ACCADEMIA NAZIONALE DEI LINCEI

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CURRENT ISSUES IN CLIMATE RESEARCH

With five messages to COP26

2021

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Cover image: Summer ice melting of Antarctic ice (Victoria Land, 2014).
Courtesy of Andrea Spolaor.

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FOREWORD

Climate change is an indisputable fact, and the major role played by anthropogenic emissions of total greenhouse gases (GHG) has been increasingly substantiated by progressive improvements in our scientific understanding of the climate system.

Confronted with an extraordinary challenge, humanity must thus take decisions of overwhelming impact for present generations to prevent calamities of unprecedented consequences for future generations. This is indeed unusual, as the possible benefits of present actions will be enjoyed by the children and grandchildren of those making decisions today. The issue is further complicated by the planetary scale of climate change, which implies that people in a country will benefit (or suffer) from the politically legitimate actions (or inactions) taken by people living in other countries.

The success of any strategy will depend on the role played by two main actors: science and politics. While the responsibility for actions will ultimately rests on the capacity of politics to let a universal common strategy emerge by smoothing the oppositions arising from vested conflicting interests, the role of science and technology is equally important.

Science cannot make 'certain' statements, yet it allows estimating the probability of occurrence of future events at the best of current knowledge. Based on such estimates, science has the major task of offering a clear and honest picture of what is known, what is less known and what is still unknown, so that the efforts required to counteract climate change can be evaluated by policy makers. Technology is expected to offer an equally clear and honest picture of what technologies are available and mature for deployment today and what promising technologies may mature in the future. Their cost, their environmental impact, the real risks associated with their deployment, and their effects on geopolitical equilibria are all fundamental components of the picture that technology is expected to provide in support of policy makers.

In preparation for the forthcoming COP26, to be held in Glasgow in November 2021, the Environmental Committee of the Accademia Nazionale dei Lincei has undertaken to contribute to an assessment of the current issues in climate research, convening an International Conference in Rome on 9-10 September 2021. The meeting has gathered some of the most prominent scientists, economists and engineers, featuring the basic science of climate change and its impact both on natural and built environments.

The present Report is intended to summarize the outcomes of the meeting for the benefit of participants in COP26. The Report is conceived as a sequence of outstanding questions, addressed by the Speakers in their talks. The brief responses provided by the Speakers reflect their scientific insights, concerns, and possibly also their personal taste. The conclusions offered by the Report include five important statements agreed upon by all the Speakers and form the final message addressed to policy makers and citizens and delivered to COP26.

Giorgio PARISI
Accademia Nazionale dei Lincei
President of the Class of Physics, Mathematics and Natural Sciences

Bruno CARLI
Accademia Nazionale dei Lincei
Co-Chair Scientific Committee of the Conference

1 UNDERSTANDING THE MECHANISMS OF CLIMATE CHANGE

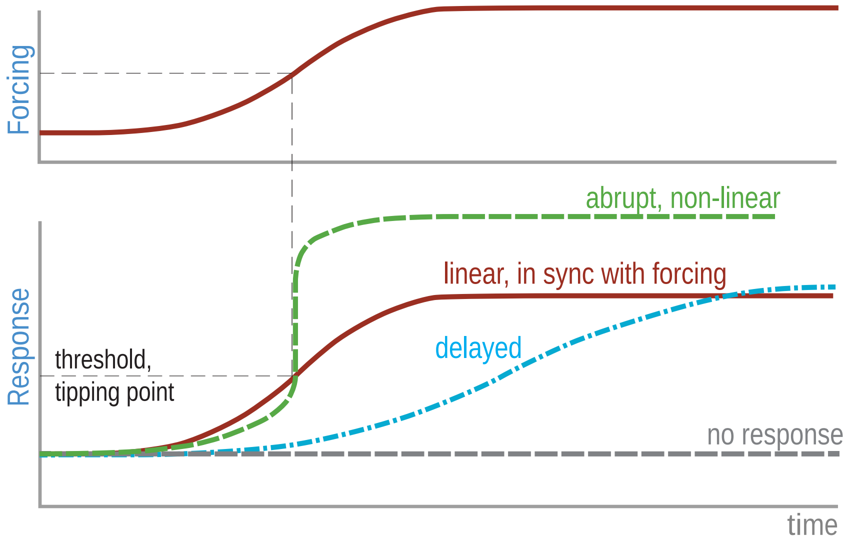
DO WE FULLY UNDERSTAND THE PHYSICAL PROCESSES THAT CONTROL CLIMATE?

This question is subtle as we need to clarify what we mean by "fully". Who asks this question, with what expectation? To a policymaker, concerned with the evolving climate crisis and negotiating the next steps in the Paris Agreement, I answer in the affirmative. *Human influence on the climate system is clear* and *Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions* are the two key Headline Statements of the Fifth Assessment Report of the IPCC (2013). They are the succinct summary of the policy-relevant scientific understanding to confront anthropogenic climate change and provide the scientific foundation of the Paris Agreement. They underpin the affirmative answer to the above question. While knowledge will always be incomplete, the associated risks are of a magnitude that do not justify postponing policy decisions (Stocker 2013).

However, to a fellow scientist my answer is No, because there are many aspects of past and future climate change that are poorly known. Our understanding of how the complex climate system works is limited. Quantification of feedback processes is incomplete and estimates of the sensitivity to perturbations is fraught with uncertainties. The amount of knowledge shrinks in lockstep with the spatial scales, and with the degree of nonlinearity of the processes. For example, changes in the statistics of extreme climate events, such as heavy precipitation or drought, are notoriously difficult to simulate with the present generation of climate models. Or, the instability of the Indian Monsoon system, the life support system of more than a billion people, is insufficiently understood to assess the risk of time shifts in its onset in a new climate regime. And most importantly: one of the whiter spots on the knowledge map is surprises or tipping points in the climate system (Broecker 1987; 1997; Lenton et al. 2019).

The public is regularly exposed to media reports and other information that future tipping points are an immediately threatening consequence of anthropogenic climate change. Tipping points are thus portrayed as an additional danger to the ongoing heating, drying, sea level rise, increased extreme events and changes in weather patterns. Examples of large-scale tipping points in the climate system are the melting of the Greenland ice sheet, the collapse of the Atlantic Ocean circulation, the dieback of the Amazon rain forest, shifts in the Earth's monsoon systems, an instability of West Antarctica, or methane release from Arctic permafrost. Tipping points trigger changes of global extent and high regional impact. They must be avoided as they arguably constitute one aspect of "dangerous anthropogenic interference with the climate system", as referred to in Article 2 of the UN Framework Convention on Climate Change (UNFCCC 1992). Our current knowledge about tipping points is incoherent, sometimes confusing, often incomplete, and consequently runs the double risk of being exaggerated or downplayed in the public. This situation is particularly difficult for decision makers as the system may react in several different ways close to a tipping point.

Science has studied instabilities in the climate system for several decades (e.g., Stommel 1961; Sellers 1969; Stocker and Wright 1991; Stocker and Schmittner 1997), but investigations were mostly limited to theoretical studies or simulations with climate models of reduced complexity. More recently, comprehensive climate models also exhibit instabilities, but verification with observations has been difficult, if not impossible. Only in the past two decades targeted in situ observations of the ocean circulation (McCarthy et al. 2020), ice sheet margins (Holland et al. 2020), paleoclimate records, and satellite remote sensing have



Qualitatively different responses to a climate forcing, both natural and anthropogenic,
e.g., orbital changes in solar irradiation, or an increase in greenhouse gas concentrations
(Figure from IPCC 2019).

provided crucial information that the climate system may be on the approach to tipping points. It is fair to say that there exists no encompassing overview or deep scientific understanding, let alone a comprehensive assessment of the science on tipping points in the climate system. Consequently, the field is wide open for uninformed views, misconceptions and misunderstandings, or simply speculations on this important aspect of anthropogenic climate change.

For the first time in its Third Assessment Report in 2001, Working Group I of the IPCC considered "surprises in the climate system". In the Fifth Assessment Report in 2013, tipping points were addressed in several chapters, and it was noted that such changes could be possible in most components of the climate system (ocean, sea ice, ice sheets, vegetation, modes of variability, etc.). The concept of tipping points has also taken an important place in the assessment by IPCC Working Group II in the context of regional impacts and ecosystem changes. In the current sixth assessment cycle of the IPCC tipping points are addressed in various places in the two special reports SR1.5 (IPCC 2018) and SROCC (IPCC 2019), and in the comprehensive report of Working Group I (IPCC2021). The current situation is that of growing but still scattered scientific information on large-scale singular events, tipping points and irreversibilities. This precludes a comprehensive overview of the state of knowledge and limits decision making in compliance with Article 2 of the UNFCCC. Currently, a consensus view on this key impact of anthropogenic climate change, with potentially high impacts regionally and worldwide, is missing. Based on the available drafts that were reviewed, progress on this issue is not expected to be significant with the IPCC Sixth Assessment Report, planned to appear in 2021, although the scientific literature has matured considerably since 2013. In particular, emerging targeted observations and accelerating climate change in recent years have accentuated the need for a comprehensive and focused assessment of tipping points in the climate system.

It is therefore timely to call for an IPCC Special Report on *Climate Tipping Points and Consequences for Habitability and Resources*, to be prepared in the IPCC seventh assessment cycle which is envisaged to start in 2023. It is important that this be a comprehensive cross-working group assessment (Drijfhout et al. 2015). Such a report would not only initiate a consensus-building process within the scientific community but also lead to a much needed focusing of observations, monitoring, and modelling of potential surprises in the climate system. For the public and the policymakers, new knowledge would come timely and well before 2030, when the UNFCCC starts its next commitment period in the framework of the Paris Agreement.

Thomas STOCKER
University of Bern and Accademia Nazionale dei Lincei

DOES THE SUN CONTRIBUTE TO GLOBAL WARMING?

The Sun is the source of 99.97% of the energy input into the Earth's climate system (Kren et al. 2017). The approximately 1,361 W m^{-2} provided at 1 AU by the Sun (the total solar irradiance) keep Earth sufficiently warm to sustain human life. Any variations in solar irradiance directly affect the amount of energy entering the climate system and, once feedback effects, natural variability, etc. have been taken into account, hence also the average temperature of the Earth's atmosphere.

Measurements of solar irradiance, available since 1978 with the required precision to reliably detect variability, have found variations of approximately 1 W m^{-2} on timescales of the solar activity cycle, i.e. roughly 11 years (Kopp 2016). The source of these variations is the evolution of the magnetic field at the Sun's surface, with the Sun being on average brighter during the high activity part of the solar cycle (Solanki et al. 2013). The magnetic field is stronger and its distribution on the solar surface is highly complex around activity maximum, when the Sun also displays more sunspots and other signs of activity, such as flares. The strength of the Sun's magnetic field can be traced back in time with the help of various proxies, including sunspots for the last four centuries and cosmogenic isotopes for nearly the entire holocene. One striking feature of past solar activity is that there were multiple periods, called grand minima, when the Sun was almost totally inactive for multiple decades. Such grand minima coincide with periods of particularly low solar irradiance. There is also mounting evidence that prior to industrialization, such prolonged dips in solar irradiance correlated with a cooler climate, at least in Europe and the North Atlantic (e.g., the last grand minimum, called the Maunder minimum coincided with a particularly cold part of the little ice age).

The behavior of solar irradiance and global surface temperatures, since 1880, is shown in the figure below. Solar irradiance has displayed considerable variations in that period of time. Particularly visible is an increase in the irradiance during the first half of the 20th century, caused by a significant rise in solar activity over the same period of time. This rise in activity manifested itself in ever-stronger solar activity cycles and culminating in the strongest solar cycle recorded to date in the middle of the 20th century. The high activity level between roughly 1940 and 2000 is often termed the modern grand maximum of solar activity and is matched by the Sun's brightness (although it does not vary quite as strongly as the activity does).

