UNDERSTANDING CLIMATE HISTORY TO PROJECT FUTURE CLIMATE CHANGE

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Abstract.
Planet Earth is now facing the growing challenge of climate change. The active responses of governments and people have been motivated by the science and its assessments that demonstrate the causes of climate change and projections of future climate change and its impacts. Understanding the climates of the past have been a strong factor in confirming our scientific understanding and in terms of verifying global climate models that can then used to project the possible futures. The Milankovic theory of climate change has provided a basis for understanding and testing. This article provides a historic perspective of the how understanding climate history and science has enabled projections of future climate change and its role in motivating global action. The climate science assessments of the Intergovernmental Panel on Climate Change are used to highlight the important scientific advances and their interrelationships influences on policy.

Key words: Milutin Milanković, Climate History, Projecting Climate Futures, International Climate Change Actions

1. INTRODUCTION

Over the past two centuries, the very large growth of the human population and the industrial revolution on Planet Earth have led to massive increases in emissions of chemical substances and gases into the atmosphere, terrestrial ecosystems and the oceans. The scientific consensus is that our planet has entered the Anthropocene, the age of dominant humans, a new geologic epoch defined by our own massive impact on the planet [51]. The UN Secretary-General António Guterres at the 2019 Climate Action Summit stated [58]: "*Climate change is the defining challenge of our time.*" There is the need to address climate change within the Global Agenda 2030, which also includes the Sustainable Development Goals and the Sendai Framework for Action Disaster Risk Reduction [33].

The World Economic Forum [56] 2020 Global Risk Report [57] (published in January 2020) ranked by impact and likelihood, the global risks (*an uncertain event or condition that, if it occurs, can cause significant negative impacts for several countries or industries within the next 10 years*). Environmental risks were ranked very high with Climate Action Failure (both mitigation and adaptation) as the number one risk by impact and the number two by likelihood. Extreme weather events (storms, floods, …) causing major property, infrastructure, and/or environmental damage as well as loss of human life, were ranked as the highest in likelihood and 4th highest in terms in impacts. These two risks are highly linked. Biodiversity, ranked as the 3rd highest risk in terms of impact and 4th highest in terms of likelihood, and Water Crises, ranked as the 5th highest in impact and 8th highest in likelihood, and are both also linked, at least in part, to climate change.

2. Foundations of Climate Science

The scientific basis [53] for understanding the climate system and its variability goes back over millennia, building on fundamental understanding of the physics and chemistry of the climate system. In 1824, almost 200 years ago, Fourier [8] developed the understanding of the greenhouse effect through the roles of the visible light from the Sun heating up the Earth and the greenhouse gases (water vapour, carbon dioxide, methane and others) absorbing some of the Earth's outgoing radiation and sending it back down to the surface, further warming the Earth. Arrhenius (1896) [1] concluded that doubling the CO_2 in the atmosphere would raise the Earth's global temperature about 5-6^{o}C. The role of solar radiation and the Earth's orbit around the Sun was enunciated in 1920 in the mathematical theories of thermal phenomenon by Milankovitch in 1920 [35]. He followed this up with climate theories in 1930 [36] and their role in glaciers in 1941[37]. This fundamental science, addressing the greenhouse gas effects and the solar radiation and planetary orbits – linked together - has been the basis for what we are now or should be doing in responding to the climate crisis.

Milankovitch's astronomical theory [43] of the ice ages was fully verified in the seminal paper by Hays et al. (1976) [12] who called it the "*pacemaker of the ice-ages*". The analysis was based upon the analysis of oxygen isotopic data from deep-sea sedimentary cores which have been further analyzed in detail by Shackleton et al. (1990) [49] who provided an alternative astronomical calibration of the lower Pleistocene timescale. Ocean cores provided excellent material for high resolution stable oxygen isotope analysis through the past few million years which matched well with orbital models and were in accord with expectations based upon the Milankovitch hypothesis.

