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Climate Change & Environmental Issues

by Kevin E Trenberth

The climate has always varied on multiple timescales, but now humans are the main agents of change and are likely to remain so for the next few centuries. Climate change is already affecting every continent and ocean, posing immediate and growing risks to people. The longer society delays taking steps to cut the release of planet-warming greenhouse gases, the more severe and widespread the harm will be. According to the Intergovernmental Panel on Climate Change (IPCC), global warming threatens food and water supplies, security and economic growth, and will worsen many existing problems, including hunger, drought, flooding, wildfires, poverty and war.

There are many facts related to climate to demonstrate conclusively that the problem is real. The observational evidence combined with physical understanding based on well-established physical principles makes this abundantly clear. However, the facts are not enough. The role of scientists is to lay out the facts, evidence, prospects and consequences, but the decisions on what to do about them resides in the realm of politics and should involve all of society.

Patrick Daniel Moynahan famously said "You are entitled to your own opinion but not your own facts". The observations and data – the facts – are of mixed quality and duration, but together tell a compelling story that leaves no doubt about the human role in climate change. Changes in some phenomena, such as hurricanes and tornadoes, are confounded by the changing observing system and shortness of reliable records. But the absence of evidence is not evidence of absence of important changes, and our physical understanding and climate modeling can fill the gaps. Climate change is happening because of human activities, but what we do about it involves value systems and politics.

The IPCC, US national assessments, reports from the National Academy of Sciences, and many other scientific organizations have proclaimed that "global warming is unequivocal" and it is mainly caused by human activities. Yet the public is not alarmed. Many politicians either do not believe in global warming or discount it. But it is not a matter of belief. From the scientific standpoint, by the time the problems associated with climate change are so blatant, it will be far too late to do anything about it. Already the costs are substantial every year from drought, wild fires, floods, heat waves, storm surges, and strife. The climate events that cause the damage are isolated events, regional in nature, and affect but few at a time. The public does not see an integrated view. A major IPCC report comes out and it is a headline for at most one day. But the problem continues, and in fact gets worse every day. Yet it is no longer news because it remains the same problem, although

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the problem has not been solved. It is easy for the public to set it aside.

Climate change is inherently an inter-generational problem. What kind of a planet are we leaving our grandchildren? It is also a problem of equity among nations. Small island states and developing countries have not contributed much to the problem but are affected by it. Costs of climate change and air pollution are not borne by those who cause these problems. There are substantial uncertainties associated with exactly what form and where climate change effects will be felt, but the risks are growing. A normal way society deals with risk is by building resilience and taking out insurance. The precautionary principle should come into play. But society is not doing enough to mitigate the problem or plan for the consequences.

THE PHYSICS OF CLIMATE CHANGE

The Sun serves as the primary energy source for Earth's climate. Some of the incoming sunlight is reflected directly back into space, especially by ice and clouds, and the rest is absorbed by the surface and the atmosphere. All bodies radiate at a rate related to their temperature, and most of the absorbed solar energy is re-emitted as infrared (longwave) radiation. The atmosphere in turn absorbs and re-radiates heat, some of which escapes to space. The components of the atmosphere playing this role are present in only small amounts: the so-called greenhouse gases (GHGs). As a rule of thumb, a GHG has more than 2 atoms per molecule and thus the main components of the atmosphere, nitrogen N_2 and oxygen O_2, do not play a role. Instead water vapor H_2O is the dominant GHG, followed by carbon dioxide CO_2, Ozone O_3, methane CH_4 and Nitrous Oxide N_2O.

Any imbalance between the incoming and outgoing radiation results in climate variability or change. Examples include the annual cycle, where the oceans take up and store heat in summer, and then release it in winter. Another example is the El Niño phenomenon whereby heat stored in the tropical western Pacific Ocean is moved around and transferred back into the atmosphere during an El Niño event, resulting in a mini global warming. Climate change comes about on longer timescales, mainly from changes in the composition of the atmosphere by human activities, as discussed below.