The rise in irradiance has partly run in parallel with the temperature rise on Earth, although the solar irradiance rise has at least part of the time lagged somewhat behind the temperature rise, in contrast to the expectations of a 1-to-1 causal link between solar brightening and global warming. The Sun may have contributed to the rise in global temperature during

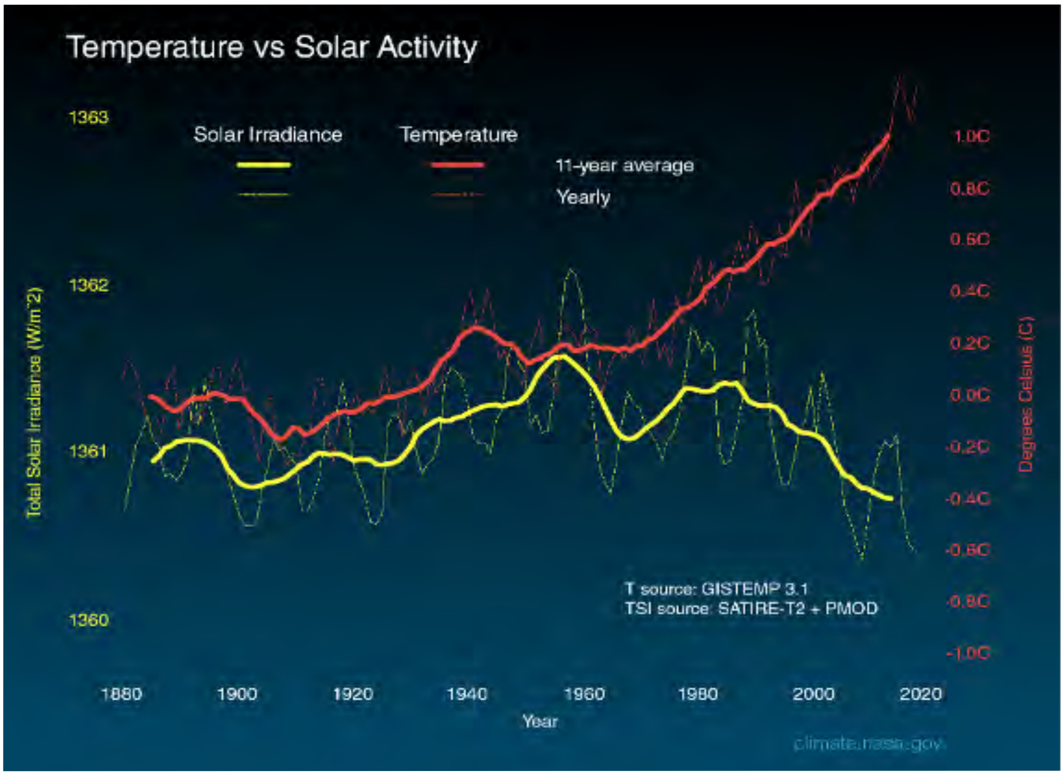


Fig. 1. Global surface temperature (red curves, right axis) and total solar irradiance (yellow curves, left axis) since 1880. Thin lines are yearly means, while the thick curves are 11-year averages. The surface temperature follows the GISTEMP 3.1 reconstruction (Lenssen et al. 2019), while the total solar irradiance curves is based on the PMOD composite of TSI measurements since 1978 (Fröhlich, 2012) and the reconstruction made using the SATIRE-T2 model by Dasi et al. (2016). Credit: NASA-JPL/Caltech.

the first half of the 20th century, but it was likely not the dominant driver.
Quite remarkable is the relative behavior of the two quantities since around 1980. Whereas global temperatures have risen dramatically in this period of time, solar irradiance has not and has even displayed a tendency to fall slightly. There is some controversy surrounding the magnitude and even the reality of this drop in solar irradiance since roughly 1980. Nonetheless, it is accepted that irradiance did not systematically increase by any significant amount in the last four decades. Both measurements and models independently support this finding. Consequently, there is a clear divergence between solar irradiance and Earth's climate in the last half century.

We can conclude from these findings that, although the variable magnetic activity of the Sun does influence Earth's climate, such effects have likely been small during the last century. Thus, solar variability may have contributed some of the rise in temperature during the first half of the 20th century, but it is highly unlikely to have played a role in the much stronger rise in global temperatures that occurred over the last half century.

What role will the Sun play in the future? This question is harder to answer, as we currently are unable to predict solar activity except the strength of the next activity cycle, and even that with a rather large uncertainty. In addition, there is no consensus on the magnitude of the change in solar irradiance between grand solar minima (such as the Maunder minimum in the 17th century) and normal levels of activity, such as at present. Estimates of this critical quantity provided by various models differ by an order of magnitude from each other. This leads to a corresponding uncertainty in the magnitude of the solar forcing.

In summary, the short answer to the question "Does the Sun contribute to global warming?" is: It is highly unlikely that the Sun has made any significant contribution to global warming in the last half century. However, there is still considerable work to be done to predict how solar activity will develop in the future and if the Sun's influence will remain equally small in the coming century.

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DO WE FULLY UNDERSTAND HOW THE CONTRIBUTION OF THE OCEAN SINK TO THE CARBON CYCLE IS CHANGING?

The oceans are a net sink, of about 25-30% of anthropogenic CO_2 emitted in recent decades. The main process limiting the uptake is the dynamics of ocean ventilation – the subduction of surface water to depth, which mostly occurs in regions where water is becoming denser by being cooled. Major regions of uptake include the Southern Ocean, both in the bottom water and mode water formation regions, the North Atlantic and its marginal seas, and regions of subtropical mode water formation.

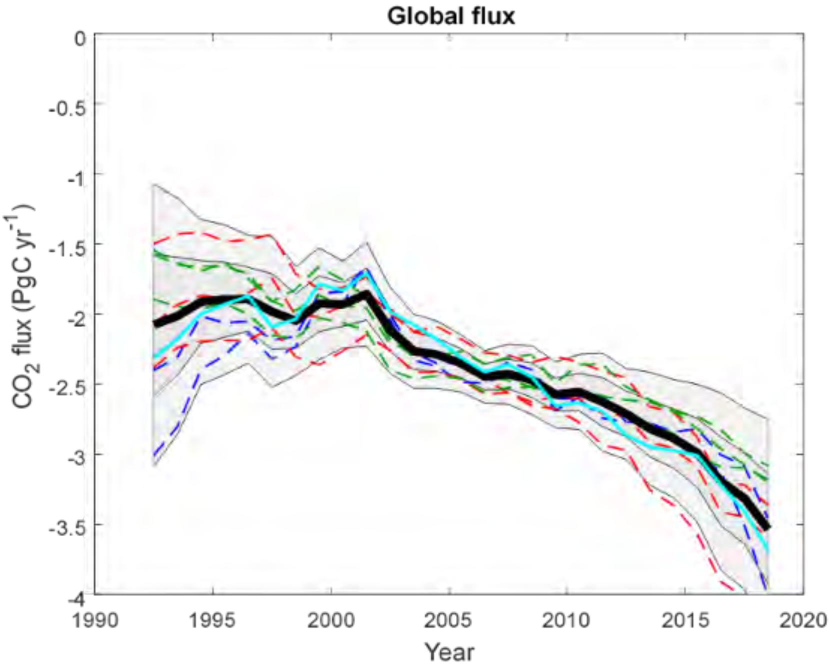
Our knowledge of ocean carbon uptake comes from several sources: ocean models are frequently used to estimate the anthropogenic flux, simultaneous atmospheric observations of CO_2 and oxygen-to-nitrogen ratios enable a global estimate of the uptake, while several methods have been developed that use oceanographic measurements to separate anthropogenic carbon in the ocean from pre-existing "natural" carbon. Surface carbon observations also allow the reconstruction of net CO_2 fluxes through the ocean surface. The figure shows recent estimates of the global net sink made from the SOCAT (www.socat.info) data base of surface pCO_2 observations.

What we don't know:

(1) There are substantial uncertainties in all the methods described above that limit present accuracy. These are due both to gaps and approximations in the theory involved, as well as imperfect coverage of observations. The Global Carbon Project for example quotes the ocean sink over the last decade as 2.5 +/- 0.6 PgC yr^{-1} with 1-sigma uncertainty, we would like to be able to specify this to better than 10% so we still have some way to go.

(2) We don't know for sure how the uptake has changed in the past, we do know the sink is increasing, and there is observational evidence that that increase accelerated around the year 2000 (see figure). We strongly suspect that the ocean uptake is variable over multi-year periods, but we are unsure why, or what this means for the future uptake under climate change. The changes are most probably governed by ocean circulation, with varying surface ventilation rates, but there may also be a biological or biogeochemical component. We don't know much about how marine primary production and the "biological pump" may be affected by rising CO_2 and by climate change.

(3) Models mostly do not reproduce the changes that we think we see in the data – in models the uptake by the oceans seems comparatively stable and predictable, but the observational data indicate greater variability. Observational data are sparse especially before the 1990s, so the reconstructions from observations are not fully reliable the further back in time we go.



Global net flux across the ocean-atmosphere interface (negative is into the ocean) over the period 1992-2019 (Watson, A. J. et al, Nature Comm. 11, art no. 4422, 2020). The colored lines show nine estimates made using different interpolation techniques applied to the SOCAT data, corrected for near-surface temperature effects. Shading indicates one- and two-sigma uncertainties around the average, which is the thick black line.

(4) At a deeper level, we need to be able to understand, and distinguish between purely anthropogenic uptake, forced by rising atmospheric CO_2, and variations in pre-existing 'natural' carbon. Ocean circulation and biology are changing, due both to human-caused climate alteration (warming and slowing of the Atlantic meridional overturning for example) and to natural variability (climate modes such as ENSO). These changes will cause net exchange of "natural" CO_2 between the ocean and atmosphere that is additional to the direct anthropogenic uptake due to rising atmospheric CO_2. We think that these additional variations may be quite large and may mostly account for the variability that observations indicate from decade to decade.

(5) The coastal and shelf seas are less uniform than the open ocean and more difficult therefore to generalize from limited measurements.

On time scales of centuries up to a million years, the partitioning between ocean and atmosphere that controls the concentration of atmospheric CO_2 between glacial and interglacial epochs is dominated by ocean processes. Ocean biology, especially as controlled by iron supply to the surface ocean, interacts in a complex way with circulation and climate to control this. Fifty years of research on this subject has meant that we know most of the processes that are important, but the role and relative importance of each is still a subject of controversy.

For the future, it is feasible and cost-effective to observe the CO_2 uptake by the ocean over large regions, and for some periods and regions (the north and equatorial Atlantic and Pacific in the 2000s for example) we have shown that we can do it well. However, lack of consistent funding and adequate international cooperation has meant that the great potential of these observations to constrain our knowledge of the global carbon cycle and the present carbon budget, has not so far been realized.

Andrew WATSON
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ARE THE FORCINGS AND FEEDBACKS KNOWN WITH THE DESIRABLE ACCURACY?

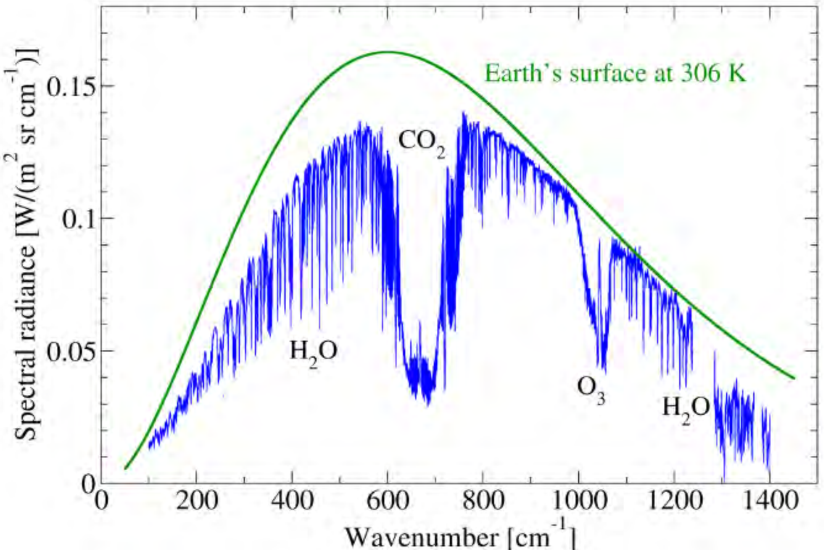
We have a good understanding of the forcings and feedbacks that have caused the observed climate warming, but small uncertainties in their quantifications have amplified effects in the projections of future climate. Therefore, the reliable determination of future risks and damages, required for cost-effective investments in mitigation and adaptation, requires a very accurate knowledge of these parameters, and further improvements are being considered with the help of space observations.

This is the case of two satellites of the European Space Agency (ESA), namely the CO_2 Monitoring (CO2M) mission (Sentinel 7 of the Copernicus Programme) and the Far-Infrared Outgoing Radiation Understanding and Monitoring (FORUM) mission (Explorer 9 of the Living Planet Programme). ESA has planned to launch these two satellites in about 5 years. The CO2M mission will provide a step-change in what is currently available for measuring carbon dioxide concentrations in the atmosphere, with significant improvements in precision and spatial and temporal resolution. Furthermore, simultaneous complementary observations of NO_2 and CO will make it possible to trace high-temperature burning and distinguish the anthropogenic carbon dioxide emissions, generated by fossil fuel, from those resulting from low-temperature natural sources.