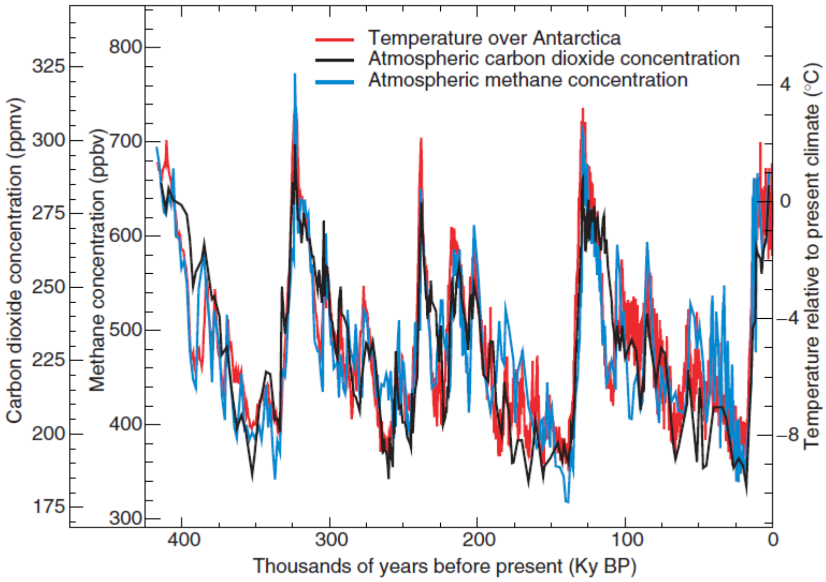

Figure 1. Variations of temperature, methane and atmospheric carbon dioxide concentrations derived from air trapped within ice cores from Antarctic [24][4][7][44]50]

Figure 1 shows the variations of temperature and the greenhouse gases, carbon dioxide and methane, over the past 400,000 years, a period of about 4 ice-age domains and demonstrates interactions within the climate system. As the Earth's orbit around the Sun varies in shape and tilt, the incoming solar radiative energy varies, following the Milankovitch cycles. The reduction in incoming energy results in a cooler climate – the red line. The cooling oceans absorb carbon dioxide from the atmosphere reducing the greenhouse effect, which amplifies the cooling, bringing the red line down further. As the climate cools further, sea ice and glaciers grow leading to the reflection of more solar energy, enhancing the cooling further – so that, as in Figure 1, there is a reduction in global mean temperature of 7-8^{o}C with large glaciation in the north, the ice age about 350,000 years ago. As the Milankovitch components of orbit and earth tilt evolve, the solar radiation increases, resulting in a rapid warming, more rapid than the cooling, as the oceans release the greenhouse gases and the melting ice reduces the reflection of solar energy. This cycle continues with ice ages about 100,000 years. The Milankovitch cycle interacts with the atmospheric, ocean, terrestrial and cryosphere components in the time changing climate. This provides an explanation of planetary history and a test bed for development and testing integrated climate models, providing, through understanding climate history. enabled projections of future climate.

3. Enhancing Climate Science for Action

Climate change became a political issue, initially in the late 1970's and more so in the mid-late 1980's, leading to enhanced scientific studies of the global climate system and greatly strengthened the knowledge base, building on the fundamental science of Newton, Fourier, Milankovitch and others. In 1979, the First World Climate Conference received the scientific evidence confirming the long-term concerns about a changing climate. The International Council of Scientific Unions (ICSU) (now the International Science Council) [17] and World Meteorological Organization (WMO) [59] created, in 1980, the World Climate Research Programme (WCRP) [55], with the scientific objectives: to determine: *the predictability of climate; and the effect of human activities on climate*. The Intergovernmental Oceanographic Commission (IOC) [15] became a co-sponsor in 1992. With the rising international concerns about climate change and related issues of global environmental change, plus emerging discussions on sustainable development, ICSU founded the International Geosphere-Biosphere Programme (IGBP) [16] to: *study earth system science and to help guide society onto a sustainable pathway during rapid global change.*" In 1991, the IGBP created the Past Global Changes (PAGES) project to improve our understanding of past changes in the Earth system in order to improve projections of the future. Their website provides links, for example, to information on "*How the Sun Affects Climate: Solar and Milankovitch Cycles"* [54].

