THE ROYAL SOCIETY

Ask about the science of climate change

Our Google Moderator forum was open from 27 February 2014 to 5 March 2014 (17:00 GMT). Answers to your top 20 voted-for questions at the close of the forum have now been posted to the site and are available below.

Question 1

"How much lower than the present annual average temperature is the optimum long-term temperature?"

If we are going to talk about an 'optimum' temperature, we have to ask the question 'optimum for whom and for what?' Human societies around the world have developed in an environment where temperatures and other aspects of climate stay within certain quite tight limits. If the climate moves outside these limits within the time-scale of a human generation or so, those societies have major problems in adjusting and adapting. Historical evidence suggests that such societies are forced to move, but with current populations and country boundaries such a response would be much more problematic. Equally, ecosystems will also have difficulty in adjusting and evolving if any change is rapid. In Polar Regions it might be thought that warmer temperatures would be preferable. However the local changes with reduction in ice and melting of permafrost would mean that present way of life would be impossible. In the day-time in the hottest parts of the world the human body would be unable to do physical work at temperatures much above those experienced today. Of course warmer temperatures would also be accompanied by changed weather patterns and rainfall with new extremes as well as sea level rise to cope with.

We must recognise that because of the emissions of carbon dioxide that have already occurred, there is a commitment to a further small rise in temperature whatever we do. Our focus now should be on how much further it will rise, rather than how much lower we would prefer it to be.

Question 2

"Is it true that global warming has been happening over and over again, for tens of thousands of years, and higher CO2 concentrations in the atmosphere are an EFFECT, and not a CAUSE?"

Climate has indeed varied naturally, both warming and cooling, regionally and at global scale. All such changes, whether natural or manmade, can and do cause disruptions to natural and societal systems. The current change is of particular concern because the forcing (increasing CO_2) is changing so fast, and is therefore leading to global climate changes that are much faster than those experienced in the past (see question 6 of our report).

In particular, it is correct that the whole Earth has cooled and warmed naturally, for example, in and out of ice ages, roughly every 100,000 years. The trigger for the warmings out of ice ages is believed to be changes in the amount of solar radiation reaching different latitudes in different seasons. This can affect the way that ice sheets grow or shrink, reflect more or less sunlight and interact with the ocean. However the full magnitude of warming in and out of the ice ages can only be understood if we take into account various amplifying factors, of which a very important one is carbon dioxide. The latest research shows that Antarctic temperature and carbon dioxide rose in step for over 6000 years between 18,000 and 11,000 years ago, just as we would expect if they are amplifying each other (Brook, E. J. (2013), Leads and lags at the end of the last ice age, Science, 339, 1042-1043.) Increased carbon dioxide is both a cause of warming, because of the increased greenhouse effect, and a consequence of warming, because of reduced solubility in the oceans and increased respiration of organic carbon. A change of either one will cause a change of the other. The range of CO_2 concentrations over the last 800,000 years had been 170-300 parts per million until the 20th century. The increase to nearly 400 parts per million in 2014 is therefore very unusual both in magnitude, and we know that the increase in CO_2 is being caused by human activity (question 2 and 3 of our report), so now we don't have to speculate about cause and effect. The natural changes of the past give us valuable clues about how the climate system works, and in the past the changes were triggered by changes of sunlight, but now they are being driven by changes of carbon dioxide.

Question 3

"Why are climate models trusted in the long run when power spectra of observational data follow the inverse power law? That is, how do we know warming at any time scale is not natural?"

It is not known whether or not the global temperature data really do follow an inverse (1/f) power law spectrum, because the time series are still not long enough to determine this. The IPCC (2007) discussion of this (AR4, Chapter 3 Appendix A) said "long-term persistence models (Cohn and Lins, 2005) have not been shown to provide a better fit to the data than simpler models."