The natural cycles of water and energy flows on Earth are very large; the absorbed heat from sunshine is moved around by winds and ocean currents but ultimately radiated back to space as infrared radiation. The natural flow of energy through the climate system is about 122 PetaWatts (122 million billion Watts) or 240 Watts per square meter of the Earth's surface. Even with over 7 billion people, the actions of humans in terms of energy use (from burning fossil fuels, electricity usage, and so forth) result in heat amounts of only about one part in 9,000 of the sun's energy flow through the climate system (14 TeraWatts or 0.03 Watts per square meter). Locally, in major urban cities, heating effects from human activities, including the effects of buildings and roads, can be a few tens of Watts per square meter, which creates a microclimate called the urban heat island. But global effects are very small.

The main way humans affect the climate is not by competing with the sun directly, but by interfering with the natural flows of energy through the climate system by changing the composition of the atmosphere. Human activities, mainly the burning of fossil fuels since the start of the industrial revolution, have increased atmospheric carbon dioxide (CO_2) concentrations by about 40%, with more than half the increase occurring since 1970. Without this greenhouse effect, life as we know it could not have evolved on our planet. But adding more greenhouse gases to the atmosphere makes it even more effective at preventing heat from escaping into space.

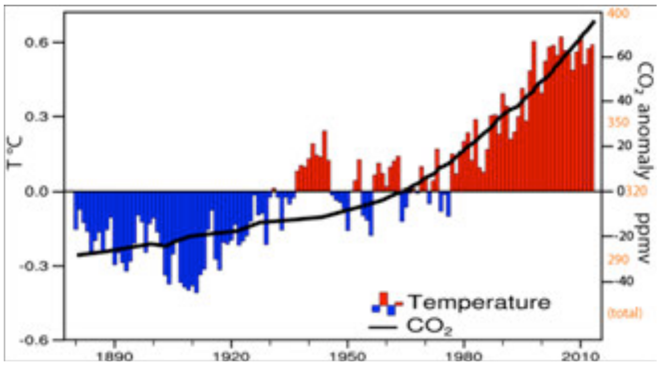

Fig. 1. Global annual mean temperature and carbon dioxide anomalies as departures from the twentieth Century mean through 2013; updated from Trenberth and Fasullo (2013). Note the accelerating rate of CO2 increase in spite of the Kyoto Protocol. Data are from NOAA.

Heat trapping greenhouse gases, in particular carbon dioxide, have increased from human activities, especially burning of fossil fuels mainly in coal-fired power stations and industrial plants, vehicles, and planes, to the point where their warming effects now exceed the noise of natural variability. The heating effect of the increased greenhouse gases is about 3 Watts per square meter, but it is offset by cooling effects from increased pollution (aerosols) in the atmosphere. Further, as a result of the energy imbalance, the Earth warms until a new balance is established by radiating more energy back to space. At present the net energy imbalance of Earth is int the order 1 Watt per square meter so that the planet is still warming.

Although the current effects are still relatively small, they are always in one direction, that of warming, and the effects accumulate. The result is warming oceans, where 90% of the energy imbalance accumulates, melting land and sea ice, raising sea levels, warming land and atmosphere, and a more vigorous hydrological cycle. Global surface temperatures have increased by 0.8°C since about 1900; 0.7°C for the oceans and 1.0°C for land areas (Fig. 1). For every degree C increase in atmospheric temperature, the water holding capacity increases by about 7%, and over and near oceans or bodies of water this sort of increase is observed; it amounts to about 5% increased atmospheric moisture since the 1970s. This in turn increases intensity of precipitation and invigorates storms. But in places where it is not raining or snowing, the warmer air sucks moisture out of plants and the ground, promoting drying and ultimately drought and wild fires. Comparisons of the thermometer record with proxy indicators of climate change suggest that the 30-year period since 1983 has been the warmest in at least 8 centuries and that global temperature is approaching temperatures last seen 5,000 to 10,000 years ago, which was the warmest period in the past 20,000 years since the last glacial maximum. Detailed analyses using climate models

Continuing Erosion in Rodanthe, North Carolina ©Gary Braasch 2014

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and observations have shown that the warming since the mid-20th century is mainly a result of the increased concentrations of CO_2 and other greenhouse gases. Continued emissions of these gases will cause further climate change, including substantial increases in global mean surface temperature and important changes in regional climate. The magnitude and timing of these changes depends on many factors. Pauses, slowdowns and accelerations in warming lasting a decade or more are expected to continue to occur, but long-term climate change over many decades will depend mainly on the total amount of CO_2 and other greenhouse gases emitted as a result of human activities.

