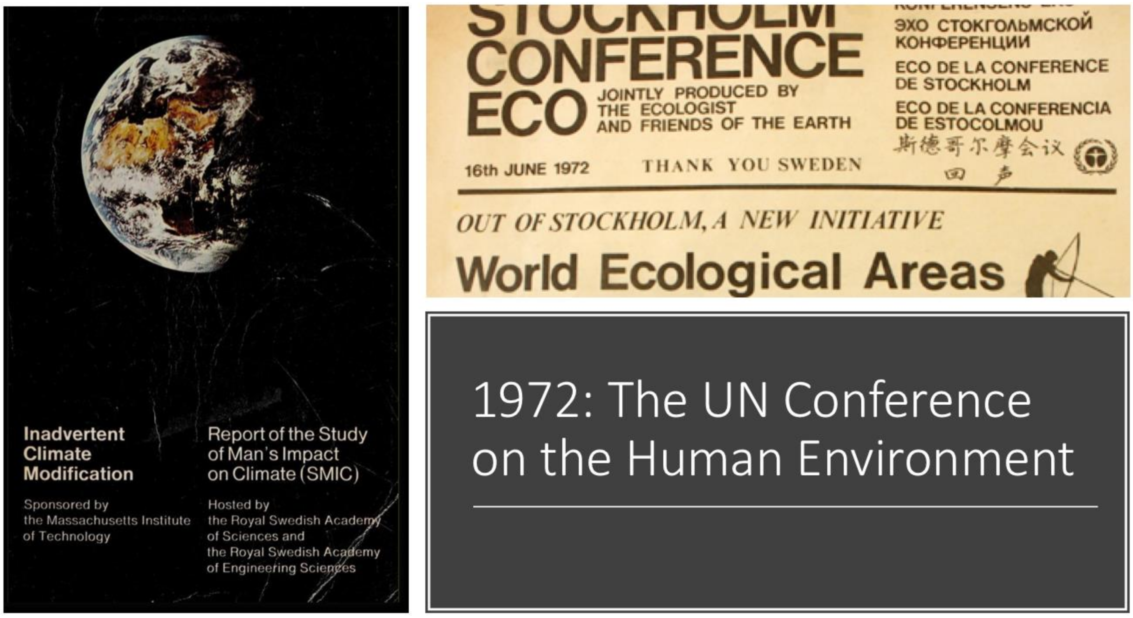
Climate change may even be qualified as a "super-wicked problem." That is, one in which the people causing the problem are the same people who must solve it; there is no central authority; there is irrational discounting (for example, people feel a problem is less relevant because the effects of current decisions will not be felt for decades); and time is running out.

Actions against climate change have been willingly delayed by interested stakeholders, through major disinformation campaigns. Organizations like the Global Climate Coalition, an apparently grassroots but in reality astroturfed campaign, played a role in that. Exxon and Shell had their climate research units pointing to the problems and Mobil even adapted its oceanic oil drilling platforms to anticipate sea level rise. But their public discourse was in the opposite direction.

"It is difficult to get a man to understand something when his salary depends upon not understanding it," said Upton Sinclair in 1935. This sentence explains what "motivated reasoning" is: if you want to keep your lifestyle, you will try to sync your beliefs with that. This happens also at the level of individual consumers, justifying the use of cars, plastic bottles, etc.

One important feature of wicked problems is that their solution depends on how one frames them. For example, the responsibility for climate change can be framed by focussing of the top national emitters: China (that has overtaken the US in the last decade), the US, the EU, and India. But another way of framing it is to look at per capita emissions. In this case, the US is far in front and China is just ahead of Europe. In reality, the US have externalized their emissions to China and bought them back in the form of products. Yet another way of framing the problem is to ask which nation has contributed most to cumulative emissions since 1750.

While there is no silver bullet to tackle climate change, there are many partial solutions. Mathematicians and computer scientists can help a lot in framing and visualizing things in the most effective way.