Like weather forecast models, climate models in the short run depend very much on the starting point (the initial conditions). As time goes on these become less important, and the results become much more strongly determined by the climate forcings (boundary conditions) and fundamental physical processes like the energy balance, and internal processes like the transport of heat and other properties. Thus they can to some extent be "trusted" more over longer periods of time. However, over very long periods of time (several centuries) they may become more strongly affected by slow processes like ice sheet loss and changes of deep ocean circulation, for which we have as yet few observations. As these may not be very well represented, modelled changes over very long periods of time should be treated with some extra caution.

The evidence that the observed warming is not natural was considered in the answers to Questions 2, 4 & 5 in our recent document (see also the answers to several of the other online questions). The observed change (of about 0.8 °C) in the global decadal mean temperatures since the late 19th century is over 10 times the estimated internal variability of these averages. Assessing how unlikely this would be to occur by chance, (i.e. if it were just a random fluctuation rather than a systematic change) is not straightforward, since it depends on both the natural variability and some assumptions about the properties of the processes involved (a statistical model). The variability arises from natural fluctuations of weather and climate, changes in both external forcings (e.g. volcanoes) and human activities, and effects of uneven coverage of the observational network. Separating the variability from longer-term systematic changes by statistical methods alone is therefore difficult.

The simplest "standard" statistical method would suggest that the probability of such a large change occurring by chance would be extremely small (far less than 0.1 %). However, it is known that the temperature data are not purely random, but are serially correlated. The IPCC (2013) allows for this (by using a more complex but still standard auto-regressive statistical model) and still finds that the change is extremely unlikely (probability less than 1%) to be chance. If the data do follow an inverse (1/f) power law spectrum, there would be longer-range serial correlation. Some authors (e.g. Cohn & Lins 2005) have made this assumption, but even so still find that the probability of the change being due to chance is still only about 7%

Question 4

"Is there a simple short but compelling answer that can be given when you run into someone who just insists "oh, the climate has always changed. This is natural and scientists just want to scare us into giving them more funding"?"

The Earth has experienced many large climate changes in the past (also see questions 6 and 7 of our report). However, current changes in climate are unusual for two reasons: first, many lines of evidence demonstrate that these changes are primarily the result of human activities (see question 2 and 3 of the report); and second, these changes are occurring (and are projected to continue to occur) at a much faster rate than many past changes in the Earth's climate (see question 6 in the report). Human societies, developed in the context of a rather stable climate, are likely to be vulnerable to the rate and magnitude of the changes anticipated through this century if greenhouse gases emissions are not curbed.

To add to this short answer: In the past, climate change was driven exclusively by natural factors, e.g., explosive volcanic eruptions that injected reflective particles into the upper atmosphere, changes in energy from the sun, periodic variations in the Earth's orbit, natural cycles that transfer heat between the ocean and the atmosphere, and slowly changing natural variations in heat-trapping gases in the atmosphere. All of these natural factors, and their interactions with each other, have altered global average temperature over periods ranging from months to many thousands of years. For example, past glacial periods were initiated by shifts in the Earth's orbit, and then amplified by resulting decreases in atmospheric levels of carbon dioxide and subsequently by greater reflection of solar radiation by ice and snow as the Earth's climate system responded to a cooler climate. Some periods in the distant past were even warmer than what is expected to occur from human-induced global changes in climate. But these changes in the distant past generally occurred much more slowly than the current ongoing changes.

Records from ice cores, tree rings, soil boreholes, and other forms of "natural thermometers," or "proxy" climate data, show that recent climate change is unusually rapid compared to past changes. After a glacial maximum, the Earth typically warms by about 4 to 7 °C over thousands of years (with periods of rapid warming alternating with periods of slower warming, and even cooling, during that time). The observed rate of warming over the last 50 years is many times faster than the average rate of warming from a glacial maximum to a warm interglacial period.

Question 5

"When was the natural greenhouse effect discovered and when was it first quantified, and has that estimated effect changed substantially in the light of more recent research ?"