The effects of warming are widespread and evident in many different variables and datasets. As well as surface temperatures, temperatures are observed to be increasing throughout the troposphere (using satellites and balloons), and throughout much of the ocean (using Argo floats, expendable bathythermographs deployed by ships, and so forth). Extremes of high temperatures are increasing along with heat waves and risk of wild fire. Arctic sea ice is melting and in late northern summer losses have been over 40%. Northern Hemisphere snow cover has decreased in late spring, glaciers and ice sheets such as Greenland are melting and cold temperatures are generally reducing. Melting of land ice plus expansion of the warming oceans contribute to sea level rise which has averaged 3.2 mm/yr since 1992 when altimeters were deployed in space to truly measure global sea level for the first time (Fig. 2). Sea level rise for the 20th Century is estimated to be about 20 cm. Water vapor has increased by about 5% over the oceans since the 1970s, and as a result, precipitation intensity has generally increased. Storms are invigorated. Warming and precipitation changes are altering the geographic ranges of many plant and animal species and the timing of their life cycles. Some excess CO_2 in the atmosphere is being taken up by the ocean, changing its chemical composition and causing ocean acidification.

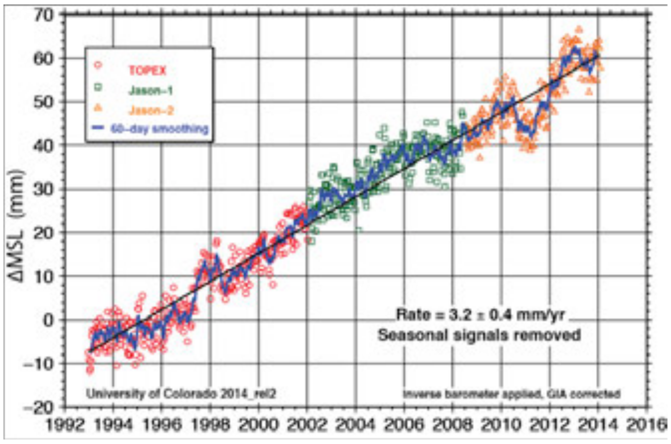

Fig. 2. Sea level rise from altimeters in space since 1993 in mm relative to a base period of 1993-1999; from University of Colorado (Nerem et al 2010). A 60-day smoothing is applied to individual 10-day estimates and a linear trend has been fitted.

The changes in external influences on the climate system affect the climate not just as a simple forcing because there are many complex feedbacks involved. The most important feedbacks involve various forms of water and a warmer atmosphere contains more water vapor, which is a potent greenhouse gas. Hence it amplifies warming. Another amplifier is from higher temperatures in polar regions which melt sea ice and reduce snow cover, leaving a darker ocean or land surface that can absorb more heat, causing further warming. However, effects of changes in clouds are less clear. Water vapor increases may cause

Nepal Farmer Grows Strawberries on the Mountainside ©Gary Braasch 2014 cloud cover to increase while higher cloud tops reduce radiation to space, and the net result depends on the changes in the horizontal extent, altitude, and properties of clouds. For instance a doubling of atmospheric CO2 concentration from preindustrial levels (up to about 560 ppm) would cause a global average temperature increase of about 1°C (1.8°F) in the absence of feedbacks. In the real world, however, the net warming estimated from climate models is 1.5 to 4.5°C.

Analysis of all data and climate model results convincingly shows that most of the observed global warming over the past 50 to 60 years cannot be explained by natural causes and instead requires a significant role for the influence of human activities.