The overarching objective is to provide the European and international communities with the appropriate means and capacity to assess the effectiveness of the 2015 Paris Agreement, verifying national emissions reports with independent data, and enabling individual countries to better understand their own carbon footprint at country and regional/megacity scales, and effectively aim at more ambitious targets.

Owing to the high spatial and temporal resolution of the measurements, with integration of information on carbon dioxide concentrations from in-situ networks of sensors, the CO2M mission has the potential to solve the full carbon cycle, including the contributions of fluxes from land-use change, forestry and geological emissions.

The CO2M mission will be a valuable source of information for climate modellers to tune



Spectrum of the radiance emitted by the Earth towards the space (blue curve) measured from a balloon at 34 km altitude by a prototype of the instrument that will fly on board of the Explorer 9 satellite. The green curve is the black body radiance of the surface. The difference between the two curves is the greenhouse effect. The main molecular species that cause this difference are marked in the figure (Palchetti et al. 2009).

climate models' representation of the carbon cycle and corresponding forcings.

The FORUM mission will measure, at high spectral resolution, the radiance emitted by the Earth towards space. This is the cooling component of the Earth energy budget, contributed by numerous physical processes responsible for driving and responding to climate change. Spectrally resolved observations of this radiance can disentangle the different components and improve our understanding of the underlying processes (Palchetti et al. 2020).

In the middle infrared, at wavenumbers greater than 667 cm^{-1}, we already have high-quality measurements of outgoing radiance, such as those provided by the IASI satellite for instance; yet, these measurements only cover about half the total cooling of the Earth. In the far infrared, at wavenumbers smaller than 667 cm^{-1}, satellite measurements of emitted outgoing radiance are scarce and low-quality.

The far infrared spectral emission is strongly influenced by upper-tropospheric–lower-stratospheric water vapour, temperature lapse rate, ice cloud distribution, and microphysics – i.e., all critical parameters in the climate system that are often linked to feedback processes and still poorly observed and understood.

The lack of comprehensive observations involves that current climate models must infer from indirect measurements the cooling effects of a spectral region that accounts for half the emitted energy. This observational gap will be overcome with the FORUM mission, which will measure the full spectrum of outgoing radiance from 100 to 1600 cm^{-1}. These measurements will have an unprecedented radiometric accuracy, ensuring that differences between observations and models are statistically significant and can be used to improve our knowledge of radiative transfer in the far infrared as well as the associated forcing and feedback mechanisms. Furthermore, such accuracy will provide the fundamental benchmark of global radiances at present times that will be necessary for future assessments of the occurred changes.

The two space missions will validate the quantification of forcings and feedbacks used by climate models and improve the quality of climate projections, enabling confident choices and better targeted investments.

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2 KNOWING THE PAST CLIMATE AND PREDICTING THE FUTURE CLIMATE

HOW CAN RECENT ADVANCES IN KNOWLEDGE OF PAST CLIMATE CHANGES IMPROVE SCENARIOS OF FUTURE CLIMATE AND ENVIRONMENTAL CHANGES?

In our past there is a lot of our future. With these simple words we can summarize the essence of paleoclimatology, the climate science branch aimed at studying the Earth's previous climates, over different geological ages up to recent times. Paleoclimatologists try to identify the causes of climate changes that occurred in the past, to better understand our present and future climates. As modern instrumental records do not cover most of Earth's climatic past, scientists must gather data preserved in nature over the millennia in environmental remains, referred to as proxy records or archives. One remarkable example is the wealth of fascinating information stored in ice cores from the polar regions. Ice cores are the only archives where one can directly probe the paleo-atmosphere, e.g., directly measure the CO_2 and CH_4 concentrations in air bubbles and simultaneously obtain information on the temperature when those bubbles were trapped, by looking at the isotopic composition of the oxygen and hydrogen that make up the frozen water. Ice core records can give insights into enigmatic periods of our recent climatic history, notably when abrupt climate changes occurred (e.g., during the ice ages), and temperatures increased by up to 10 °C within a few decades, triggering dramatic changes in environmental conditions.

Athough the abrupt climate change events have been studied thoroughly, an understandable explanation of their main causes and mechanisms is still lacking. Analysis of the paleoclimate archives and modelling simulations are performed to obtain these missing pieces of the puzzle. Understanding the causes and the mechanisms of the abrupt climate changes that occurred during the last glacial period is of crucial importance as we are now experiencing similar events due to global warming. Understanding how the Earth system works and how human actions can affect these functions is essential, if we are to provide necessary knowledge on the transition, we are now facing and on how to reduce the risks and impacts these changes pose on economic development. Furthermore, such understanding is essential as we should be able to manage the climate conditions that may appear as a response not only to large perturbations, but also to small perturbations heightened by feedback mechanisms.

In particular, past abrupt climate change events show that a small and gradual change in one of the climatic system components might result in large changes within the entire system. The relationship between global warming and abrupt climate change events lies in a short timescale. Present global warming, which covers increases in both surface air and sea surface temperatures, has been developing over the last 200 years. This is similar to the timescale of past abrupt climate change events. The main reason for the global warming phenomenon is the increase in greenhouse gases in the atmosphere. Although any changes resulting from the increase in greenhouse gas concentrations may take a few decades to occur, feedback mechanisms related to these changes might trigger more abrupt climate jumps. In order to be prepared for such abrupt changes, it is necessary to analyze past abrupt climate changes and understand their underlying reasons, mechanisms, and spatial and temporal scales.

This is our legacy to the future: to prevent the negative consequences of climate changes, we need improve our knowledge with scientific research and better comprehend how the Earth system functions and where its critical thresholds stand. Accordingly, we must fully understand the characteristics of past short-timescale abrupt climate changes, be prepared for a proper response, including adaptations, and understand what impacts such current changes might have in the future.

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WHICH MAIN IMPROVEMENTS HAVE WE ACHIEVED AND WHAT FURTHER IMPROVEMENTS CAN WE ENVISAGE IN OUR CAPABILITY OF PREDICTING CLIMATE?

In weather and climate science we need a hierarchy of models with different levels of complexity, to understand and quantify the predictability of our climate system (Hoskins 1983). Unlike in some other fields, few in the meteorological sciences believe that "one size fits all". In particular, idealised models with relatively few degrees of freedom can be important in assessing the relevance of certain mechanisms or processes. On the other hand, since the climate system is a high-dimensional chaotic system, there is no alternative to simulating this system as comprehensively as possible if one wants quantitative predictions. Herewith, I will give some examples where this synergy between elements of the hierarchy is important.

Some years ago, I wrote a paper (Palmer 1999) on regional climate change making use of the iconic three-component Lorenz model (Lorenz 1963). The key idea was that in a model with distinct nonlinear regime structure, which the Lorenz model certainly has, the response to some external forcing (such as associated with our carbon emissions) is very strongly determined by this regime structure, and less strongly determined by the precise details of the forcing itself. The paper was written to draw attention to the importance of nonlinear dynamics in determining the regional response to climate change.

On the other hand, if one is asked by government for a quantitative assessment of the manifestation of climate change on the weather patterns of one own's country, there is clearly little one can say from a three-component model of climate! Instead, one needs a comprehensive model of climate. Modern weather prediction models have more than a billion degrees of freedom and if one's projection of climate change is to include not only changes in the statistics of typical weather patterns but also of extreme weather patterns, then one needs to represent these billion or more degrees of freedom as accurately as possible.

However, it turns out that most contemporary climate models do a relatively poor job in simulating nonlinear circulation regimes – typically such regimes are under-persistent (Strommen and Palmer, 2019). An example is the Euro-Atlantic blocking anticyclone. CMIP5 climate models were woefully poor in simulating long-lived blocks and whilst the more recent CMIP6 models are better, they still under-simulate especially long-lived blocks of several weeks or more (Schiemann et al. 2020). According to the picture presented in Palmer (1999), this suggests that confidence in projections of regional climate change over the European-Atlantic sector are not especially high.

One of the interesting results from the Schiemann et al. study is that higher resolution climate models do a better job at simulating these weather regimes than lower resolution models. Why should this be? One reason is that Earth's topography is more accurately represented in higher resolution models and the dynamics of nonlinear circulation regimes depends critically on topographically forced Rossby waves (Charney and Devore 1979). However, there is a second reason, associated with the internal dynamics of the model and the fact that weather regimes such as blocking anticyclones are known to be maintained against dissipative effects by the injection of low potential vorticity associated with baroclinic processes (Shutts 1986) into a blocking anticyclone. This injection often occurs through highly filamentary structures known as warm conveyor belts (Grams 2018).

It appears that there is no alternative than to increase the resolution of climate models if we are to model the topographically forced waves, and the interactions between transient eddy activity and the larger-scale flow, accurately. For example, the parametrisation of topographically forced gravity waves will not be needed if we can increase the resolution of global climate models to about 1 km (Palmer and Stevens 2019). According to the nonlinear picture painted above, we will not have confidence in regional estimates of climate change until global models can reach these resolutions.

Indeed, an ability to predict future climate reliably is vital for a number of reasons: for predicting tipping points (vital for mitigation strategies), for determining adaptation strategies, for estimating the effects of geoengineering (vital for determining whether spraying aerosols in the stratosphere will have unintended consequences), and for early warnings on timescales of days, weeks and seasons (vital for making society more resilient to the changing nature of weather extremes).

Most individual nations will have neither the human nor the computational resources to develop global 1 km climate models. For this reason, I have campaigned for some time for an international "CERN for Climate Change" (Palmer 2011; see also Slingo et al. 2021). The equivalent of the LHC at such a centre would be an exascale supercomputer dedicated to climate. The EU's programme Destination Earth is a first step in this direction – providing funding to develop high-resolution "digital twins" of the climate system.

In short, understanding and predicting climate requires a hierarchy of models, for the idealised to the comprehensive. Interactions between members of the hierarchy is essential. We have some way to go before we can say we have a climate model that can pass the Climatic Turing Test – where we can't tell the difference between a digital twin and the real thing. Investments at the international level in the next few years could be critical.

Tim PALMER
University of Oxford and Accademia Nazionale dei Lincei

CAN WE PRESCRIBE GENERAL RULES FOR A METHODOLOGICALLY SOUND ASSESSMENT OF STATISTICAL UNCERTAINTY IN THE GENERAL CLIMATE DISCOURSE?

Statistical uncertainty is conventionally divided into *aleatory uncertainty*, or random variation, which arises from treating observed phenomena as one of many possible realizations from a stochastic system, and *epistemic uncertainty*, which quantifies what can be learned about that system from the available data. The use of stochastic models for the description of natural processes is based on Kolmogorov's axioms of probability and is largely uncontroversial. The two main approaches to epistemic uncertainty are *frequentist*, which compares the observed data with other datasets that might have been observed, and *Bayesian*, which uses Bayes' theorem to update prior uncertainty in light of observed data. There have been many major recent advances in computational methods for large-scale Bayesian inference, which is increasingly widely used in the enviromental sciences. Although Bayesian computation is often more straightforward, many applications require elements of both inferential approaches, often leading to inferences valid from both viewpoints.

Machine learning involves the fitting of complex predictive `black box' functions to data, but such functions incorporate known physical laws with difficulty, may be hard to interrogate when their outputs are surprising, and at best provide a naïve assessment of uncertainty. They may nevertheless have specific roles in climate simulation, such as representing processes that are too complex or too little understood to be modelled by more conventional means.

Climate simulators can be used to answer `what if?' questions about the past, present and future. They range from simple conceptual models designed to probe specific issues to massive numerical models intended to mimic the climate system. The latter are based on well-understood physical principles and are continually refined to incorporate improved understanding of climate processes and to better match observational data. However, they are subject to biases due to computational and modelling constraints and to data inadequacies, and ensembles of them are commonly run with differing parameter values and initial conditions in order to assess the effects of these variables on the output. Differing implementations of physical processes have led to a complex genealogy among climate simulators, which probably leads to underestimation of overall modelling uncertainty, despite the use of ensembles. Further uncertainty stems from a lack of knowledge of climate impacts, for example from valuing potential damage and from the consequences of interventions and their societal effects.

Although these uncertainties are daunting, Bayesian modelling can often be used in a principled way to combine simulator output ensembles and observational data. This leads to a clearer view of the overall uncertainties and of what further data and/or modelling is required to illuminate aspects that are insufficiently understood. Increased computational power and modern methods should lead to more realistic and detailed statistical modelling, leading to a more solid, principled assessment of overall climate uncertainty, though inevitably a system so delicate and complex as our habitat will reserve many unanticipated and unwelcome surprises.