The scientific basis for understanding how heat-trapping gases affect the Earth's climate dates back to the French scientist Joseph Fourier, who established the existence of the natural greenhouse effect in 1824. The heat-trapping abilities of greenhouse gases were corroborated by Irish scientist John Tyndall with experiments beginning in 1859 (also see question 2 of our report). In 1896, Swedish scientist, Svante Arrhenius published the first radiative transfer analyses of the greenhouse effect showing that an increase in atmospheric carbon dioxide concentrations could lead to warmer global temperatures (e.g., see rsclive3.rsc.org/images/Arrhenius1896_tcm18-173546.pdf). His estimate of the warming effect of doubling CO_2 was about double most modern estimates. Since then, scientists have developed more tools to refine their understanding of human influences on climate, from the deployment of the thermometer, to the development of computerized climate models, to the launching of Earth observing satellites that, together, provide global data coverage. High-resolution numerical modelling of the radiative transfer in the Earth's atmosphere now give us a quite complete picture of the absorption by water vapour, carbon dioxide, and other radiatively important gases and particles, that is well verified by satellite observations. Recent analyses show that without the presence of (even natural levels of) carbon dioxide in the Earth's atmosphere that this would likely be a frozen planet.

Question 6

"Is there a simple way to explain why an increase of greenhouse gas concentration causes a cooling of the stratosphere?"

The details of the greenhouse effect depend on the vertical temperature structure and also on the overall flows of energy through the climate system. Greenhouse gases like carbon dioxide let most of the sun's energy through but absorb and then re-emit the heat given off by the Earth. The gases re-emit this heat in all directions, including back towards the surface of the Earth, so making it warmer. Higher in the atmosphere, in the stratosphere, they help to cool because of their ability to emit heat radiation out to space. For an increased level of greenhouse gases this cooling is stronger and so the stratosphere cools.

Question 7

"How might a possible forthcoming "Maunder Minimum" impact projections on climate change?"

The number of sunspots observed varies with an approximately 11 year cycle. However during the Maunder Minimum, 1645-1715, very few sunspots were seen. Compared to previous cycles, the number of sunspots in the last few years has been low, prompting the suggestion that we might be entering a new Grand Solar Minimum (GSM), similar to the Maunder Minimum. However, even a GSM has only a very small effect on the amount of energy from the Sun received at Earth (see question 4 of our report). The latest estimates suggest a change in incoming radiation of order 0.1%, similar to the changes over a typical 11 year cycle, and much less than the changes induced by increased carbon dioxide over recent decades. Larger variations in ultraviolet radiation, as solar activity changes, can also influence other aspects of Earth's atmosphere but still the net effect on climate appears to be small. In summary, a GSM would likely offset only a very small proportion of the warming from increased greenhouse gases – and of course the minimum would be expected to end, reversing the effect, before CO_2 concentrations decreased (see question 20 of our report).

Question 8

"How does climate science address the problem of confirmation bias? Can you specify any data that would emerge in future that would falsify the explanatory framework presented? Is climate science non-falsifiable? Is that what "settled science" means?"

Confirmation bias, in which people favour information that confirms their beliefs, is a potential problem, but tends to be destroyed in the constant give and take among scientists when they present and publish their results – or the scientist gets labelled as biased. Science is not simply a matter of beliefs and opinions. So "settled science" means there are basic facts (well accepted observational and empirical evidence), and well-tested theory (as opposed to opinions) that should be recognized in spite of the many other issues or uncertainties.

There can be a risk of "group think" but any theory or result is constantly subject to scrutiny and scientists try to build understanding into models. Weather prediction uses atmospheric computer models that are a central part of climate models. These are used to issue weather forecasts every day, and they are then routinely verified, tested and upgraded. Skills have improved so that 6-day forecasts today are now as accurate as 3-day forecasts of the 1970s. Climate models used for long-term predictions clearly cannot be verified in the same way, except as "hindcasts". Hence their performance can be tested using the past 100 years or so, and also in simulating palaeo climate: the climates of millennia or even millions of years ago as best they can be reconstructed using proxy data. But confidence in models is also built in other ways, by ensuring that the processes included are represented with fidelity, and by examining responses to particular events (such as a volcanic eruption). Models are being continually improved as understanding increases from new observations (such as from space) and computers get faster.