Predictions of the future climate rely on climate model results. However, because human activities are not predictable, and indeed may well be influenced by the results of climate models, rather that predict the future population and energy use, various emissions scenarios are used as possible futures for use in driving climate models to see "what if" outcomes. These are called projections and they go hand-in-hand with an emissions scenario. Ideally the models are run many times to get the average results and to sample the range of possibilities thereby taking weather and natural climate variability fully into account. Differences among models from different Centers are also factored in. The robust results then form the basis for projected outcomes.

All model projections indicate that Earth will continue to warm considerably more over the next few decades to centuries. If there were no technological or policy changes to reduce emission trends from their current trajectory, further global warming of 2.6 to 4.8°C (4.7 to 8.6°F) in addition to that which has already occurred would be expected during the 21st century. Rising sea levels, more intense storms and heavier rainfalls and amplified droughts and risk of wild fire are projected with confidence.

Natural variability modulates the expectations from the changing atmospheric composition from human activities. Large volcanic eruptions, which occur from time to time, increase the number of small particles in the stratosphere that reflect sunlight, leading to short-term surface cooling lasting typically 2–3 years, followed by a slow recovery. Ocean circulation and mixing vary naturally and cause variations in sea surface temperatures as well as changes in the rate at which heat is transported to greater depths. For example, the tropical Pacific fluctuates between warm El Niño and cooler La Niña events on a time scale of 2 to 7 years. Following an El Niño event a mini global warming takes place as heat escapes from the ocean into the atmosphere, while the ocean cools. Similar processes also occur from one decade to the next.

CHANGES IN EXTREMES

Even though an increase of a few degrees in global average temperature does not sound like much, global mean temperature during the last ice age was only about 4 to 5°C colder than now. Global warming of just a few degrees will be associated with widespread changes in regional and local temperature and precipitation as well as increases in some types of extreme weather events. These and other changes (such as sea level rise and storm surge) have serious impacts on human societies and the natural world.

Extremes are classified in two main ways. One is when values exceed certain thresholds, such as 30°C temperature. Another is events that are outside the bounds of normal experience at that location. In this case the events are inherently statistically rare, and often not well documented owing to short incomplete records. But when the climate changes, while most of the time the weather experience is still within the bounds of previous experience, the changes in extremes can be several hundred percent and records are broken. Because of the rarity of such events, they are often very damaging.

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Much of the cost of climate change occurs in association with extremes.
There are many examples in recent years of major extremes that have occurred in association with human-induced climate change, ranging from heat waves and wild fires in Russia in 2010, to the USA in 2011 (Texas, Arizona) and 2012 (widespread), and Australia and China in 2013; super storm Sandy in the United States in 2012; flooding in Pakistan, Colombia, and United States in 2010; Australia in 2010-11, Argentina, the Elbe in Germany, India, Brazil, Alberta, Canada, and Colorado, United States in 2013, and the U.K. in 2014.

The World Meteorological Organisation's (WMO) state of the climate report for 2013 was released recently, and provides a very useful overview of last year's weather and climate events. It confirms that 2013 was the 6th warmest year in the long term record (tied with 2007), that 13 of the 14 warmest years in that record have occurred this century, and that the litany of extreme weather events that struck the planet is in line with what would be expected on a warming planet. A list of some key climate events of 2013 likely exacerbated by climate change include:

- Greenhouse gas concentrations in the atmosphere reached record highs.
- Typhoon Haiyan (Yolanda), one of the strongest storms to ever make landfall, devastated parts of the central Philippines.
- Surface air temperatures over land in the Southern Hemisphere were very warm, with widespread heat waves; Australia saw record warmth for the year, and Argentina its second warmest year and New Zealand its third warmest.
- Angola, Botswana and Namibia were gripped by severe drought.
- Heavy monsoon rains led to severe floods on the India-Nepal border.
- Heavy rains and floods impacted northeast China and the eastern Russian Federation.
- Heavy rains and floods affected Sudan and Somalia.
- Major drought affected southern China.
- Northeastern Brazil experienced its worst drought in the past 50 years.
- The widest tornado ever observed struck El Reno, Oklahoma in the United States.
- Extreme precipitation led to severe floods in Europe's Alpine region and in Austria, Czech Republic, Germany, Poland, and Switzerland.
- Israel, Jordan, and Syria were struck by unprecedented snowfall.
- The global oceans reached new record high sea levels.