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HOW WILL CLIMATE CHANGE AFFECT THE OCCURRENCE OF HURRICANES AND SEVERE CONVECTIVE STORMS?

Civilization is very highly adapted to the uniquely stable climate of the last 7,000 years, so much so that even relatively small climate change (in any direction) can be disruptive. As a practical matter, we are well adapted to potentially destructive events that occur at least once in one or two human generations, but poorly adapted to rare, highly destructive events. Large increases in damage and mortality can take place when previously rare, very intense events become commonplace. For this reason, one of the potentially most costly and deadly effects of climate change will be to increase the incidence of certain high impact weather hazards. Here we review what is known about how climate change might affect two such phenomena: Hurricanes and severe convective storms.

Since 1970, hurricanes have on average killed 15,000 people and caused $20 billion in damages annually. Although these storms are usually portrayed primarily as violent windstorms, almost all the loss of life and much of the damage is done by extensive floods caused by torrential rain and, on coastlines, by storm surges, tsunami-like phenomena driven by high winds and low pressure. Most of the damage and mortality are caused by the rare, very intense cyclones.

Hurricanes are thermodynamic heat engines, extracting heat from the ocean at high temperature, and rejecting it in the upper atmosphere, at low temperature. The theory of how such heat engines work is well developed and places an upper bound on how strong the storms can get in any given climate state. Although few storms reach this upper bound, the statistical distribution of wind speed over a large sample of storms, when normalized by this upper bound, yields a universal probability distribution. For this reason, we have some confidence that the intensity of hurricanes scales with this upper bound, which is straightforward to calculate from coarse-resolution climate data, including the output of climate models. Increases in greenhouse gases increase this upper bound, and such an increase has been measured. Very recent work has suggested that the proportion of high intensity hurricanes has risen in tandem with the bound.

On the other hand, we know comparatively little about what controls the frequency of hurricanes, with some models suggesting that the frequency may decline. This is considered an unresolved issue in hurricane science. Nevertheless, the increase in the bound suggests an increased incidence of the very strongest storms, which in practice do most of the damage and cause the largest storms surges. Surge levels will also go up because sea level itself is rising. The amount of rainfall produced by hurricanes is projected to increase greatly, because the concentration of water vapor rises exponentially with temperature. Together with projected increases in surge levels, climate scientists project with some confidence a steep increase in hurricane-induced flooding. We have developed highly detailed projections of hurricane 2 statistics, but these can vary greatly with the particular climate model used to drive the algorithms, reflecting the continued uncertainty in global climate projections.

Far less is known about the effect of climate change on severe convective storms, whose effects include tornadoes, lightning, hail and flash floods. Since 1970, these storms on annual average have killed 500 people and caused about $7 billion in damage globally. While lightning is fairly common, large damaging hail and tornadoes are rare and affect relatively small areas, so detecting them has been difficult. While some highly developed nations maintain networks of modern radar capable of detecting very heavy rain, hail and circulations associated with tornadoes, these phenomena can go largely undetected elsewhere.

Thus, there are virtually no records of these phenomena that are long enough and of high enough quality to detect trends. Moreover, the very small scale of severe convective storms renders them incapable of direct simulation by today's climate models.

Severe convective storms require certain key ingredients of their larger scale environment. These include large quantities of stored thermodynamic energy, called "Convective Available Potential Energy" (CAPE) and plentiful wind shear in the lower troposphere. Global climate models can quantify these environmental conditions, although the skill with which they do so has not been extensively examined. Most climate models produce an increase in CAPE but also an increase in the thermodynamic inhibition to deep convection, suggesting that there may be fewer but more violent convective storms. But research in this area is still in its infancy and much more work needs to be done to better quantify how the risk of severe convective storms may change with climate.

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3 CLIMATE CHANGE AND BIODIVERSITY

WILL CLIMATE CHANGE FOSTER INCREASING PATHOGEN SPILLOVERS, POSSIBLY TRIGGERING FURTHER PANDEMICS?

The question of the effects of climate change on potential pathogen outbreaks is a complicated one, and hence no simple answer is available. Host-pathogen relationships obviously involve differential effects on at least the two focal species, and this is complicated in the case of vectored diseases by the biology of the vectors. Less obvious, perhaps, is the importance of indirect effects that might be exacerbated by climate change, such as human migrations as well as changes in land use, for example involving agriculture, and the overall simplification of ecosystems. The latter are ongoing already, but climate change will have a strong influence on the patterns of change.

Even predicting the effects of climate change on respiratory diseases is tricky, as is evident from current uncertainties about the seasonal variations in COVID-19. For influenza, there certainly are clear seasonal effects, some due to the viability of the virus but some simply attributable to individuals, especially schoolchildren, spending more time indoors and in close contact as summer gives way to fall. Towers and colleagues (Towers et al. 2013) analyzed data on influenza epidemics in the U.S. over a period of about 15 years, and found that warm winters were followed usually by “severe epidemics with early onset”; the explanation, however, illustrates the complexity of the problem. In their analysis, they showed that warm winters lead to smaller numbers of infections, leaving larger pools of susceptibles for the following years. Thus, to make predictions as to what effects climate change will have on respiratory ailments, one needs to take into account not only the likely increase in mean temperatures, but also changes in the variance and in year-to-year correlations.

For vectored diseases, the effects are even more complex, as already mentioned. With increasing temperatures, host behaviors will change; for humans, this likely will mean more time outdoors in some regions accustomed to colder temperatures, but more time indoors in other regions where heat becomes oppressive. The viability of the pathogen will also be affected, complicating the estimation of the intrinsic rate of reproduction of the disease agent. Vectors are widely expected to undergo range shifts, hence the concern for increased spread of diseases like plague, cholera, malaria and dengue into new regions; but all is not so simple. Increasing temperatures, for example, may lead to increased biting rates by mosquitoes, but also to higher mortality of the vectors (Rohr et al. 2011). Rohr et al. go on to argue that many human parasites will go extinct in tropical regions because of their specialization on single vector species; and that the overall effects on disease prevalence are impossible to predict, even in terms of whether prevalence will increase or decrease. Harvell and colleagues (Harvell et al. 2002) conjecture that the greatest potential negative effects are likely to occur from a “relatively small number of emergent pathogens,” which will spread in populations with little or no experience with and resistance to those pathogens. That of course is what we are seeing with the current pandemic. They concluded, even nearly 20 years ago, that climate change would indeed lead to range expansion of pathogens, but again that other factors such as land-use changes (which as mentioned above could be triggered as well by climate change) were also factors.

The COVID-19 pandemic provides for us an immediate example of possible effects of climate change on disease spillovers. Rodó et al. (Rodó et al. 2021) argue convincingly that, as discussed above, the full transmission chain must be part of predictive and management models going forward, from the classical host-parasite interactions to changes in host behaviour. Especially relevant for human diseases, and widely ignored in models prior to the current pandemic, is the role of social norms as they affect mitigation measures such as mask-wearing, self-quarantining and vaccine hesitancy. Rodo et al. also emphasize the importance of indirect effects of climate change on spillovers from other animal hosts to humans, including such factors as land-use changes, and their effects on reducing biological diversity and increasing human contacts with wild and farm populations.

In summary, forecasting the effects of climate change on disease dynamics, including especially the potential for zoonoses, i.e., spillovers from other animal hosts to humans, is going to require a comprehensive modelling approach that integrates dynamics on multiple scales, from the immune systems of the hosts to the dynamics of pathogens and vectors and their interactions with hosts, to the direct and indirect effects of human behavioral responses to climate, disease and other factors.

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WHAT IF WILD ANIMALS CANNOT COPE? CAN WE MAP THE EXPECTED EXTINCTION PATTERNS? ARE THERE SYNERGIES WITH OTHER GLOBAL CHANGES?

At the Académie des Sciences, we have recently published a report on the alarming reduction in insect populations. It is indeed not only the populations of wild animals that have a huge patrimonial value, such as of big cats or great apes, which are being critically reduced, but also of many species whose populations have a major economic importance due to the Ecosystem Services they provide to humans. Among these are obviously the widely known services provided by pollinators, whose extinction would have catastrophic economic consequences. The many other ecosystem services provided by animals were widely reviewed in the scientific literature. Yet, while plant biodiversity has until now been widely used as source of biomedical innovation, a recent Nobel conference organized by the Karolinska Institut in Stockholm showed that wild animals may be also an important source of biomedical innovation. Many wild animals have already been found to possess particular mechanisms of great interest in fighting diseases, that so-called “standard laboratory animals” do not possess. Among these are for example the antibiotic molecules produced by insects, amphibians, mammals and birds, which are obviously of a major interest with the growing concern about the increasing antibiotic resistance in the treatment of human diseases. Another example is the efficient anti-cancer mechanisms of some mammals, such as mole rats or elephants.

An important question for future generations is therefore to what extent the ecological consequences of climate changes will jeopardize all these services provided by animal biodiversity to humans.

In this context, as shown a few years ago by the WWF for more than 80% of those wild animal species whose populations are greatly reduced, it is important to emphasize that most of the present reduction in animal biodiversity is not due to climate change. It essentially results from direct consequences of human activities: intensive agriculture, pesticides, insecticides, overfishing, urbanization, deforestation, draining of wetlands, animal disturbance… An additional concern today is an increasing speculation on agricultural land.

This means that climate change will have an aggravated impact on animal biodiversity, by superimposing its effects on wild animal populations already weakened by human activities. This superimposition also makes more difficult to identify the impact of climate change, an obvious prerequisite to predict and map possible extinction patterns according to climatic scenarios. Thus, in order to specifically identify the effects of climate changes on animal biodiversity, there should be a particular international scientific focus in those areas where the impact of human activities can be neglected. For example, for seabirds, both climate change and overfishing are similarly affecting, i.e. reducing, their marine resources. The drops in breeding success and survival of seabirds are therefore indicators of this reduction in resources. But it is then extremely difficult to separate the superimposing effects of overfishing and climate on seabirds in northern seas, whereas the impact of the sole effect of climate change on Antarctic seabirds can be easily assessed because the Antarctic region is still essentially untouched by overfishing. If the effects of climate changes on marine resources are clearly identified, such as the drop of these resources or a moving location, its impact on animal populations can be mapped and a possible extinction can be predicted from the observed change in the individual breeding success, survival and emigration or immigration. If we want to assess such changes, we obviously need to find ways of funding long-term scientific monitoring.

The case of Antarctic seabirds is obviously particular. For most other animal species, where climate changes and direct human effects are superimposing, it is obviously urgent to anticipate a critical impact of climate change by reducing the human-induced drop in their populations. Thus, there should be a priority for acting against those human direct actions on animal biodiversity listed above. Reducing urbanization or engineering the reconstruction of wetlands or other natural habitats is necessary but it will take time, so we need to find ways that will be quickly efficient. One of these is the reduction of animal disturbance, whose importance was illustrated in France last year by the rapid improvement in the breeding success of wild animals due to the lockdown induced by Covid-19. Reducing animal disturbance can be associated with the establishment of new ecological corridors and natural reserves. Concerning overfishing, while red tuna populations almost disappeared in the years 2000, their rapid recovery after an imposition of severe fishing quotas indicate that such a strategy may also be very efficient. For the recovery of insect populations, there is no choice other than the suppression of insecticides in agriculture. This means however that more efficient and less destructive strategies need to be developed, very likely inspired by the natural defenses of plants against their pests. As remarkably illustrated with the reintroduction of wolves in the Yellowstone Park, since an excess of cervids jeopardize forest regeneration, another efficient way to restore animal biodiversity may be the reintroduction of predators.

In conclusion, to anticipate a critical effect of climate changes on an already weakened animal biodiversity, a priority for future generations is to urgently allow its recovery.

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GIVEN THE INTERACTIONS BETWEEN BIODIVERSITY LOSS AND CLIMATE CHANGE, IS THERE A COMPETITION OR A SYNERGY BETWEEN THE INTERVENTIONS REQUIRED FOR THE MITIGATION OF THESE TWO PROBLEMS?

The biosphere is a tangled web of ecosystems operating at various speeds and spatial scales. Ecosystems are capital assets. They are also highly non-linear. Together, they supply vast numbers of regulating and maintenance services (soil regeneration, climate regulation, pollination, water filtration, nitrogen fixation, waste decomposition, and so on), which are complementary to one another. They are not independent of one another, and far less, substitutes of one another.