The problem of climate change was already known in the '70s but action was delayed, often intentionally.

6. Public perceptions of Climate Change

> *While awareness of climate change is still an issue, concern can be raised by diversifying those that speak about the issue, explaining why scientists can be trusted, and reducing the psychological distance with the problem.*
>
> ***Jennifer Marlon***
> *Research scientist, Yale's School of Forestry and Environmental Studies and the Yale Program on Climate Change Communication (YPCCC)*

The big five ideas for talking about climate change are: a) It's real, b) it's bad, c) it's us, d) scientists agree, and *critically* e) there's hope. In other words, temperatures are increasing, this is ultimately bad for the majority of people and species and it is related to human-caused pollution. Scientists agree on all the above and we know many of the solutions.

Figures allow us to measure the level of penetration of these ideas among the American public, and increasingly in other countries as well. Awareness, in the first place, is still an issue: 4 out of 10 people in the world have never heard about climate change, especially in underdeveloped countries. For example, ¾ of the population in Bangladesh have never heard about it, although they are vulnerable to glaciers shrinking and sea level rise.

On the other hand, those that are aware and think it's serious are mostly in the developing countries. For example, 73% of US citizens think climate change is happening, according to 2018 data, but just 67% think it will harm future generations, and only 42% think it will harm them personally.

Increasing awareness in the South and concern in the North are the first two communication recommendations one can make, based on data.

Regarding the causes of climate change, only 62% of Americans attribute it to human activity, while 23% still believe it is natural, caused by factors such as solar forcing, volcanic activity, El Niño, etc. This major persisting misperception goes against the evidence that human fingerprints are all over our climate system.

For example, if it solar forcing were causing Earth to warm, one would expect daytime temperatures to be warming faster than night-time temperatures, yet the opposite is most often the case. If it were the sun, the summers would be warming faster than the winters, but the reverse is generally true. We also find fossil fuel signatures of carbon in trees and corals.

Scientists are very confident that it's humans causing the warming. The degree of scientific consensus is 97% among climate scientists, stronger than the supporting link between tobacco and lung cancer among doctors. However, those who think that climate change is happening and human-caused among the general population in the US are about 53%. If you ask the public how many scientists agree on climate change, only 15% will give a number above 90%. The majority think there is debate in the scientific community.

There are in fact six "Americans," when it comes to global warming. 29% are alarmed (this percentage has doubled in the last five years) and 30% are concerned, but don't see it as an urgent issue. Among these, the ongoing conversation focuses mainly on what the world and individuals can do to reduce global warming.

Then, there are people that are cautious (17%), don't know (5%), and doubtful (9%). Among these, the main question is: why should I care? And finally, 9% of Americans are dismissive of climate change, and believe that it is simply a hoax. Within this group, the underlying question they have for the scientific community is: how do you know it's true? It's a tiny minority, but it's much more organized and well-funded than the other side of the spectrum.

Strategically, it may be cleverer to focus on the middle, where the majority of the people are, and don't put too much hope in convincing extremists who will likely never be convinced. However, when talking to skeptics, it is useful to listen and understand where their attitude comes from.

Usually, it comes from fear or from different values, so the best way is to ask, talk about one's experience (e.g. how I became worried, experience of climate variability, etc.), identify shared values, develop a relationship, and see where it goes. Also, contentious issues can be leapfrogged to jump to solutions that may appeal them (e.g. technological innovation).

An underlying question shared by all groups that doubt (skeptic or not) is: why should I trust you? For this reason, it's important to diversify the pool of people talking about the issue, including community leaders, religious leaders, musicians, etc. that may raise trust in different groups.