Models should be as detailed and complex as necessary to depict reality, but not with so many knobs that they are not falsifiable. Climate models are tools to be used with knowledge of their shortcomings and strengths. The questioner is right that their predictions cannot easily be tested as quickly as we would like, but over several and many decades they are certainly falsifiable.

Question 9

"Why have so many regional and global temperature records for the early 20th century been revised downward, increasing the apparent warming of the 20th century? How do we know better than those who took the measurements at the time?"

In the early days of weather observations, there was rather poor coverage of the world, and most thermometers were in Europe and North America, and they were not necessarily well-sited using standardised enclosures. Interpreting the early data is therefore not straightforward, as there are various possible biases in the observations that should properly be allowed for, and there are also problems in dealing with the non-uniform spatial coverage. Several groups routinely produce and maintain long-term estimates of global and regional temperature, and they all try to manage these difficulties in different ways. When new information becomes available (e.g. from historical research or data "archaeology") they can use it to readjust early observations to make them more comparable to later ones, so past data may be revised (either upwards or downwards). Reassuringly they all get very similar results after about 1880. Occasionally problems may be introduced, as well as corrected, and the question may relate to a specific adjustment made in the NASA global temperature record in December 2009, which was a downward adjustment to US temperatures owing to confusion over whether or not the records received from NOAA had already been adjusted or not. This affected the records after 2000, but the effect globally was very small, and it was quickly corrected, see http://www.columbia.edu/~jeh1/mailings/2009/20091216_TemperatureOfScience.pdf .

Recently another (and sceptical) group used a new and quite different statistical method to reanalyze the historic data, and they have obtained extremely similar results too, so it seems that these adjustments do not have a big effect on the main findings.

(see http://berkeleyearth.org/about)

Question 10

"Assuming for a moment, that the upward global temperature trend is caused by Humans, what is the causal link to CO2? i.e. is all of this based upon a correlation? (earth warming, co2 concentrations up, therefore co2=warming?) why not H2O?"

Many lines of evidence demonstrate that human influences on the changing concentrations of carbon dioxide and other radiatively important gases and particles are primarily responsible for the observed changes in climate over the last five decades (also see question 2 of our report). The link between warming and carbon dioxide is based on well-established scientific principles, and is certainly not just an empirical correlation. First, basic physics dictates that increasing the concentration of CO_2 and other heat-trapping gases in the atmosphere makes it harder for heat radiation to penetrate and leave the atmosphere, and will cause the climate to warm. Second, modelling studies show that when human influences are removed from the equation, climate would actually have cooled slightly over the past half century. And third, the pattern of warming through the layers of atmosphere demonstrates that human-induced heat trapping gases are responsible, rather than some natural change.

Scientists are continually designing experiments to test whether observed climate changes are unusual and then to determine their causes. This field of study is known as "detection and attribution." Detection involves looking for evidence of changes or trends. Attribution attempts to identify the causes of these changes from a line-up of "suspects" that include changes in energy from the sun, powerful volcanic eruptions – and today, human-induced emissions of heat trapping gases.

Scientific detection and attribution studies have been applied to study a broad range of observed changes in the climate system. These studies have found that the changing concentrations of carbon dioxide and other radiatively important gases and particles are the only credible explanation for the observed changes in climate over the last half-century. Such observed changes include increases in surface temperatures, changes in atmospheric vertical temperature profiles, increases in ocean heat content, increasing atmospheric humidity, increases in intensity of precipitation, and indirectly estimated through changes in ocean salinity, shifts in atmospheric circulation, and changes in a host of other indices. For example, the observed warming of the troposphere and cooling of the stratosphere is consistent, using radiative transfer analysis, with the observed changes in concentrations of CO_2 (and other human affected gases and particles), but is not consistent with changes in the solar irradiation.