The human economy is embedded in the biosphere, it is not external to the biosphere. We depend on those services to produce food, clothing, shelter, transportation, and amenities. And yet many of Nature's serves are free in the marketplace, worse, negatively priced (global subsidies for Nature's goods and services amount to some 4-6 trillion US dollars annually). The Dasgupta Review on *The Economics of Biodiversity* (2021) notes that over the past 70 years humanity has been running down the biosphere at an unprecedented rate. To reverse direction, we need to act at all spatial and political scales.

As illustrations, we need at the local level to invest a lot more toward creating green spaces in urban areas – there are serious health benefits from doing that. At the national level, we must reduce environmental subsidies, which we could invest in Nature conservation and restoration projects. At the international level, we should create a transnational institution with the remit to manage the global commons such as the open seas (e.g. charging people for their use) and help to negotiate resource transfers to countries that house peatlands and the tropical rainforests (they are global public goods).

Crude calculations suggest that such a global institution could be self-supporting, perhaps it may even enjoy a surplus that could be used for development purposes. Separating climate regulation from the rest of the biosphere's services has been a most unfortunate feature of received climate economics.

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4 THE UNCERTAIN FUTURE OF COASTAL SETTINGS

FOR THE SECURITY OF COASTAL COMMUNITIES, TO WHAT EXTENT CAN WE TRUST THE AVAILABLE PROJECTIONS OF FUTURE SEA-LEVEL RISE?

Relative sea level (*rsl*) is measured[1] with respect to a land surface and is therefore a measurement of the relative displacements of the ocean and land surface. It is also the quantity that determines the impact of sea level on human activity in coastal environments. Neither the ocean nor land surface is static through time and hence sea-level change is the result of a combination of solid earth and oceanographic signals driven by geophysical[2] and climate processes that occurred in the past and that will occur in the future; some with long lag times that result in sea-level change long after the primary force ceased to exist. In addition, sea-level is affected by mostly short-period meteorological, tidal, and environmental factors and we define a mean (mostly annual) sea level to reduce their impact. Under a multitude of forces, the sea-level response is spatially variable and characterizing it by a single parameter, the global mean sea level rise or fall, is only one part of future projections.

Modelling of past and future sea level has at least five requirements: (1) a data base of past sea levels, globally distributed and extending back to the onset of the last Glacial Maximum; (2) an understanding of the geophysical contributions to land deformation; (3) climate effects on ocean volumes and circulation; (4) feedback between (2) and (3); and (5) an understanding of 'secondary' contributions to future global sea level. The dominant feedback is the isostatic response (glacial isostatic adjustment, *GIA*) of the planet's surface, gravity and rotation to the growth and decay of ice sheets since Late Pleistocene time, including any recent ice-load change. This is arguably the best understood and quantifiable component of sea-level change although dependent on a knowledge of the history of the ice sheets, one based on geological data, glaciological modelling and inversion results of sea-level observations from 'tectonically quiet' sites (aseismic; away from large subsiding deltas; last interglacial (*LIg*) shorelines within a few meters of present sea level).

Past sea levels have been dominated by glacial cycles with globally averaged changes of the order 120-150 m and other 'secondary' contributions (e.g. thermal expansion or contraction of the water column, changes in terrestrial water storage) were insignificant and well within the noise level of both observational *rsl* data and ice sheet knowledge. Within an interglacial period, the sea level fluctuations are much reduced: globally-averaged fluctuations have not exceeded ~20-25 cm during the past 5000 years (a limit determined by the geological data accuracy for this period) although locally larger fluctuations are sometimes reported. For recent decades, the role of these secondary effects is proportionately more important[3] (thermostatic ~1.3±0.4 mm/yr; Greenland and Antarctic ice loss ~0.4±0.1 mm/yr for each; mountain glacier mass loss ~0.6±0.1mm/yr; terrestrial water storage ~-0.3±0.2 mm/yr) with their total consistent with observed global *rsl* rise of ~2.8 mm/yr for the same period.

Mean rates are only one part of the answer and the spatial variability is of greater interest for coastal communities that cannot avoid tectonically active areas. The Italian Peninsula provides a good case study for assessing this, with land uplift attributed to the complex tectonic dynamics of a Mediterranean basin and subsidence through sediment loading within the river deltas and by ground-water and hydro-carbon extraction. Observational evidence for vertical land movements comes from different sources; direct measures of land displacement from *GPS* surveys for which the records are short (at most ~20 years) and seismic evidence representative of the past ~100 years, and from *GIA*-corrected *rsl* on longer time scales – Roman era *rsl* inferred from archaeological data and average geological *rsl* estimates for the post-glacial period (the last 6000 years) and back to the *LIg* period. Each record has its own characteristics and uncertainties of interpretation and, where estimates are available for different epochs, rates can actually differ in sign, indicative of cyclic tectonic displacements. Apart from such exceptions, for the Italian coast the patterns of uplift and subsidence for the different time scales are reasonably consistent, if not accurate in rate. Models of the present-day climate-driven spatial variability are equally uncertain in terms of rates, particularly that of the thermostatic component, uncertainties[4] that are compounded when extrapolated to a warming planet environment.

To summarize, a brief response to the question 'for the security of coastal communities, to what extent can we trust the available projections of future sea-level rise?' would be: *the science of sea-level projections is still in its infancy, resting on uncertainties of the observational data base of past change, on the limited understanding of the response of the different components of the Earth system (atmosphere – oceans – ice sheets – solid earth), individually and collectively, to the climate and tectonic forces that drive the change. But considerable progress has been made in the past decade, both on global and regional scales, that have sharpened the research and observational questions and we can have confidence in the general directions of the projections, albeit it with less confidence in their rates.*

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[1] With the exception of satellite altimetry measurement that measure the sea surface with respect to the satellite orbit, though that orbit is defined by observations from the earth's surface which itself is deformed by a variety of forces.

[2] By tectonic forces deforming the lithosphere, by mantle convection and by changes in surface loading of sediments and ice.

[3] For the altimetric period ~ 1993-2015, from Cazenave et al. 2018.

[4] For example, a comparison of 17 model predictions reveals considerable consistency in the pattern of variability that is consistent with the observed pattern for (1992-2002) but the rms of the individual models range from ~0.13 to 0.43 m (Yin et al. 2010).

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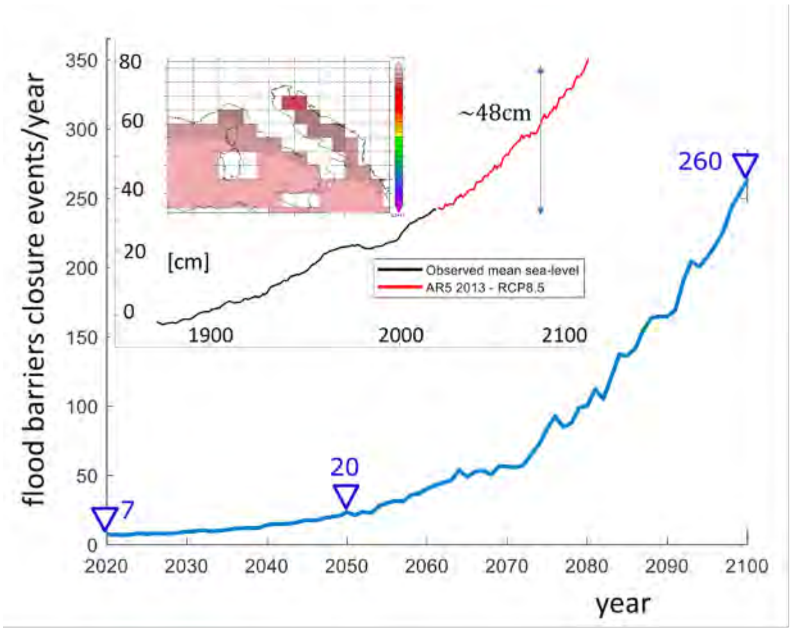
IS VENICE THE CENTRAL EPISODE OF THE CRISIS OF MODERNITY?

Venice's fate is still a case study of paramount importance. On the one hand, the intrinsic relevance of the at-risk cultural heritage inevitably commands global attention. On the other, the quantitative evaluation of the ecosystem services jeopardized by the effects of climate change proves complex in this context. The very notion of sustainability, which rests on the social worth of the entire set of capital assets of the Venetian economy (including the current natural capital), builds upon a long history of change and must not assume the biosphere to be external to the human economy (Dasgupta 2021). The lack of a characteristic reference state of the environment, however, weighs in: lagoons are unstable tidal landforms exposed to the vagaries of nature shaping temporary balances of production and transport of sediments. A benchmark natural capital does not exist, as the Venetian transition ecosystem has been radically changed through the centuries to suit the shifting models of the city's social and economic development, primarily for military purposes long gone by now. The lagoon would have disappeared hundreds of years ago, if left to spontaneous evolution, lost to fluvial silting up from inland sediments and to the typical cycles of relevant morphological processes, as occurred for hundreds of similar lagoons that once festooned the Northern Adriatic Sea. The history of Venice shows the interests of the built environment systematically prevailed over those of the natural environment, resulting in the ecosystem services we experience today. It now seems legitimate to pose a hierarchy-related question, namely whether history repeating could be sensible and broadly agreed upon lest modernity – e.g., the disintermediation spree – pitches in. André Chastel (1990) blended all this into the iconic definition of Venice as the central episode of the crisis of modern civilization.

The Venice case thus recapitulates a broad context faced by modernity. Sea-level regressions and transgressions have always shaped the cycles of the fortunes of coastal areas; only during the Anthropocene did we conceive resisting such evolutionary forces. Should we simply accept the notion that in the long run Venice will become one layer of a sedimentary deposit? Should we instead unleash today's nearly unlimited technological options in engineering the Earth and its risks? Whichever your instinctive answer, you cannot invoke some idyllic golden age of the past when nature was in equilibrium with man, for it never existed. Open, dissipative systems endowed with many degrees of freedom, like lagoons, deltas or alluvial plains, entail several possible equally-likely lagoons, quite different from one another and from the ones we see today. The single realization we have been left to observe is a rather artificial byproduct of decisive transformations operated by man: major fluvial diversions; massive littoral reinforcements and coastal defenses; vast alterations of the margins of the lagoon domain; cutting of channel heads, tidal meanders, salt quarries, closures and openings of tidal mouths; progressive reshaping of sea inlets replacing maintenance lest the sand bars impeded navigation at sea-lagoon interfaces; the dredging and maintenance of navigable channels suited to everchanging ships and vessels, among others (Rinaldo 2009).

My conclusion is that, due to the effects of climate change within this century, Venice and its lagoon cannot remain the ones we know. Extremes will not be of concern within that timespan, should proper maintenance be in place for the flood barriers built after a controversial debate lasted more than 50 years. Soon (2050-2100) sea-level rise will require further interventions aimed at rethinking the sea-lagoon interface and the lagoon domain(s). The time is now to set in motion a proper discourse, given modern Venice's track record in deciding and taking action. Scientists should act affirmatively in their sentinel responsibility to alert the society (Oreskes 2020), making the case of Venice a template for the global challenges posed by climate change ahead of us.



Mean of the projected regional mean sea level in the Adriatic Sea near Venice until 2100 (IPCC, 2013) (inset) and the related number of required annual closures of the existing tidal barriers under a reasonable set of assumptions (Caruso and Marani 2021). By 2100, a mean estimate hints at approximately about 48 cm of mean sea-level increase. Regardless of technical details, it is clear that within the next century Venice and its lagoon (including all the related ecosystem services) will not be the ones we see now. While the barriers – if maintained operational – will likely protect against exceptional storms even in the year 2100 (and their warranting flood security for nearly a century would need to be labelled as a success story), sea levels will soon require a substantial revision of the whole set of natural assets upon which the built and the natural environments of Venice rest. As the timespan for major actions historically cover some decades (notably when involving earth engineering, due to its intrinsic controversial character), we must act affirmatively now – in a context bound to become a template

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HOW WILL CLIMATE CHANGE IMPACT THE SUSTAINABLE DEVELOPMENT OF VENICE, A UNIQUE CULTURAL HERITAGE LOCATED IN A UNIQUE ECOSYSTEM?

Most of the impacts of climate change on human beings and Earth's ecosystems concern urban environments; on the other hand, cities and their environments contribute to the large majority of the world's GHG emissions, mainly because the large majority of the global energy generated is consumed in cities.

More than fifty per cent of the world population already lives in urban areas; predictions are that for the middle of the century it will rise to near three-quarters, meaning that urban environments will need to host three billion additional inhabitants by 2050.
Hence, impacts of climate change on urban environments are expected to increase in the next decades; and the way urban environments will be managed will have a crucial impact on mitigation and adaptation to climate change.