4. Assessments of Climate Science for policy

With the increasing global concern about the climate and possible human-caused climate change, the Intergovernmental Panel on Climate Change (IPCC) [18] was created in 1988 to: (*i) assess available scientific information on climate change, (ii) assess the environmental and socio-economic impacts of climate change, and (iii) formulate response strategies*. Over the years, the scientific programs planned and coordinated by the WCRP and the IGBP (now part of Future Earth [10], created by merging IGBP with other international projects) have been the major source of scientific results for the IPCC assessments. The IPCC is structured with three Working Groups: Working Group I assess the physical science underpinning past, present, and future climate change and how it is changing in response to human activity – and is the focus of this article. Working Group II assesses the impacts, adaptation and vulnerabilities related to climate change and Working Group III focuses on climate change mitigation, reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere.

The advancements in science and the increased warming of the climate system and concentrations of greenhouses have been reflected in the IPCC's assessments. The IPCC First Assessment Report (FAR) [20], completed in 1990, includes Chapter 2 on Radiative Forcing of Climate, addressing the issue of climate variability due to orbital changes. As they said: "*Variations in climate on time-scales ranging from 10,000 to 100,000 years, including the major glacial/interglacial cycles during the Quaternary period, are believed to be initiated by variations in the Earth's orbital parameters which in turn influence the latitudinal and seasonal variation of solar energy received by the Earth (the Milankovitch Effect).*" They went on to comment on the factors seen in Figure 1. The orbital parameters and the Earth's climate provide a "*compelling argument in favour of the Milankovitch theory"*, while the internal feedback processes, as discussed above, are very important. Chapter 7, on Observed Climate Variations and Change [21], concluded that the Milankovitch orbital effects (Berger, 1980) [2] "*appear to be correlated with the glacial-interglacial cycle since glacials arise when solar radiation is least in the extra-tropical Northern Hemisphere summer"*. Regarding the important question - has the climate changed and is the change due to human activities - the FAR states: *"The observed increase (in temperatures) could be largely due to natural variability; alternatively this variability and other man-made factors could have offset a still larger man-made greenhouse warming."* The Report also laid out a scientific action plan [30] for improved prediction of global climate change to narrowing the uncertainties

This IPCC First Assessment Report (FAR) was presented to the Second World Climate Conference [48] in 1990 and the Conference, including many heads of state, made a recommendation to the 1992 United Nations Conference on Environment and Development (UNCED) [52], also called the Earth Summit, held in Rio de Janeiro, which created the Framework Convention on Climate Change (UNFCCC) [9].

The IPCC Second Assessment Report (1995) (SAR) [22] examined the many issues of climate change including analyses of changes in sea examining the geological and geophysical effects (Chapter 7) with a focus on long-term sea-level changes and issues of post-glacial rebound [6][39][40]. Among their conclusions were that adjustments to the effects of deglaciation throughout the Holocene period (last 10,000 years) are important [42] and the use of paleo-data and the Milankovitch connections were important in evaluation of internal variability and feedbacks in climate system [41]. Adjustments of the post-glacial rebound-related land movements as estimated from tide gauge records and use of Peltier's model [42] were cited. The Assessment [31 included the recommendations: "*to build confidence in the decade-to-century time-scale natural variability simulated by models, there is a need to compare model attempts to mimic the climate of the last 1000 years with variability estimates from paleo-climate data with comparable time resolution. …. the need to identify the forcings, for example solar, volcanoes, deforestation, … phase lags and leads at very large spatial scales which are potentially testable given appropriate paleo-data."*

Following the FAR statement the SAR examined the whether the climate was changing and its cause and noted that: "*Changes in climate have occurred in the distant past as the distribution of continents and their landscapes have changed, as the so-called Milankovitch changes in the orbit of the Earth and the Earth's tilt relative to the ecliptic plane have varied the insolation received on Earth, and as the composition* *of the atmosphere has changed, all through natural processes.*" "*More convincing recent evidence for the attribution of a human effect on climate is emerging from pattern-based studies*" and that "*The vertical patterns of change are also inconsistent with those expected for solar and volcanic forcing*" were conclusions. Building on this information and atmospheric temperature analyses and model studies of Santer [47] and Mann [29], the conclusion was that: "*the balance of evidence suggests a discernible human influence on climate*".