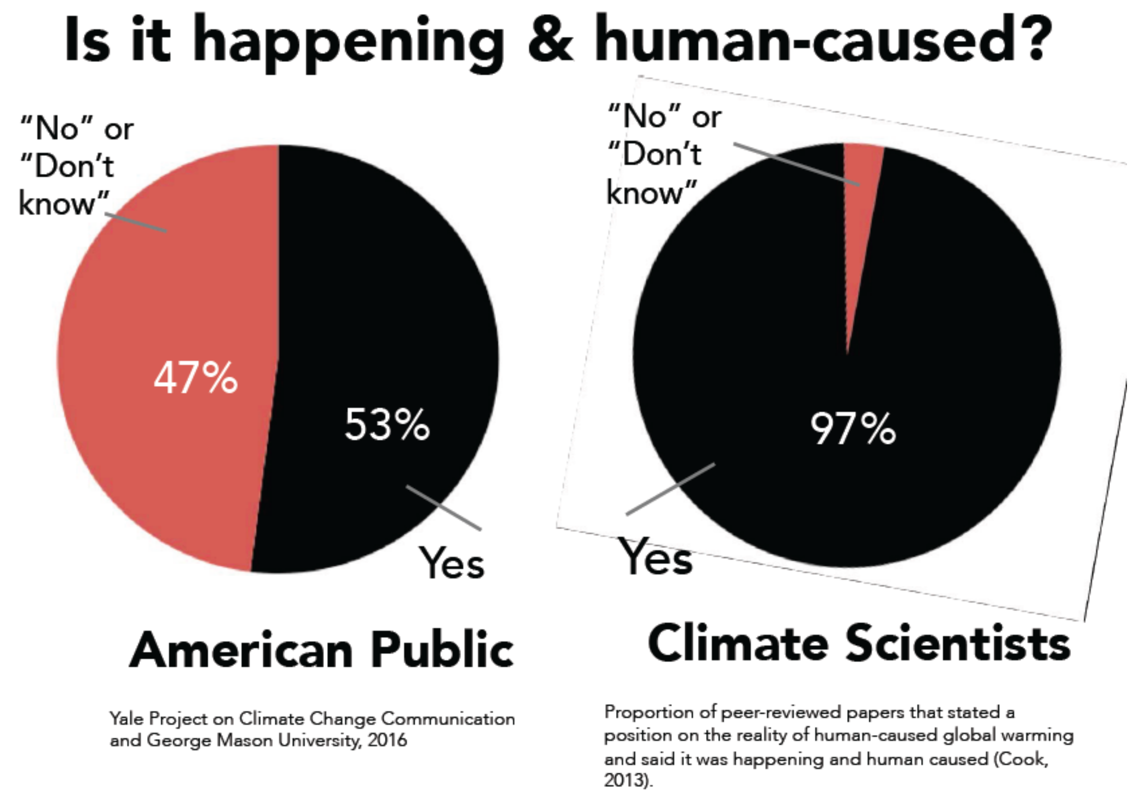
It's very important to avoid overblown statements that can undermine trust, be honest about what we know, what we don't know, and inform the public about the process that brings us results: the meaning of uncertainty, how scientists get their information, how they defend their integrity, and what certifies any of them as a credible representative, or not, of a body of knowledge. Simply informing the public about the degree of scientific consensus can make big changes.

Another aspect to be taken into account is psychological distance. People tend to feel they are immune to climate change, and that it affects polar bears and future generations. Reducing this psychological distance often means reaching people's hearts, rather than their heads. Individual stories about something that people care about can play an important role.

Finally, scholars who are vocal about the issue are key-players. Talking to friends and family may inspire them want to seek out more information and consider taking small sustainability actions, which can have cascading effects through social networks. But most importantly, talking to the media allows scientists to use the main channel through which people gain awareness of the problem. In the US, 22% said that they heard about climate change once a week in the media in 2018. Now we are at 32%. This number is still far too low given the gravity and far-reaching effects of the problem.

People do change their minds and find different ways to relate to the issue. For example, in the US there is a surge in support for climate change concern as a high priority among Democrats, but not among Republicans. 52% of Republicans think climate change is happening (vs. 91% of Democrats) and 36% think it's human-caused (vs. 79% of Democrats).