This will concern not only reducing emissions from major urban sectors (such as buildings, transport and waste management), but also contributing to making urban systems increasingly resilient to adverse climate impacts and risks of disasters. This is particularly difficult when the urban realities are locked in unsustainable development models and inappropriate policies have negatively impacted on the economy, society and cultural heritage.
More innovative and inclusive models are needed that should involve not only the public sector but also the private sector and community groups in society.

The relation between urban environments and climate change depends on the nature and history of these environments, differences clearly appearing once urban realities are considered in their relation with the surrounding ecosystems and cultural heritage.

The special case of Venice, a city not only located in a unique ecosystem but also characterized by a unique cultural heritage, is emblematic in showing the features of a project of a sustainable development dealing with the challenges of climate change. Such a project should, first, provide adequate protection from sea level rise in an urban environment located on coastal areas and from the loss of biodiversity protection in a wetland, such as the lagoon in which Venice is located.

Second, a low-carbon economic development of the city should be promoted, avoiding excessive specialization in unsustainable activities, such as unregulated tourism in Venice, and the consequent unsustainable social fragmentation.

Third, cultural heritage should be protected in physical buildings and artistic physical expressions damaged by climate change, and promotion of cultural and research institutions should crucially contribute to the low-carbon economic development.

Such a project should be implemented through an appropriate governance framework involving the public sector, the private sector, and different community groups.

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ARE CLEAN ENERGY TECHNOLOGIES ON TRACK?

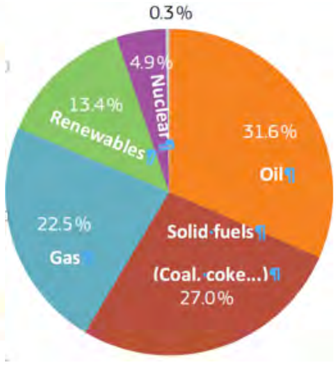
Any attempt at reducing carbon dioxide emissions associated with energy production must account for the following obvious identity:

$$Emission = (Energy)\ (Emission/Energy)$$

As long as world energy consumption continues to increase, reducing the last term on the right-hand side of the latter expression is what we actually need. As the modern industrial economy is based on oil, it is not surprising that its main activity, combustion, is releasing billions of tons of carbon dioxide per year into the atmosphere (Carrà 2020). Hence, efforts must be focused on improving present technologies and seeking new ones characterized by reduced GHG-emissions-per-unit energy. Renewable resources, notably photovoltaic (PV) cells and wind turbines, do satisfy the latter requirement, yet at a major price. The scale of the necessary transition would involve enormous infrastructural changes, owing to the low power densities of energy flows in PV cells and the stochastic nature of wind. Despite considerable efforts and generous governmental subsidies, the contribution of both renewable sources currently accounts for less than 8% of the electric energy (2% of total energy) generated worldwide. Over 64% of the world's electric energy still comes from fossil fuels (Fig. 1).

(TWh/y)

	2000	2005	2010	2015	2017	2018
Solid Fuels	5994	7317	8662	9534	9860	10160
Petroleum and Products	1184	1129	970	1028	846	784
Gas	2775	3706	4842	5526	5889	6150
Renewables	2829	3296	4203	5522	6268	6700
Hydro	2613	2935	3448	3894	4071	4214
Solar/Wind/Other	54	140	408	1126	1622	1871
Biofuels and Waste	163	228	367	517	598	637
Geothermal	52	58	68	81	85	89
Nuclear	2591	2768	2756	2570	2636	2710
Other	54	67	90	100	112	115
Total	**15427**	**18283**	**21524**	**24280**	**25612**	**26619**



Evolution of electric energy production (in TWh/y) from different sources (IEA statistics, August 2020).

The actual question is then: is it feasible to achieve the net-zero goal by relying mainly on renewables? Several reasons underlie my skepticism.

The first bottleneck is in the intermittent nature of both PV and wind energies. Unless their deployment is complemented with further energy production based on nonintermittent sources, the need for massive storage of electric energy arises. And in spite of considerable technological progress in the field of batteries and renewed efforts to revive hydrogen, storage remains a major issue far from being satisfactorily settled. Secondly, as stated, renewables are diluted. Customarily, electricity is produced in large plants and distributed, without large losses, through shared grids with short accumulation times. Massive deployment of renewables would require equally massive networks of transmission lines, impacting on land use and environment. Amazingly, the 'green' movements do not seem to realize how severe such an impact will be for agriculture, avifauna and cultural inheritance of densely populated areas.

Thirdly, the construction of PV cells and wind turbines is critically dependent on availability of raw materials, whose consumption is expected to increase drastically in the coming decades. Several countries, most notably EU, are heavily dependent on imports for several raw materials and exposed to vulnerabilities in material supply. The most significant example concerns rare earths (e.g., dysprosium, neodymium, praseodymium and terbium) used in permanent magnet-based wind turbines. Estimates (Carrara et al. 2020) suggest that, in the most severe scenario, the EU annual demand for these rare earths can increase by 6 times by 2030 and by up to 15 times by 2050 versus 2018 values. In other words, by 2050 the deployment of wind turbines according to EU decarbonisation goals will alone require most of the rare earths currently available to the EU market!

Fourthly, the massive deployment of renewables will lead to a massive production of waste materials, some of which contain toxic substances. As known for some time (Öhrlund 2011), "…for most of the metals that are used in advanced and emerging technologies, recycling schemes are not in place and recycling rates are poor...".

Last, but not least, it is hard to expect significant technological improvements on solar technologies. The discovery of the photoelectric effect dates back to 1839 (Becquerel), and the perspectives of its large-scale application boosted extensive research, which focused on polycrystalline and amorphous silicon but also explored the potential exploitability of other materials and molecular systems of various natures. The semiconductor p-n junctions theoretical model by Shockley and Queisser (1961) predicted an upper limit of performance for silicon equal to 31%, a kind of Carnot theorem for solar cells. The perspective of improving the yield by taking advantage of the presence of multiple junctions and quantum dots in silicon, or by employing organic materials, has also proven inconclusive. Therefore, most modern photovoltaic cells are still made of crystalline silicon. Their efficiency, expressed as the fraction of incident power converted to electricity, is around 0.20 – quite a satisfactory value when compared with the theoretical limit of 0.31.

Therefore, are clean energy technologies on track? Based on the above evidence, one must fully share the conclusions by Clack et al. (2017): "Policy makers should treat with caution any visions of a rapid, reliable, and low-cost transition to entire energy systems that relies almost exclusively on wind, solar, and hydroelectric power". This negative statement, however, must be viewed in light of the results of a recent, admittedly complex, exercise of predicting the values of concentration of carbon dioxide and temperature resulting from different scenarios depending on different political, economic and technological choices: the best scenario (CO_2 concentration at 340 ppm; rise in temp: 0.4 °C) turned out to be the path that includes the contribution of nuclear power (The Economist 2020). This leads to my conclusion: gradually eliminating fossil fuels requires the contributions of renewable sources and nuclear fission, waiting for the forthcoming availability of biofuels obtained through synthetic biology. We are fully aware of the resistance to this inconvenient truth in some rich countries. However, it is a duty of the scientific community to warn that the actual alternative for humanity lies in having to choose either the incommensurable risks of uncontrolled climate change or the need to overcome emotional and ideological reluctance to accepting the deployment of increasingly safer fourth-generation nuclear plants. A further inconvenient truth.

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IS ENERGY TRANSITION TO POST-FOSSIL ACHIEVABLE WITHIN THE PARIS AGREEMENT TIMEFRAME?

Any reflection on how to tackle climate change must start from recalling the essential role energy has always played for the progress of nations; for the well-being of populations; for billions of human beings to exit poverty; for future generations. Reducing the carbon footprint is a must; yet, ensuring the widest accessibility and security of energy is not less important. Hence, the two leading challenges the world must pursue are: on the one hand, ensuring to the whole humanity the needed quantities and qualities of energy, primarily for those who still have no access thereto; and, on the other hand, reducing the resulting flows of greenhouse gas emissions, hence their concentration in the atmosphere. In December 2015, almost all the States around the globe agreed to include the latter priority in the Paris Agreement, pledging to limit, versus pre-industrial levels, the increase in global warming to 2 °C and possibly to 1.5 °C, as recommended by the Intergovernmental Panel on Climate Change (IPCC), namely the United Nations body for assessing the science related to climate change. More recently, a large number of States, starting with the 27 members of the European Union, have shared the goal of achieving full carbon neutrality by mid-century. Nevertheless, the course of events has not been in line with the commitments undertaken. Emissions linked to energy use, instead of decreasing, have continued to grow (net of the unfortunate outcomes of the Covid-19 pandemic).

Whether this gap between ambitions and actions is due – as claimed by William Nordhaus, Nobel Prize in Economics – either to the impossibility of reaching the Paris goal or to the inadequacy of the instruments put in place by politics is highly controversial. The strategy identified as successful consists in initiating a new ‘energy transition’ in the supply structure: shifting from the current dominance (80%) of fossil fuels to low carbon technologies associated with a drastic reduction of energy-use intensity (energy/output). However, these technologies are at a predominantly embryonic stage – just a quarter of them are able to contribute to the carbon neutrality goal; as such, employing them in commercial terms will take a very long time. The barycentric role of supply in energy policies has led to neglecting the relevance of parallel actions on the demand side and, in particular, of individual behaviors estimated to be responsible for up to two thirds of global emissions. Instead, mitigating global warming would require drastic behavioral changes from billions of persons. Being the main cause of this phenomenon, they must be part of its solution. Energy transitions have marked the course of history. Analysing their succession means going through the cycles of human civilization in terms of ways of life, economic organization, social structure. Such transitions are, by their nature, multi-dimensional and co-evolutionary processes, which require and generate radical changes in the configurations of economic systems; they are driven by ‘disruptive innovations’ of prime engines – starting, looking at the last few centuries, with the steam engine – which undermined the then-dominant source in each historical phase.

Technology and the market were the great drivers of transitions. The question to be posed is whether the new path toward a low-carbon economy involves the virtuous circuit that marked past transitions. Indeed, the new ‘energy transition’ is driven not by technological *breakthroughs* and market convenience, rather by the policy will to achieve environmental aims that markets would not be able to pursue inertially. To understand the complexity of this transition, it is necessary to be aware of the great changes and immense economic resources required to transform both energy and economic systems in terms of their *tangible* and *intangible* components.

Regarding tangible elements (technologies, infrastructures, plants), energy transition requires a total reconversion of the existing capital stock; regarding intangible ones such as behaviors, energy transition requires changing investment, production, and consumption models, as well as lifestyles for the wide range of actors involved. A global energy transition is a highly complex and uncertain process in its dynamics, and the *time factor* is decisive for containing the impact of climate change. I fear it is illusory to argue that a global energy transition can be fully and easily achieved within a few decades – i.e., attaining full carbon neutrality by 2050 – based on the complexity of the problems to be addressed and on what history has so far taught us. In energy, more than in other fields, *history matters* in order not to reject the need for a sought-after revolution, rather – and quite the opposite – to be fully aware of its implementation. From the past replacement cycles of sources, it is possible to seize time constants, both on the supply and demand sides, which do not allow, except within very long and unpredictable time, overcoming the *path dependence* of energy systems, which is a legacy of past technological paradigms.

Several studies show that the hypothetical timespan for a new energy source to become dominant can take up to a century. This is what coal took to undermine wood, which was still the dominant energy source in the mid-nineteenth century. Similarly, oil took a century to dethrone coal in the aftermath of World War II, while natural gas took ninety years to rise to a fifth of consumption. It will be very difficult for new renewables to become dominant in a much shorter time. Although necessary, they cannot be the only instruments to pursue a decarbonized energy system. Three alternatives are laid down as follows.

First: On the supply side, widening the use of all technological opportunities across the market that can carry on the transition, both ensuring the security of supply and affordable energy prices. In particular: carbon capture and storage, new generation nuclear power, hydrogen from renewable resources and natural gas, direct air capture, and other technologies placing them on a level of neutrality in policy choices, and not of contrast with one another on the grounds, at times, of ideological connotations.

Second: On the demand side, intervening on individual behaviors to steer them towards more attentive use of energy. A revolution that would require a profound change in our lifestyles and related system of values. The 'energy transition', in essence, is not just a question of money, technologies, and infrastructures; it is also a 'cultural transition' of the values that shape our daily behaviors and habits: those that have led to endangering nature cannot be the values that can save it.