The IPCC Second Assessment Report was presented to the 1996 Climate Convention Conference of Parties (CoP2), in Geneva. The delegates agreed to the Geneva Ministerial Declaration [11], which stated: "*2. Recognize and endorse the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) as currently the most comprehensive and authoritative assessment of the science of climate change, its impacts and response options now available. … a scientific basis for urgently strengthening action at the global, regional and national levels, particularly action by Parties … 3. Believe that the findings of the Second Assessment Report indicate that the continued rise of greenhouse gas concentrations in the atmosphere will lead to dangerous interference with the climate system, given the serious risk of an increase in temperature and particularly the very high rate of temperature change.*" The Geneva Declaration was presented at the opening of the 1997 CoP3 in Kyoto and contributed to the agreement of the Kyoto Protocol [27].

The Third Assessment Report (TAR) [24] concluded that: "*There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities.*" Chapter 2 on Observed Climate Variability and Change was especially important as it examined the temperature of the past 1000 years and addressed the questions of the "little ice age", the "Medieval warm period" and the volcanic and solar effects in the recent record. The conclusion is that the "*rate and magnitude of global surface 20th century warming is likely to have been the largest of the millennium, with the 1990s and 1998 likely to have been the warmest decade and year, respectively in the Northern Hemisphere*". The Assessment examined the Holocene, which began about 11,000 to 10,000 before the present. The early Holocene was generally warmer than the 20th century with variations between regions. Ice cores from northwest Canada (Ritchie) [46] documented an "*early Holocene Milankovitch thermal maximum*". Chapter 6 of the Assessment, on the Radiative Forcing of Climate Change, examined atmosphere-ocean general circulation models (AOGCM) and compared present-day versus paleoclimate (e.g., last glacial maximum) simulations, including those of Rind et al. (1989) [45] and Berger et al. (1993) [3].

The 2013 IPCC Fifth Assessment Report's Chapter 5 [28] on Information from Paleoclimate Archives included that: "*Recent modelling work provides strong support for the important role of variations in the Earth's orbital parameters in generating long-term climate variability. In particular, new simulations with GCMs (Carlson et al., 2012)* [5]*; Herrington and Poulsen, 2012* [14]*) support the fundamental premise of the Milankovitch theory that a reduction in NH summer insolation generates sufficient cooling to initiate ice sheet growth*". Helama et al. (2010) [13] examined Milankovitch solar forcing of past Holocene climates. The Fifth Assessment Reports were provided to the UN Climate Convention Conference of Parties in 2015, in Paris, leading The Paris Agreement [38]. The next full IPCC Assessments will be published in 2021.

Throughout the now almost 30 years of IPCC scientific assessments, there has been examination and support of the Miliankovitch theory and its utilization in understanding the climate system and assisting in the development and verificaiton of projection models, and its importance in terms of providing international climate science assessments addressing the IPCC objectives and the international policy dimensions.

5. Seeing the Future - Prediction

To address the issues for sustainable development, there is an essential need for science-informed decision making [33]. There are significant issues of sciences and policy on how to "*see the future*". To look ahead to the future, we need to have evidence-based predictions of our global system, including environmental, societal and technological changes (Figure 2, left).