Bangla Bhola town Edge ©Gary Braasch 2014

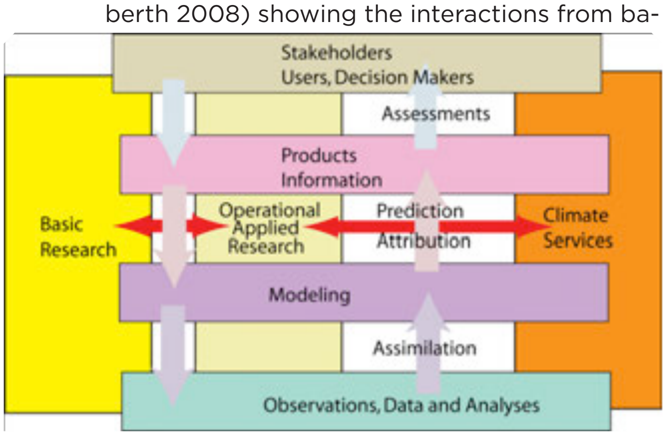
On the other hand, the Antarctic sea ice extent reached a record daily maximum, a likely consequence of the changing atmospheric circulation and especially changing winds over the southern oceans, and frigid polar air plummeted into parts of Europe and the eastern United States, again a regional consequence of changes in the atmospheric circulation. Indeed, there will always be some regions that exceed the global mean values and some will be much less or even with another sign; that is an inherent part of natural variability and weather.

WHAT IS TO BE DONE?

There are three main approaches that should

be followed. The first is often referred to as "mitigation" and it refers to the reduction of emissions of greenhouse gases to greatly slow or even stop further climate change from happening. The second is "adaptation" which recognizes that climate change is happening and it is essential that we all adapt to the changes. In fact we will adapt in some form, either autonomously or through planning, building resiliency, and coping with the changes, or by suffering the consequences. The third is to build an information system to tell us what is happening and why, what the prospects are for the future on different time horizons, and thus what we must adapt to. As a whole we are not doing nearly enough of any of these.
The climate observing system is in decay and satellite observations are in jeopardy, and climate models must continue to improve. Building climate services is a priority of the WMO, but one that is struggling in some countries. In particular, many more observations are needed of social science aspects to properly enable adaptation. The benefits of building a climate information system occur regardless of whether or not climate change occurs.

Fig. 3. The climate information system (Trenberth 2008) showing the interactions from basic, to applied research to operational climate services, and the activities from observations, their processing, the modeling and interactions with users and decision makers.



There are several steps under the adaptation heading. These include assessing the impacts of the projected climate change effects on various regions and sectors, assessing vulnerability to the impacts, making plans to reduce the vulnerability and build resiliency, and generally cope with the expected changes, including extremes. The longer society delays steps to cut the release of planet-warming greenhouse gases, the more severe and widespread the harm will be, according to the IPCC. Global warming threatens food and water supplies, security and economic growth, and will worsen many existing problems, including hunger, drought, flooding, wildfires, poverty and war. The IPCC WG II emphasizes eight major climate risks:

1. Death or harm from coastal flooding
2. Harm or economic losses from inland flooding
3. Extreme weather disrupting electrical, emergency, or other systems
4. Extreme heat, especially for the urban and rural poor
5. Food insecurity linked to warming, drought, or flooding
6. Water shortages causing agricultural or economic losses
7. Loss of marine ecosystems essential to fishing and other communities
8. Loss of terrestrial and inland water ecosystems.

A case can be made that many of the biggest potential issues arise in association with water availability owing to increasing demand and changes from climate change, especially the extremes of drought and flooding.
According to IPCC WG II, global adaptation cost estimates are substantially greater than current adaptation funding and investment, particularly in developing countries, suggesting a funding gap and a growing adaptation deficit. The most recent global adaptation cost estimates suggest a range from 70 to 100 US$ billion per year in developing countries from 2010 to 2050. The IPCC concludes that the world's poorest people will suffer the most as temperatures rise, with many of them

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already contending with food and water shortages, higher rates of disease and premature death, and the violent conflicts that result from those problems.