Third: Global warming is by its nature a global issue, as the benefits of actions undertaken in individual States are felt worldwide, while their costs are local. Hence closer and more effective international cooperation is required to make the fight against climate change successful.

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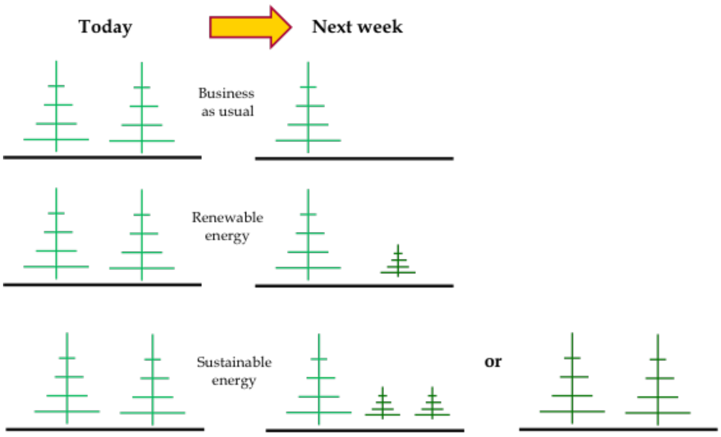
CAN NEGATIVE EMISSION TECHNOLOGIES CONTRIBUTE TO THE OBJECTIVES OF THE PARIS AGREEMENT WITH A SIGNIFICANT REDUCTION OF ATMOSPHERIC CO_2 CONCENTRATION?

Negative emission technologies (NETs) have been identified by the IPCC as essential for achieving the Paris goals. A problematic detail is that there is quite some doubt about the *de facto* existence of NETs, as was pointed out in an EASAC report (EASAC policy report 35, February 2018). Especially for bioenergy integrated with carbon capture and storage (BECCS), the level of development and the speed of implementation are low and do not seem to progress towards what is expected. Not only is the deployment of CCS disappointing while its business case depends on either large government subsidies or extraction of fossil carbon fuels via enhanced oil or gas recovery (EOR/EGR), but also the availability of biomass-derived fuels competes with food production, drinking water availability and land use. A grim picture then for the wide deployment of BECCS.

Overall, the science behind NETs is often inconclusive and leaves room for (short term business) trends in a direction away from the Paris agreement. Much depends on what facts or alternative facts are used as political instruments.



Bussiness-as-usual versus renewable versus sustainable biofuel use (from: Zevenhoven 2021).

Increasingly, carbon capture and utilization (CCU) is entering political discussion and the CO_2-producing business sectors, but there it is found that markets for so-called CO_2-neutral products are very limited, that the time until the converted CO_2 is released to the atmosphere is short and/or costs too high unless, again, significant subsidies are made available. The general picture is that for a significant change in business and consumer practice, strong support of international and national governments is necessary while new markets for CCU products are identified and developed.

And then there is another dilemma. In the free world of democratic societies with free markets driven by cheap energy it is very difficult to come to a long-term political consensus that can motivate the large capital investment required for a drastic change. In less democratically steered as well as many developing countries the motivation or simply the finances needed for a change are absent.

Unfortunately, climate change and global warming result in natural disasters and poverty and other social challenges for many people, which has put the fulfilment of the 17 Sustainable Development Goals of the UN by 2030 on a crash course with the Paris agreement as a result of lack of commitment and powerful action. Equally problematic is the development of so-called green trends that worsen the situation rather than lead to a more sustainable future for humans and nature: one example is the production of green versus blue versus grey hydrogen or the production of "renewable" fuel from hydrogen and fossil-derived carbon. Besides such technology-driven "greenwashing" there is of course the "clever accounting and creative PR" identified by G Thunberg, making the bad sound good, for the business-as-usual time being.

To finish: it remains to be shown by the response of the climate system whether NET is what it seems to promise. The biggest challenge will be to identify changes for the better as well as coming to consensus on that.

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WHAT IS THE STATE OF BIOFUEL SYNTHESIS USING THE METABOLIC ENGINEERING OF BACTERIA?

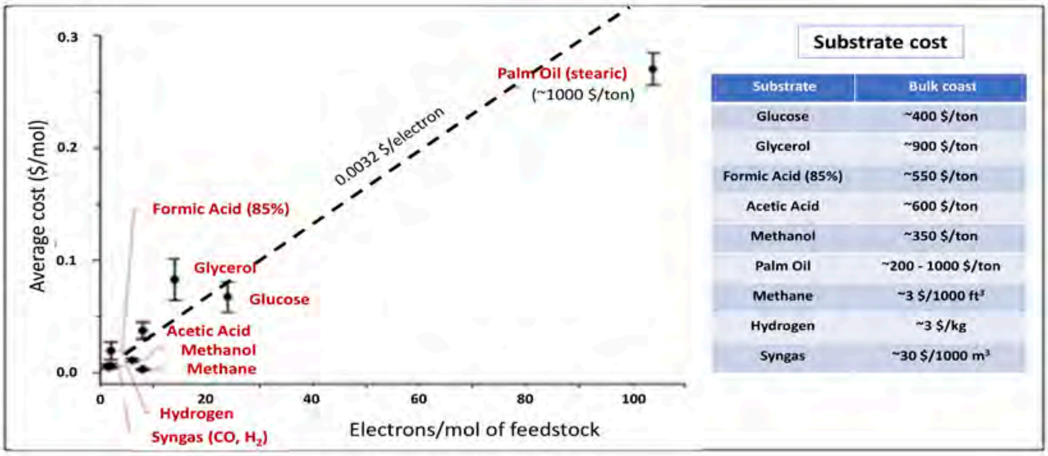
Forces of change. A confluence of factors is forcing us to reevaluate the way we think about resource utilization and supply of energy. Despite current lower energy prices, the cost of energy over the past 150 years has been steadily increasing, its sources are becoming less accessible, strategic concerns about its steady supply are rising, and, most importantly, concerns about climate change are mounting. We may have temporarily pushed aside concerns about adequate supply of fossil fuels but we are clearly running out of space to store the products of fossil fuel combustion within a thin sliver of atmosphere surrounding planet Earth. These concerns necessitate that we consider alternative, more sustainable sources of energy and in particular fuels.

Biofuels and Biotechnology. Although typically biofuels refer to ethanol produced from crops like corn and sugar cane, the term is broader and includes fuels produced from renewable biomass feedstocks or through the use of biocatalysts and biological processes. As such, fuels other than ethanol (such as oils, higher or branched alcohols, fatty acid methyl esters, isoprenoids) produced from sugars or other renewable sources, should also be considered as biofuels. More importantly, considering that all fuels derive their energy from combustion of free electrons, fuels derived by converting free electron carriers via biotechnological methods would also be biofuels. This is important as modern biotechnology is a powerful technology for converting renewable resources to desirable forms of energy (such as liquid fuels for aviation and the trucking and shipping industries), and at higher yields and productivities relatively to chemical methods. As such, biotechnology is a key technology for developing sustainable liquid fuels for transportation.

Biotechnology and lignocellulosics. The primary focus of biofuels research over the past 60 years has been production of bioethanol from renewable biomass feedstocks, such as agricultural residues, energy crops, forest products and other plant matter. This can be a plentiful source of fuels with estimates of available biomass in the US approaching 1.4 billion tons per year. As this amount would be sufficient to provide between 30-40% of the US needs of liquid fuels, the challenge of developing cost effective processes for converting this biomass to bioethanol and other fuels has attracted strong interest and large investments. Yet, despite significant efforts during this period and at all levels (fundamental studies, technology development, subsidies for plant construction, biofuel price supports) presently there are only one or two cellulosic ethanol plants operating in the world and these at partial capacity. This falls way short of the more than 15 billion gallons/year of bioethanol projected to be produced this year from lignocellulosic sources when the Renewable Fuel Standard (RFS) was instituted in the US about 15 years ago. So, the question naturally arises, *can biotechnology deliver cost effective fuels for transportation with reduced carbon footprint?*

A different approach: converting gases to biofuels. We mentioned earlier that a fuel derives its energy from the combustion of its free electrons. It is then natural to ask what is the cost of free electrons? The figure below plots the price of various fuels per mole as function of the electron-moles per mole of the corresponding fuel. It is quite remarkable that diverse fuels produced by different technologies, from diverse feedstocks of widely varying costs and over extended periods of time seem to follow a pattern valuing the cost of free electrons at 0.32 cents/electron mole. Furthermore, this plot provides a basis for comparing the potential of hydrogen as fuel feedstock to, for example, carbohydrates. The plot suggests that hydrogen at \$3/kg would be equivalent to carbohydrates like sugars at \$400/ton or ~18 cents/lb. Put differently, if renewable hydrogen becomes available at a third of this price or \$1/kg, this would be equivalent to a sugar cost of 6 cents/lb. We note that a 10 cents/lb sugar from hydrolysates of lignocellulosic biomass has been the holy grail of numerous DOE programs, which has not been achieved after more than 60 years of research and billions of dollars of R&D investment. On the other hand, hydrogen cost is near \$1/kg from reforming of natural gas (NAS 2004) and this figure is within reach by splitting water with continuous declining photovoltaic electricity, if one excludes the costs of transportation and storage.

During the past 15 years we have been exploring the concept of biological, non-photosynthetic CO_2 fixation using H_2 or CO as reducing gases and conversion of the products to liquid fuels such as oils and alka(e)nes.



Substrate cost

Substrate	Bulk coast
Glucose	~400 $/ton
Glycerol	~900 $/ton
Formic Acid (85%)	~550 $/ton
Acetic Acid	~600 $/ton
Methanol	~350 $/ton
Palm Oil	~200 - 1000 $/ton
Methane	~3 $/1000 ft^3
Hydrogen	~3 $/kg
Syngas	~30 $/1000 m^3

The process comprises a two-stage system whereby CO2 is fixed anaerobically in the first stage by the acetogen Moorella thermoacetica to produce acetic acid, which is converted to oils or alka(e)nes by an engineered oleaginous yeast Yarrowia lipolytica in an aerobic sec- ond stage. In a series of publications (Hu et al. 2016, Sonawane et al. 2016, Lin et al. 2018, Park et al. 2019, Qiao et al. 2017) we have demonstrated that the fixation of CO2 can take place at rates comparable to ethanol production by yeast and the CO2 fixation product can be converted to oils at almost theoretical yields. These figures of merit are best ever report- ed and support the concept of liquid fuel production at scale if sufficient amounts of CO2 can be sourced and renewable hydrogen is available at approximately $1-2/kg. As the fixed CO2 will be released back to the atmosphere upon combustion of the fuel, the process is a scheme for converting hydrogen electrons to liquid fuels or converting hydrogen energy to a chemical form of energy that can be stored and accessed on demand. Additional advan- tages of this scheme are that. (a) the process produces heavy fuels for transportation used in trucking, shipping and aviation, (b) the process is scalable as the main feedstocks required can be sourced at scale, (c) the above high-level calculation suggests a cost-competitive process, (d) the process is not coupled to land use, and (e) our results to-date provide opti- mism about the deployment of the components of this technology for production of liquid fuels at scale.

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ARE THE UNCERTAINTIES OF SCIENTIFIC PROJECTIONS OR THE NATIONAL POLITICAL INTERESTS THE GREATEST OBSTACLE TO AN AGREEABLE PRICING OF ENERGY EXTERNALITIES?

Uncertainties abound. That much is clear. But it is equally clear that the greatest obstacle to price climate and energy externalities is political rather than the underlying science.

To take one national example. The formal "interim" U.S. social cost of carbon, for one tonne of carbon dioxide emitted in 2020, in 2020 dollars, is around $50. The US government also presents an "upper bound" of sorts, technically the 95th percentile of the social cost distribution, attempting to account for risks and certainties. Its value: $150. There are good reasons to believe that the $50 estimate will more than double to at least $100 in the Biden administration's revisiting of the social cost (Wagner 2021; Wagner et al. 2021). A simple calculation would, thus, also lead the $150 upper-bound value to more than double to at least $300.

The difference between $100 and $300 is uncertainty, the difference between $0 and either $100 or $300 is politics.

More specifically, the United States shows how it is significantly more difficult to get from

$0 to $100 per tonne of carbon dioxide than from $100 to $300. The difficulty is in getting started and overcome significant opposition by vested interests. None of that, of course, is new. Niccolò Machiavelli said as much in Il Principe, in 1532: Nothing was more difficult "than to take the lead in the introduction of a new order of things. Because the innovator has for enemies all those who have done well under the old conditions, and lukewarm defenders in those who may do well under the new." (Machiavelli 1532). In other words: politics. None of that, in turn, means that uncertainties are not important. They are. There is, for example, no single correct social cost for each tonne of carbon dioxide or other greenhouse gases emitted. There is a wide distribution of possible numbers. That, too, complicates the politics.