Still, 80% of Republicans support renewable energy (vs. 93% of Democrats) and 62% are in favour of regulating CO_2 as a pollutant (vs. 82% of Democrats). Change can happen, and can happen rather quickly.



There are still major gaps between scientific consensus and public perceptions on climate change.

7. The psychology of climate change, based on evolutionary biology

> *Evolution provided humans with hardwired rules to overexploit resources. Subjective expectation of low risk, free riding, and intergenerational discounting hamper a cooperative solution against climate change.*
>
> ***Manfred Milinski***
> *Founding director of the Max Planck Institute for Evolutionary Biology*

Tackling climate change is extremely complicated because of psychological rules that have been produced by evolution and we apply unconsciously.

The power of these unconscious rules is shown by an experiment, in which students in a campus had to pay their tea by introducing money in an unsupervised honesty box. Students paid more when the box was decorated with watching eyes. This reflects that being watched make people behave more cooperatively in an unconscious way, i.e. even when at a conscious level one knows that those eyes are just a drawing.

The problem is that evolution always favoured better exploiters of resources thus producing ruthless exploiters. Our ancestors did not have the technical means to overexploit resources, so we have not developed unconscious rules to stop doing it.

This leads to the concept of “tragedy of the commons,” formulated by Hardin in 1968: “Whenever people have free access to a public resource, the resource will be overused and collapse.” Many examples proved Hardin right, for example, we have removed already more than 60% of species of fish by overfishing.

Global climate can be seen as a natural public good. But people do not accept to preserve it and help future generations, by giving up some personal comfort.

This has been shown in an experiment in which a group of people had to put together a certain amount of money to be donated, knowing that they will loose all their remaining they had, in case they failed, simulating dangerous climate change.

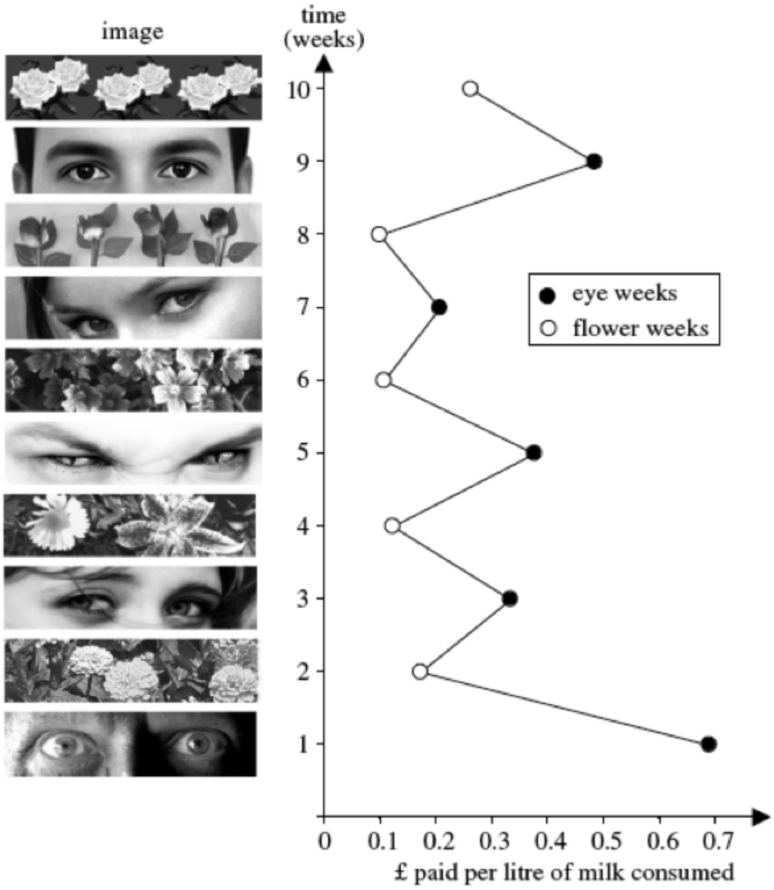
Initially, 6 people were given 40 euros each and required to put about 50% of the money in a climate account, that would be used to pay advertisements in the media to inform people on climate change. In each round of the experiment, the participant could contribute 0, 2, or 4 euros to the account. If they reached 120 euros in the account after 10 rounds, they would keep for them the remaining money (the target sum would be reached by contributing 2 euros per round per person, on average). Otherwise they would loose everything with a probability of 10, 50, or 90%. After each round, they were shown the balance of the account.