Water vapour is the most important naturally occurring heat-trapping greenhouse gas, but small increases in heat energy absorption by carbon dioxide and other heat-trapping gases trigger increases in water vapour that amplify the infrared trapping, leading to further warming. The concentration of water vapour in the atmosphere is strongly and rapidly coupled to temperature (because of evaporation and precipitation as rain and snow if the concentration becomes much greater or less than the maximum (saturation) vapour pressure). As a result, water vapour is considered a "feedback" rather than a direct forcing on climate. The globally observed changes in atmospheric humidity are consistent with this picture but not with changes in atmospheric water content totally driving the observed changes in climate.

Question 11

Why does one refer to model results when observations give a different answer (No trend)? (I.e for example frequency of hurricanes, flooding etc?). Isn´t that like trying to change reality to the map?"

Model results tell us what is expected for a given set of assumed inputs (forcings of the model climate system, such as via emissions scenarios). If we run a model multiple times then we can generate an ensemble of results that samples the internal natural variability of the weather and climate system, and hence we can see what the range of possible outcomes could be. Nature provides us with but one of those outcomes. The system is not deterministic, but when the forcings change, such as with changes in the atmospheric composition, then the odds change for the outcome.

Many observational datasets are quite short and most have problems and perhaps spurious changes due mostly to the continually changing observing system (e.g., as new instruments are flown on satellites and other new technology is deployed or old methods are deemed too expensive and terminated).

This is the case for hurricanes, for instance: in many parts of the world the record is only somewhat reliable since satellites were deployed about 1970, but even since then the instrumentation has changed and become more sophisticated with higher resolution. We therefore use our observations and high resolution modelling of hurricanes to build understanding, such as to how hurricanes respond to higher sea surface temperatures. Confidence is therefore built that with global warming, hurricanes are expected to be bigger and more intense but there may be fewer of them as the climate changes.

Flooding is another complicated example. Heavy rains have generally increased but are only one part of flooding. Whether a flood develops relates a great deal to drainage systems and water management, as well as surface conditions (vegetation, ground wetness, etc), and many cities, counties, states, and countries have departments whose job it is to prevent floods in spite of any changes in rainfall. Sometimes levees designed to prevent floods have made them worse when they were breached.

Question 12

The least-squares trend on the RSS monthly global mean surface temperature dataset shows no global warming at all for 17 years 5 months. How many runs of how many climate models predicted so long a hiatus even though CO2 concentration is rising fast?

The RSS monthly temperatures are not at the surface, but are one version of the satellite temperature record, and we presume the questioner refers to the so-called TLT (Lower Troposphere) record. This does reveal an upward trend that fits reasonably well with that suggested by models although on the low side (see the detailed analysis of this by Santer et al. 2014 Nature Geoscience, (23 February) doi:10.1038/ngeo2098.) What is outside most model simulations is the 1997/98 El Niño warming, and the questioner appears to have taken the highest point on that curve to produce a very misleading estimate of the recent trend. Question 10 of our document addressed this question, and it is also addressed in several other recent publications: see in particular several articles in Nature Climate Change in March 2014.

The ability of climate models to simulate the recent slowdown in global mean surface temperature has also been addressed in a recent (three-part) outreach document by the UK Meteorological Office http://www.metoffice.gov.uk/research/news/recent-pause-in-warming. Please see in particular Fig 2 of part II of this series. It shows probability distributions of temperature trends from almost 7000 years of a "control" integration of a contemporary climate model, and thus it deals only with internal natural variability and does not include influences from other effects such as the sun, volcanoes, or air pollution. Separate trend distributions have been estimated based on 10-year, 15-year, 20-year and 30-year averages. These distributions have been offset to represent a greenhouse-gas induced trend of 0.2K/decade and the recent observed trends superimposed. The net result is that the recent observed trends lie a little inside the 5th percentile of the modelled distributions - that is to say, in the tails of the distributions but not outside.