For example, while the United States do not have a national carbon price or anything close to it, thirty of its fifty states plus Washington, D.C., have renewable portfolio standards to set renewable quantity targets in the power sector (Shields 2021). Roughly half of the total growth of renewable electricity generation since 2000 is due to them (Barbose 2018). They also come at a price: roughly between $60 and $300 per tonne of avoided carbon dioxide emissions (Greenstone, Nath 2020). It would be too tempting to look at that range, compare them to the current $50 estimate, and dismiss them as too expensive. That step would clearly be inappropriate, precisely because of the large uncertainties around the true social cost of carbon, where even $300 appears to be well within the range of possible values.

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6 CONCLUSIONS: OUR MESSAGES TO COP26

THE NEED TO IMPROVE CLIMATE MODELLING

It is well established that understanding and predicting climate requires a hierarchy of models. Assessing the relevance of specific physical mechanisms may benefit from idealised models with relatively few degrees of freedom; yet, reliable quantitative predictions of future climate would require global climate models with approximately 1-km resolution to fully account for the nonlinear high-dimensional nature of the system and reduce the need for semi-empirical parameterizations (***Palmer***). We are not there yet; hence most contemporary climate models do a relatively poor job in simulating nonlinear circulation regimes, thus limiting the reliability of regional climate-change projections. More importantly, the overwhelming threat of the possible, anthropogenically driven, occurrence of tipping points in the climate system (e.g., melting of the Greenland ice sheet, collapse of the Atlantic Ocean circulation, or methane release from Arctic permafrost) cannot be reliably predicted (***Stocker***). Such threat is aggravated by the fact that abrupt climate change events observed in ice core records show that a small and gradual change in one of the climatic system components has in the past caused large changes in the entire system (***Barbante***). On a different topic, Bayesian modelling can help combine the output of ensembles of simulations with observational data (***Davison***), shedding light on the overall uncertainties and possibly suggesting the need for further data and/or modelling to make progress. Modelling limitations entail several further consequences. Projections of hurricane statistics vary greatly depending on the specific climate model used, and severe convective storms (tornadoes, lightning, flash floods and hail) have such a fine scale that analyzing their responses to climate change is hardly possible with present climate models (***Emanuel***).

The First Message

An International Centre for Climate Change Modelling, equipped with an exascale supercomputer dedicated to climate research, is urgently needed, in analogy with international research enterprises of similar scale in other fields.

FORCINGS AND FEEDBACKS

In general, available knowledge of forcing effects acting on the climate system is sufficiently accurate. In particular, data on solar irradiance have adequate precision and results available since 1978 indicate variations of the order of 1‰ on timescales of the solar activity cycle, i.e., roughly 11 years. Although there is no consensus on the magnitude of the change in solar irradiance during past centuries, comparison between solar irradiance variations and average Earth temperature variations throughout the last century strongly suggests that solar effects are likely small (***Solanki***). In other words, *it is highly unlikely that the Sun has made any significant contribution to global warming in the last half century.*

Less satisfactory is our knowledge of the feedback mechanisms that are responsible for abrupt *climate changes and the occurrence of tipping points.* This shortcoming is directly connected with our incomplete capability of observing the outgoing radiance that controls cooling of the Earth. Major progress is expected with the FORUM space mission, which will perform complete spectrally-resolved observations of this radiance with a full spectral coverage that can disentangle the different physical processes that contribute to the cooling component of the Earth energy budget and improve our understanding of feedback amplitude (***Carli***).

The Second Message

The outgoing radiance and its spectral structure is a direct measure of the cooling processes that control the energy budget of our planet; models should now simulate this quantity and use the forthcoming measurements for more stringent verification of their assumptions.

CARBON CYCLE

A major role in the *carbon cycl*e, a process still inadequately understood, is played by the ocean-atmosphere exchange of CO_2. Although we are fairly confident that the oceans have acted as net sinks for roughly 25-30% of anthropogenic emissions of CO_2 in recent decades, the issue of achieving accurate time-resolved estimates of the global ocean-atmosphere CO_2 flux is hardly settled. On one hand, the reconstructions from observational data, notably sparse before the 1990s, are not fully reliable the further back in time we go. On the other hand, their interpretation by current ocean models suffers from substantial uncertainties, due both to gaps and approximations in the theory involved and to imperfect coverage of observations (***Watson***).

A major role is also played by the availability of accurate measurements of CO_2 concentration in the atmosphere. An improvement in this direction will likely be achieved through the forthcoming CO2M space mission. This has been designed to perform measurements with high spatial and temporal resolution that will allow us to distinguish anthropogenic contributions from those originating from low temperature natural sources. With the further help of data from in-situ networks of sensors, various steps of the carbon cycle, including the contributions of fluxes from land-use, land-use change, forestry and geological emissions, may be better understood, providing valuable inputs to tune the representation of the carbon cycle in the framework of climate models (***Carli***).

The Third Message

Consistent funding and adequate international cooperation are needed to extend observations of CO_2 uptake by the ocean over large regions, which recent efforts have shown to be feasible and cost-effective.

CLIMATE CHANGE, HEALTH AND BIODIVERSITY

Forecasting the *effects of climate change on disease dynamics*, primarily including the potential for zoonoses, is an open research issue. It will require a comprehensive multiple-scale modelling approach, integrating the immune systems of hosts, the dynamics of pathogens and vectors, and their interactions with hosts up to, at a larger scale, the direct and indirect effects of human behavioral responses to climate, disease and other factors (***Levin***).

An important question for future generations is to what extent the ecological consequences of climate change will jeopardize the major services provided by animal biodiversity to humans. This is a difficult question, as most of the present reduction in animal biodiversity is not due to climate change; rather, it is a direct consequence of human activities (intensive agriculture, pesticides, insecticides, overfishing, urbanization, deforestation, draining of wetlands, animal disturbance, etc.). Identifying the specific effects of climate change will require an international scientific focus in those areas where the impact of human activities may be neglected. In the meantime, it is urgent to anticipate a critical impact of climate change on already weakened animal biodiversity, by promoting actions that enable its rapid recovery (e.g., creating new ecological corridors and natural reserves, imposing fishing quotas, suppressing insecticides in agriculture, reintroducing predators) (***Le Maho***).

Although the human economy is embedded in the biosphere, plenty of Nature's services are either free in the marketplace or, even worse, negatively priced. The Dasgupta Review on *The Economics of Biodiversity* notes that ecosystems are capital assets and suggests a variety of actions at all spatial and political scales (see the Fourth Message below) such to reverse the current practice whereby, over the past 70 years, humanity has been running down the biosphere at an unprecedented rate (***Dasgupta***).

The Fourth Message

Following one of the suggestions set forth in the Dasgupta Review, a transnational institution must be created with the remit to manage the global commons, such as the biosphere, the oceans and the atmosphere, and help negotiate resource transfers to countries that implement protective policies for such global public goods.

THE UNCERTAIN FUTURE OF COASTAL SETTINGS

The science of sea-level projections is still in its infancy. It rests on uncertainties of the observational data base of past changes and on the limited understanding of the responses provided by the several components of the Earth system (atmosphere, oceans, ice sheets, solid Earth) to the climate and tectonic forcing. This notwithstanding, the considerable progress made in the past decade suggests we can have confidence in the general directions of projections, albeit with lower confidence in their rates (***Lambeck***).

This conclusion encourages giving reasonable credit to mean estimates of an approximately 48-cm mean sea-level increase in Venice in 2100, which lead to an inconvenient truth:

within the next century, Venice and its lagoon will not be the ones we see now. While the barriers – if maintained operational – will likely protect against exceptional storms even in 2100, sea levels will soon require a substantial revision of the whole set of natural assets underlying Venice's built and natural environments. This forecast calls for immediate action to plan adaptive measures, which will likely require a few decades to be agreed upon and accepted within a highly conflicting environment such as Venice. Successful choices will likely make Venice a template for the fate of coastal areas worldwide (***Rinaldo***).

Such choices must also be supported by a project for low-carbon economic development of the city, avoiding excessive specialisation in unsustainable activities such as unregulated tourism and consequent social fragmentation. Cultural heritage should be protected in physical buildings and artistic physical expressions; promotion of cultural and research institutions should be enhanced through appropriate governance of this unique city (***Musu***).

WHAT ENERGY TRANSITION?

The need for an energy transition characterised by a sharp reduction of GHG emissions is undisputable. Solar and wind energies would satisfy the latter requirement, albeit involving a number of shortcomings. Solar and wind energies are *intermittent*, therefore they need either further continuous sources (fossils or nuclear) or massive storage of electric energy (a critical issue at the required scale). Furthermore, they have low power density and thus require extensive land areas to be massively deployed. Moreover, their construction is *critically dependent on the availability of raw materials*, whose increased consumption will hardly be sustainable and will expose the transition to vulnerabilities in material supply. Their massive deployment will lead to *a massive production of waste*, most of which contains toxic substances and cannot be recycled. Finally, solar and wind energies cannot be used for efficient liquid fuel production, which is needed to fuel aviation, as well as tracking and shipping industries. This casts considerable doubt on the sustainability of a net-zero path mainly relying on renewables (***Carrà***).

On the other hand, currently proposed net-zero paths (IEA, 2021) explicitly declare "… the road to net-zero emissions is uncertain …" and depend crucially on the deployment of a number of 'negative emission technologies (NETs)'. Nevertheless, as discussed in a recent EASAC Report on *Negative emission technologies: What role in meeting Paris Agreement targets?* (EASAC 2018), the financial and technical feasibility of NETs is rather uncertain (***Zevenhoven***).

More optimistic is the future of *biofuels*. This is a major issue as we desperately need cost-effective fuels with reduced carbon footprint to be used in sectors that are not easily decarbonised (e.g., trucking, shipping and aviation). The production of bioethanol from agricultural residues, energy crops, forest products and other plant materials has been widely investigated, with limited success. Much more promising are the currently developed technologies whereby biological non-photosynthetic CO_2 is fixed by using H_2 or CO as reducing gases, and the products are converted to liquid fuels such as oils and alka(e)nes. Liquid fuel production at scale appears to be within reach as long as sufficient amounts of CO_2 can be sourced and renewable hydrogen is available at approximately 1-2 $/kg (***Stephanopoulos***).

On the economic side, we must realize that, unlike all previous ones, the currently desired energy transition is neither driven by technological *breakthroughs* nor by market convenience. On the contrary, it will require immense economic resources to transform both *tangible* and *intangible* components of energy and economic systems. Hence, on the one hand, such energy transition requires new technologies, infrastructures, plants, as well as a total reconversion of the existing capital stock. On the other hand, it will entail novel models of investment, production, consumption, and new lifestyles for the wide range of actors involved. Will such a complex and uncertain process of energy transition be compatible with the *time constraint* that is indeed crucial to contain the impact of climate change? (***Clò***).

Pricing climate and energy externalities might accelerate the transition. However, this is also quite controversial, as politics rather than science is ultimately responsible for such choices, and politics is reluctant to counter significant opposition by vested interests. Science, on the other hand, can provide limited help due to the large uncertainties around the true social cost of carbon, with values falling in the range 50-300 \$/tCO_2 range deemed equally possible (***Wagner***).

Waiting for future technological breakthroughs, *humanity seems to be ultimately forced to choose* between the incommensurable and real risks of uncontrolled climate change and those of an extensive deployment of *the only available technology that may allow us to meet the time constraint posed by climate change*, namely fourth-generation nuclear plants (***Carrà***). Overcoming the emotional and ideological reluctance of some populations to accept the latter alternative is the job of politicians.

The Fifth Message

Achieving the net-zero goal is an immense undertaking which requires determination and cannot be left to emotionally and/or ideologically motivated decisions.
Enhancing the deployment of solar and wind technologies is necessary, but their scale must be compatible with the severe constraints entailed by their intermittent nature and set by land occupation, vulnerabilities in material supply and massive production of nonrecyclable waste. Conventional biofuel technologies based on biomass hydrolysis have failed to deliver cost-effective biofuel production.
Nevertheless, new very promising approaches have emerged that utilize non-photosynthetic CO_2 fixation; they must now be widely and strongly supported. Energy transition plans should realistically and urgently acknowledge the shortcomings of renewables, and revisit the mix of mature technologies required to achieve the sought transition.

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