When the risk of loosing all the money was just 10%, most individuals applied the money-maximizing strategy of not investing anything. On average, they assembled 72 euros. This shows that the expectation of low risk (which is a subjective perception rather and an objective fact, when applied to climate change) causes people to invest less.

When the risk of loosing all the money was 90%, the group made it on average. But only on average. 50% of the groups failed. This shows the appearance of the tragedy of the commons: even being fully informed (which is not the case in reality, when dealing with climate change), it’s too tempting to free ride and hope that somebody will compensate.

This benchmark experiment has been used with variation to check different hypotheses. For example, it has been shown that people tend to invest more when their reputation is at stake, as often an increase in reputation results in receiving help in other instances.

They also invest more when the effect of their actions is closer in time. In an experiment in which not-invested money was paid out also when the target was not reached, the delivery of a considerable extra award to the participants, when the target was met, happened the day after the experiment, after 7 weeks or was delivered to future generations (in the form of planting oak trees). The number of groups that succeeded dropped sharply in function of time. This is a problem for climate change: it models the “intergenerational discounting” happening when people tend to take less actions if the benefits are for future generations.



Bateson, Nettle & Roberts *Biol. Lett.* (2006)

People pay more to an unsupervised honesty box when there are eyes printed on the box.

8. Readings and webpages

Foundations of climate science:
- Chris Budd, *The mathematics of climate change*, Gresham Lecture, 13/11/2018
- Chris Budd, *Can maths predict the future?*, Gresham Lecture, 9/10/2018

Current situation of climate change:
- Science Advisory Group of the UN Climate Action Summit 2019, United in Science (2019)
- IPCC, *AR5 Synthesis Report: Climate Change 2014*
- IPCC, *Special Report: Global Warming of 1.5 ºC*
- Vogel, M. M., Zscheischler, J., Wartenburger, R., Dee, D., and Seneviratne, S. I., *Concurrent 2018 hot extremes across Northern Hemisphere due to human-induced climate change*, Earth's Future, 7, 692–703 (2019)

Future scenarios outcoming from the current climate crisis:
- Sonia I. Seneviratne et al., *The many possible climates from the Paris Agreement's aim of 1.5 °C warming*, Nature, 558, 41–49 (2018)

Frontiers of research on mathematics and computer science applied to climate change:
- Tim Palmer, *A personal perspective on modelling the climate system*, Proc. R. Soc. A 472: 20150772 (2015)
- Tim Palmer, *A CERN for climate change*, Physics World (March 2011)
- Lea Beusch, Lukas Gudmundsson, and Sonia I. Seneviratne, Emulating Earth System Model temperatures: from global mean temperature trajectories to grid-point level realizations on land, Earth System Dynamics Discussions, 1-28 (2019)

On the history of climate change science and its diffusion:
- Paul N. Edwards, *A Vast Machine, Computer Models, Climate Data, and the Politics of Global Warming*, MIT Press, 2013
- Carbon Brief, *Timeline: The history of Climate Change modelling*, (2018)
- Benjamin Franta, *Shell and Exxon's secret 1980s climate change warnings*, The Guardian (2018)
- Yale Climate Connections, *James Hansen's 1988 testimony after 30 years. How did he do?* (2018)