Two points arise from this analysis. If the recent trend is indeed close to the 5th percentile of internal climate variability, then relatively large sized ensembles of climate model integrations will be needed to reliably simulate it. For example with only 50 model integrations, there is a chance none will capture the recent trend. This does not imply a shortcoming in current generation climate models, but rather it means that these hiatuses are relatively unpredictable aspects of climate variability with relatively low intrinsic frequency of occurrence.

However, in the real world there are other “forcings” of the climate system occurring: the quiet sun, a number of small volcanic events that have added aerosol to the lower stratosphere that block the sun, and air pollution within the troposphere, especially from east Asia. All of these are analysed in several recent publications (including the Santer one noted above), and all effects have contributed to a slow down in the rise of global mean temperatures.

However, one cannot exclude the possibility that the current generation of climate models is not simulating the internal dynamics associated with the recent hiatus with perfect realism. It is now understood that this slowdown is mostly linked to decadal-timescale variability associated with air-sea coupling in the tropical Pacific region (linked to what is sometimes referred to as the Pacific Decadal Oscillation) and ocean heat uptake, and current climate models do exhibit systematic biases compared to observations in this region. It is already apparent that with better numerical resolution in the models' representation of the oceans and atmosphere, plus the addition of the forcings, the recent trends in surface temperature will lie more in the main body of the distribution than is currently the case.

In short, the recent temperature trends do not invalidate predictions from contemporary climate models, but recent observations suggest there is every reason to continue to develop and improve these models.

Question 13

"Climate science is complicated, and results are often fraught with uncertainty. How should climate change scientists usefully communicate this uncertainty to citizens and those who make policy in government?"

Climate science is indeed complex, but many basic aspects are not uncertain, and climate scientists should (and do) try to be clear about what is well established and what is less certain (see RS 2010 http://royalsociety.org/policy/publications/2010/climate-change-summary-science).

Climate change is no more uncertain than many other issues on which policy decisions have to be taken (for example, on economic policy) and need not be treated as a special case. Scientists should use plain language carefully (as the IPCC does for example in its carefully calibrated statements about likelihood and confidence levels, see http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf). High levels of certainty and precision are not always necessary for good decisions to be taken, and it may be sufficient to know just the direction of change, e.g. that one should do more or less of something, and whether it needs to be done very quickly or whether there is plenty of time to act later. Calls for ever higher precision and more certainty are often used in order to avoid taking actions that may cause difficulties. Given likely climate changes, it is important to assess the vulnerability of people and activities to the possible effects, and to build increased resilience to them. Many sensible decisions along these lines can help cope with uncertainties.

Question 14

"Will farmers have to change their current farming methods more in the future with the onset of increased floods and climate change?"

With increased temperatures, and changes in mean rainfall, water availability and in the extremes of weather, it is likely that farmers may want to grow different crops that are more suitable to the new conditions. It is also likely that in many areas soil moisture will decrease and they will need to be much more efficient with their usage of water. Because of their different crops and the conditions in which they are growing, farmers will likely adapt their general practices of tilling, sowing, fertilising and harvesting. However given the expectation of heavier rainfall events in many parts of the world, a priority for the wider community may be that the farming practices satisfy the requirement for farming land to absorb and retain excess water, so as to minimise run-off. This may bias the choice of crops; it may demand practices that do not compact the soil; and it may require that the soil is bare for minimum periods only. Another strategy is to have deep ponds to store water for times of need (and deep to minimize evaporative losses).

Question 15

"Thank you for your simple and clear explanation. Are you able to publish a version that is referenced to the various research papers that support the information you provide? eg. the research about quantifying and identifying CO2 sources (Q&A 3)."