For mitigation, many good things are happening in towns, cities, States, and some countries, which responsibly attempt to limit their carbon footprint. However, in general the national and international framework is missing, yet it is essential. If one region implements a carbon tax, for example, some companies and even industries threaten to move to the next town or State or even overseas. The main international discussions occur through the annual meetings of the Conference of Parties to the UNFCCC, which was most effective with the adoption of the Kyoto Protocol at COP-3 in 1997. On February 16, 2005, the Kyoto Protocol was ratified by 164 countries, but it did not include Australia and the USA. Australia ratified it much later

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in December 2007 and it has been ratified by 192 parties but not by the United States. The Kyoto Protocol was designed to limit carbon dioxide emissions and those of other greenhouse gases from developed countries, but did not impose restrictions on developing countries. Some good progress was achieved in Europe, but undermined by the tremendous industrialization and emissions from China, in particular, and other developing countries. Great hopes for a further agreement occurred after the IPCC AR4 report in 2007, which announced that "global warming was unequivocal" and the IPCC shared the Nobel Peace Price with Al Gore in 2007. These hopes were carried forward into COP-15 in Copenhagen in 2009, but failed to be realized. One factor was the development of so-called "Climategate" whereby a large number of emails were stolen from the University of East Anglia server, and cherry picked, distorted and abused by climate change deniers to carry out malicious attacks on some scientists who participated in the IPCC report and thereby undermine the scientific basis for the agreements. Although there was no basis for these claims, they appeared to achieve their purpose. Six major investigations of the scientists involved in the hacked emails showed some minor violations of Freedom of Information Acts but complete vindication of all other aspects.

Many arguments relate to the long lifetimes of carbon dioxide, which means it is the accumulated emissions of carbon dioxide rather than the current values that matter most, and therefore developed countries mainly caused the problem. So why should the developing countries be penalized? Many arguments relate to emissions per capita, and that this should be one metric of allocation of responsibility, but the atmosphere cares not one iota about emissions per capita, only about total emissions. In recent years, China has emitted more carbon dioxide into the atmosphere than any other country. And so population should be a major factor. Somehow it isn't! The population and its standards of living relate directly to the demands on precious natural resources that are inherently limited. In that sense, climate change is but part of the major issue of sustainability. Far too many things being done and exploited by humans are simply not sustainable, and it is easy to argue that the world is already way over-populated if we are to eliminate poverty and upgrade standards of living.

The issue really boils down to one of the "tragedy of the commons". The oceans are one major commons, and there is very limited protection of the oceans from the Law of the Sea. The atmosphere is the other major commons. Air over China one day is over North America 5 days later, and over Europe in another 5 days or so. It is in everyone's interest to exploit the atmosphere and use it as a convenient dumping ground for pollutants and emissions. This applies to individuals, companies, industries, cities, counties, states, and nations. But there are major costs, in terms of air quality and climate change that are not borne by the users. There ought to be a principle of "user pays" in which case there is a great need for a price on carbon that is universal. This can be implemented in many ways, through cap-and-trade schemes, fees or a carbon tax, combined with tariffs for international trade involving non-compliant countries.

To this observer, it is not clear that the COP is the right framework to hammer out an agreement. Rather leadership must come from the G7/G8 and G20. The United States has reduced emissions in recent years, in part from deliberate actions by the government under the Obama administration, but without compliance by the Congress. US leadership internationally, along with Europe and China, could set the stage.

There is no doubt that there are winners and losers, and some regions can benefit from climate change through things like a longer growing season. Moreover, climate change is not necessarily bad; after all climate has always varied, but rapid climate change is always disruptive. Further, the climate is changing at unprecedented rates. It may well be that the climate locally changes to be one that is better in some respect, but it won't stay that way because it keeps changing, and changing, and changing. Even short-term benefits sooner or later become negatives as the climate continues to change. So a key point of climate change is the "change" part. No sooner has the climate changed to be nicer than it changes again. It behooves us to greatly slow the pace of climate change in order to provide the future generations with a manageable and livable planet.