Climate change communication:
Matthew H. Goldberg et al., *Discussing global warming leads to greater acceptance of climate science*, PNAS 116 (30) 14804-14805 (2019)
Tieng Min Lee et al., *Predictors of public climate change awareness and risk perception around the world*, Nature Climate Change 5, 1014–1020 (2015)

Social and psychological dynamics related to climate change:
- Ding Ding et al., *Support for climate policy and societal action are linked to perceptions about scientific agreement*, Nature Climate Change 1, 62–466 (2011)
- Manfred Milinski et al., *The collective-risk social dilemma and the prevention of simulated dangerous climate change*, PNAS 105 (7) 2291-2294 (2008)
- Manfred Milinski et al., *Stabilizing the Earth's climate is not a losing game: Supporting evidence from public goods experiments*, PNAS 103 (11) 3994-3998 (2006)
- Jennifer Jacquet et al., Intra- and intergenerational discounting in the climate game, *Nature Climate Change* 3, 1025–1028 (2013)
- Manfred Milinski et al., *Humans choose representatives who enforce cooperation in social dilemmas through extortion*, Nature Communications 7, 10915 (2016)
- Kelly Levin et al., *Overcoming the tragedy of super wicked problems: constraining our future selves to ameliorate global climate change,* Policy Sci (2012) 45: 123

Visualization of the CO_2 *emitted in a day in the world, as a mountain of bubbles above New York City.*

ANNEX: Report for the Workshop "Mathematics and Climate"

Author: Dr. Makrina Agaoglou

Abstract

This is a report on the workshop "Mathematics and Climate" at the 7th Heidelberg Laureate Forum. They were 48 participants from different countries and universities, from Bachelor students to Postdoc researchers. The participants were from different scientific backgrounds from the areas of mathematics and computer science.

Introduction

The importance of the climate change and its effects is a fact. The purpose of this workshop was to bring into light the connection between the climate modelling and mathematics and how mathematics and computer science can contribute to the development of the climate modelling.

Structure of the workshop

The study material for the participants was the following books:
- Lynch, P. (2006): The emergence of numerical weather prediction: Richardon's dream. Cambridge: Cambridge University Press.
- Strogatz, S. H. (1994): Nonlinear dynamics and chaos. Cambridge: Perseus Books Publishing.
- Sorbjan, Z. (1996): Hands-on meteorology: stories, theories, and simple experiments. Boston: American Meteorological Society.
- Schneider S. H. and Dickinson R. E. (1974): Climate Modeling. Reviews of Geophysics and Space Physics.

And webpages:

European Centre for Medium-Range Weather Forecasts (ECMWF), European Network for Earth System modelling (ENES),National Oceanic and Atmospheric Administration (NOAA), National Center for Atmospheric Research (NCAR), National Aeronautics and Space Administration (NASA)

The structure of the workshop was divided into three parts. The first part was a quiz with questions related to the subject of mathematics and climate. The second part was a brief introduction to the subject. Finally, the last part was a conversation between all the participants and to fill a questionnaire with the following questions:

1) What is your research area?
2) What mathematical techniques can be brought to clarify our current understanding and make predictions for the future, qualified by clear measures of uncertainty?
3) Are you familiar about any existing climate model? If yes, which one?
4) Can you think of any way that your research area can contribute to the improvement of the climate models? Yes or No?
5) If yes, can you give a brief description about your ideas?
6) What other aspects we should take into consideration for climate change?
7) What new computes science techniques could be used to improve performance of the calculation of the climate models?

The aim of this questionnaire was two-fold. To combine the scientific areas of mathematics and computer science and to bring new ideas into light that not only can lead to new perspectives but to overcome some of the difficulties that people, that use and develop climate models, face. The results are presented below.

Results

In this section, we present the results from the questionnaire that was given to the young researchers during the workshop.