There are a number of other reviews and assessments of the science that provide extensive references, and the main international climate assessments are by the Intergovernmental Panel on Climate Change, which has issued major assessments about every 6 years (1990, 1995, 2001, 2007, 2013) in 3 parts dealing with the science and physical basis, the impacts and adaptation, and the mitigation of climate change.   Each of the 3 parts of all recent reports is of order 1000 pages long, and they cite all of the literature bearing on all of the questions. In recent reports, the summaries refer back to each chapter and section to provide documentation. The reports are published and available at http://www.climatechange2013.org. Many nations also have their own reports. For the CO_2 sources the relevant part of the latest IPCC assessment report, with references, is in chapter 6, specifically the bullet point list at the end of section 6.3.2.3, on pages 493-4.

The challenge is to distil all of this information into fairly simple and clear explanations, and we thank you for your endorsement that we have achieved this.

Question 16

Scientists such as Piers Corbyn say that the Sun does have a significant influence on climate. (Q4) It's more complex than irradiance, factors such as proton flux and cosmic rays are significant. Why does the Royal Society ignore such things?

Question 4 deals with the possible role of the Sun in climate change in recent decades. Whilst our latest overview document did not refer to the possible impact of cosmic rays on climate, this has been considered and was tackled in section 7 of our earlier outreach document "Climate Change Controversies"

http://royalsociety.org/uploadedFiles/Royal_Society_Content/policy/publications/2007/8031.pdf

The proposed causal link between cosmic rays and cloud cover has been studied in the intervening years, and found to be essentially non-existent. Several early studies that found correlations with apparent cloud changes were flawed because the cloud data contained spurious changes associated with satellite changes, and the studies have not stood up to tests on independent data.

Recent studies have found that cosmic rays and solar activity have a minor impact on warming in the twentieth century. The abstract of a paper by Sloan and Wolfendale (Astronomer Royal between 1991 and 1995) - Cosmic rays, solar activity and the climate:

Environ Res Lett 8 0145022 (2013) - reads: "Evidence is presented from which the contributions of either cosmic rays or solar activity to this warming is deduced. The contribution is shown to be less than 10% of the warming seen in the twentieth century." The CLOUD experiment at CERN has been studying the mechanisms of cloud nucleus formation, and concluded that cosmic rays generally play only a very small role (Nature, 502, 359–363 (2013).

In short, the Royal Society does not ignore such factors. However, they are believed to be relatively unimportant and were therefore not included in the recent outreach document. Whether cosmic rays are important aspects of the mechanisms proposed by Piers Corbyn is unclear, because there is no scientific literature reference to his ideas. If Piers Corbyn is prepared to submit a paper based describing his hypothesis to the peer-reviewed literature, and explain how it has been tested, then scientists will then be able to put his work under the scientific microscope.

Question 17

Wouldn't the increase in CO2 in the atmosphere help to increase crop yields?

In systems that are limited by the availability of CO_2, and not by other factors such as water availability, it is correct that extra CO_2 in the atmosphere can cause greater growth of many plants and trees. For example, when Earth emerged from the last glacial period (colloquially known as the last ice age) between 18000 and 11000 years ago, increasing CO_2 was one of the factors that led to a growth of the terrestrial biosphere, partially compensating the CO_2 increase.

This CO_2 fertilisation effect has to be taken into account, along with many other factors that can affect crop yields. Higher temperatures will tend to reduce frost damage and give a longer growing season. However extreme temperatures at crucial flowering times and in summer heat-waves could be damaging. Perhaps of more importance is the availability of water. The increased temperatures and higher evaporation from soil and transpiration by plants will mean that soil moisture will decrease in many places. A move towards the rain coming in heavier events will lead to more mini-droughts and more flooding events that are likely to be detrimental to crop growth. The net effect is likely to be increased production in some areas and decreased in many others.

Question 18

Where did all the carbon in limestone come from? What role does this play in global carbon balances?