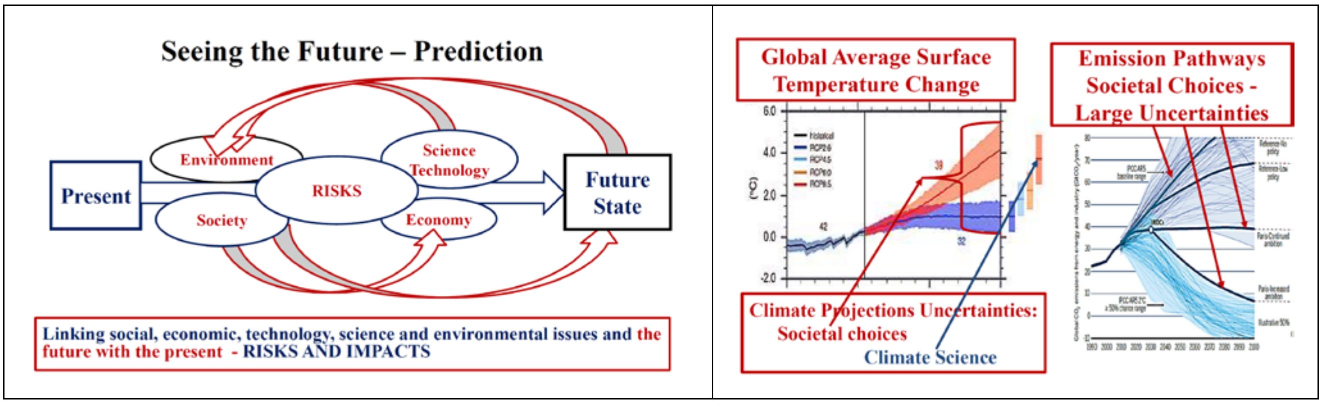

Figure 2. Seeing the Future – Prediction. The interactions between social, economic, science and technology and environmental issues with feedbacks (left)[32]. Choices in responding to climate change – and their uncertainties – climate science and societal choices (right). (*Based on IPCC, 2014 Assessment [26].)*

Predictions [32] of future states require understanding and incorporating the implications of science and technology and society in iterative ways, recognizing that changes in technology result in changes in society and vice versa. Further, as the future state becomes clearer for a specific projection based on the "*best*" estimates of technological and societal changes, these may "*feedback*' into the societal response, resulting in the modifications to the prediction of the future state. A fundamental role of the science and technology community is to work closely with the social science community to enable the prediction of future states through an integrated, continuously iterative process of refinement to reduce uncertainty and provide the "*best*" estimates of futures states as well as clarification of the assumptions inherent in the prediction such that the societal processes can, when possible and appropriate, modify societal changes.

For some natural science issues, such as the tides and related lunar orbits, there are laws of physics that relate the present state to the future state. Milankovitch theory and cycles built on laws of physics to provide the driving forces for variations in solar radiation energy. Projecting climate over the next century not only includes the uncertainties in the present state and the natural scientific relationships, but, equally importantly, the actions that societies will or will not take to reduce their interference with the climate system through emissions of greenhouse gases and the changes in the conditions of the planetary surface.

Seeing the future climate (Figure 2, right) means understanding the climate as a natural system and how it changes with increasing greenhouse gas concentrations and, also understanding human societies and their choices on greenhouse gas emissions resulting in changing the concentrations. There is uncertainty in the natural science models for projecting the temperature change, depending on which emissions scenario will happen in the decades to come. There is even larger uncertainty on which emission scenario global society will effectively follow. It is very important to understand the interconnectivity between actions and responses across and around the planet with its major societal, logical and philosophical issues. Understanding science, all sciences, is a fundamental way to look ahead – see how things are now and use relationships to see the future. Uncertainty in the natural science models' projections of temperature change for different emission scenarios are smaller than the larger uncertainty on which emission scenario global society will effectively enact.

As shown schematically, projections or predictions of future states require understanding and incorporating the implications of science and technology and society in iterative ways, recognizing that changes in technology result in changes in society and vice versa. Further, as the future state becomes clearer for a specific projection based on the "*best*" estimates of technological and societal changes, these may "*feedback*' into the societal response, resulting in the modifications to the prediction of the future state. There is need for the natural (physical-chemical-biological-geophysical-mathematical…) sciences and technology communities is to work closely with the social science communities to enable the prediction of future states through an integrated, continuously iterative process of refinement to reduce uncertainty and help to provide the "*best*" estimates of futures states.

6. Concluding Comments

Over the past decades, Planet Earth has seen a changing climate and the scientific understanding of the complex climate system has been greatly enhanced, through leading scientists who applied fundamental scientific thinking to develop and test hypotheses and theories, leading to understanding and predictions of the future. Professor M. Milankovitch was one of those scientists. His development of the Milankovitch theory and the explanations of the driving forces for the last million plus years of climate and the ice ages provided a basis for climate system scientific understanding. He continued his contributions over decades and his science has provided a basis for many scientists to further develop and extend our global understanding of the complex climate system enabling predictions.

7. Acknowledgments

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