Question 1:

Most of the participants (77%) were from the area of mathematics. The young researchers from the area of computer science were 13% whereas 10% of the participants were working/studying in both areas.

Question 2:

The young scientists suggested several areas from which many mathematical techniques can be used in order to clarify our current understanding and make predictions for the future. Most of the people suggested that statistical modelling and/or Artificial Intelligence, in particular Machine Learning can be our way out for better climate predictions. These are the answers:

From the people working in the area of Mathematics

- Statistical modelling such as Bayesian modelling, regression analysis, time series analysis, stochastic partial differential equations (6 answers)
- AI and especially ML (3 answers)

- uncertainty quantification (2 answers)
- probability theory (1 answer)
- big data analysis (1 answer)
- model reduction (1 answer)
- analyse the Earth's system as geometrical object (1 answer)
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<u>From the people working in the area of Computer Science</u>

- Understanding on how to incorporate the extent of intervention needed for climate change into the output of prediction models (1 answer)

<u>*Question 3:*</u>

Most of the young scientists weren't familiar with any existing climate model. Only three people had heard of the following climate models before:

- E3SM (Energy exascale Earth System Model) (1 answer from a mathematician)
- Spatio-temporal forecasting (Deep learning models) (1 answer from a computer scientist)
- Regional Climate Models (RCMs) (1 answer from a mathematician)

<u>*Question 4 & Question 5:*</u>

The young scientists could think about ways that their research area can contribute to the improvement of the climate models.

<u>From the people working in the area of mathematics:</u>

- better PDE models
- topological data analysis
- optimization theory relates to computational feasibility
- geometric integration can make long-term simulations more reliable
- computational acceleration, accuracy by using differential geometric methods
- building new numerical methods
- inversion-based learning approach
- model reduction
- special functions

<u>From the people working in the area of computer science:</u>

- Speeding up climate models dealing with distributed data prediction and pipeline supercomputing results into smaller models for faster predictions.
- Novelty approach to the problem as opposed to an objective model. If the goal of the model is not to “predict” but rather to “learn” or just to explore possibilities of climate.
- Building and modelling specialized processors for climate model algorithms.
- Graph Neural Networks (GNNs)

<u>*Question 6:*</u>

From the outcome of this question, it seems that the aspects about climate change that we should focus on more are the following:

- Social impacts such as access to education

- Does is make sense to add more computing power? (which seems to be harmful to the environment since to run these models it requires a lot of electric power that adds more to the global warming). Discuss about the cost of the problem approach
- More effective climate change communication within and outside the scientific community and especially among politicians
- Impact of humans to the climate change
- Pollution (i.e. air)
- Predicting what actions will best prevent from further damage
- Take action (i.e. produce less waste)
- Scientific and economical changes in the renewable energy business
- Test any new technology before it will be widely used in the aspect of affecting the climate
- Green urban infrastructure

Question 7:

Among the answers, the young scientists agree that the new computer science techniques that can improve the performance of the calculation of the climate are the following:

- AI and in particular ML (10 answers)
- Graph Neural Networks (GNNs) (1 answer)
- Adaptive mesh generation (1 answer)
- Quantum computing (2 answers)
- Data compression techniques (1 answer)
- Parallel computing (1 answer)
- Dimensionality reduction methods (1 answer)

Conclusion

Climate modelling is one of our newest biggest challenges. The importance of improving the existing climate models or building new more accurate climate models is evident and have impact in our everyday life. In this report we can see that although not many of the young researchers are familiar with climate models they could suggest several ways/methods, related to their research area, that they think could possibly help to improve them. Furthermore the participants were very keen on finding other aspects that we should take into consideration for climate change such as more effective climate change communication, since it seems that even though people have heard of climate change they don't seem to truly understand what it is and how it can affect us, green urban infrastructure, social impact etc. Finally, one of the findings is that most of the researchers seem to agree that through Artificial Intelligence and/or statistical modelling we can improve the calculation of the climate.