All the carbon on Earth, including that in limestone, originally comes from nuclear reactions in stars, and it is likely that the atmosphere of the early Earth contained a very large amount of carbon dioxide, as that of Venus still does today. Atmospheric carbon dioxide is continually being exchanged with the oceans, and some dissolves in seawater. Many living marine organisms (including corals and planktonic plants and animals) make their shells out of calcium carbonate, which incorporates carbon dioxide that has dissolved in seawater. As the organisms die, they sink to the sea floor, and over geological time (many hundreds of millions of years), the accumulation of these shells on the seafloor has formed limestones, which now contain most of the carbon from the primeval atmosphere.

Nowadays, these rocks are carried on moving plates within the Earth's crust. When two plates collide, one sinks beneath the other and the rocks melt under extreme heat and pressure. The heated rock releases carbon dioxide which is then injected back into the atmosphere through volcanic activity. Atmospheric carbon dioxide combines with atmospheric water to form mildly acidic rain. This rain can dissolve rocks including limestones and rivers carry a variety of products (including calcium and various types of carbonate) into the oceans.

This natural cycle now takes place over timescales of hundreds of thousands of years, and involves only a tiny fraction of all the buried limestones. It will eventually remove extra carbon dioxide from the atmosphere, and is important when one wants to understand global carbon balances on these long timescales. However, these processes are much less important when trying to understand how the carbon dioxide concentrations in the atmosphere will change in the coming century or so due to human emissions of greenhouse gases. Human-induced emissions of carbon dioxide each year are now typically one hundred times greater than the volcanic emissions of the natural cycle.

Question 19

"Which parts of the world is global warming going to impact more than others?"

Focusing first on the direct effects of climate change, we cannot yet be very precise about the local and regional changes that would go with global warming. However, most people and their ways of living are more or less adapted to the conditions they are used to, so most would have problems. The impacts are generally likely to be much bigger where there is poor infrastructure in poorer and developing countries, while developed countries can cope better. People in the hot tropics would experience temperatures that human society has not had to cope with before. There is also the likelihood of some more intense tropical cyclones. Monsoon rainfalls are projected to become stronger in many places but may shift in location and the impact would be huge in those regions. Dry regions in the subtropics becoming even drier could pose significant problems from water shortages and wild fires. Those in high latitudes would have problems with melting land and sea ice and thawing permafrost. Heavy rainfall events are likely to become even more intense for most people. People living in low lying coastal regions would experience sea level rise and the extra problems of greater storm surges and coastal inundation.

People in some places could think that the direct effects of climate change might be more beneficial than not. However, because we live in a world of global trade, travel and communication the indirect impacts of climate change elsewhere in the world due to their triggering of social problems and disruption of trade are likely to be significant for all and may well be more significant for many than the direct effects.

Question 20

Is it true that amounts of carbon dioxide were 10 times higher during an ice age than they are now? If this is indeed true, could you explain why we had cooling instead of warming temperatures? This is an argument of global warming skeptics.

During the glacial periods (colloquially referred to as ice ages) of the last 800,000 years, the carbon dioxide concentration was actually always lower than during the warmer interglacials, and a lot lower than it is in 2014. The lower CO_2 concentration contributed as an amplifying effect to the extent of change between the cold and warm parts of these ice age cycles. This is discussed in question 7 of our report. However I think you must be referring to much earlier periods in Earth history. It is very hard to get good estimates of the CO_2 concentration in the atmosphere at such times, and equally hard to get good estimates of the dates associated with such estimates. Previous ice ages (many millions of years ago) generally seem to be associated with reduced levels of CO_2, and there is really no evidence for unusually high CO_2 concurrent with the existence of large amounts of ice on Earth. Earth's climate is under the control of the amount of solar radiation it receives, the amount that is reflected back into space (for example by ice and clouds), and the composition of the atmosphere (greenhouse effect). In fact many of the large changes in climate that occurred in the past can only be understood if we take account of a change in the strength of the greenhouse effect.