REFERENCES AND FURTHER READING

For more detailed discussion of the topics addressed in this document (including references to the underlying original research), see:

General reports and assessments:
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Appendix 1: Climategate

A number of independent enquiries have investigated the conduct of the scientists involved in the hacked emails. All have cleared the scientists of any wrong doing, but the hackers have not been found:

In February 2010, the Pennsylvania State University released an Inquiry Report that investigated any 'Climategate' emails involving Dr Michael Mann, he was fully vindicated.

In March 2010, the UK government's House of Commons Science and Technology Committee published a report finding that the criticisms of the Climate Research Unit (CRU) were misplaced.

In April 2010, the University of East Anglia set up an international Scientific Assessment Panel, in consultation with the Royal Society and chaired by Professor Ron Oxburgh. The Report of the International Panel assessed the integrity of the research published by the CRU and found "no evidence of any deliberate scientific malpractice in any of the work of the Climatic Research Unit".

In June 2010, the Pennsylvania State University published their Final Investigation Report, determining "there is no substance to the allegation against Dr. Michael E. Mann".

In July 2010, the University of East Anglia published the Independent Climate Change Email Review report. They examined the emails to assess whether manipulation or suppression of data occurred and concluded that "The scientists' rigor and honesty are not in doubt".

In July 2010, the US Environmental Protection Agency investigated the emails and "found this was simply a candid discussion of scientists working through issues that arise in compiling and presenting large complex data sets."

In September 2010, the UK Government responded to the House of Commons Science and Technology Committee report, chaired by Sir Muir Russell. On the issue of releasing data, they found "In the instance of the CRU, the scientists were not legally allowed to give out the data". On the issue of attempting to corrupt the peer-review process, they found "The evidence that we have seen does not suggest that Professor Jones was trying to subvert the peer review process. Academics should not be criticised for making informal comments on academic papers".

February 2011, the Dept Commerce Inspector General independent report of the emails and found "no evidence in the CRU emails that NOAA inappropriately manipulated data".

9August 2011, National Science Foundation concluded "Finding no research misconduct or other matter raised by the various regulations and laws discussed above, this case is closed"

Dr. Kevin E. Trenberth

Dr. Kevin E. Trenberth is a Distinguished Senior Scientist in the Climate Analysis Section at the National Center for Atmospheric Research. From New Zealand, he obtained his Sc. D. in meteorology in 1972 from Massachusetts Institute of Technology. He was a lead author of the 1995, 2001 and 2007 Scientific Assessment of Climate Change reports from the Intergovernmental Panel on Climate Change (IPCC), and shared the 2007 Nobel Peace Prize which went to the IPCC.

He served from 1999 to 2006 on the Joint Scientific Committee of the World Climate Research Programme (WCRP), and he chaired the WCRP Observation and Assimilation Panel from 2004 to 2010 and chaired the Global Energy and Water Exchanges (GEWEX) scientific steering group from 2010-2013; he is still a member and chairs the 7th International Scientific Conference on the Global Water and Energy Cycle Committee.

He has also served on many national committees. He is a fellow of the American Meteorological Society (AMS), the American Association for Advancement of Science, the American Geophysical Union, and an honorary fellow of the Royal Society of New Zealand. In 2000 he received the Jule G. Charney award from the AMS; in 2003 he was given the NCAR Distinguished Achievement Award; in 2013 he was awarded the Prince Sultan Bin Abdulaziz International Prize for Water, and he received the Climate Communication Prize from AGU.

He edited a 788 page book Climate System Modeling, published in 1992 and has published 520 scientific articles or papers, including 60 books or book chapters, and over 235 refereed journal articles. He has given many invited scientific talks as well as appearing in a number of television, radio programs and newspaper articles.

He is listed among the top 20 authors in highest citations in all of geophysics.