A Model of Earth System Operation as a Basis for Planetary Restoration

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Abstract

We introduce a theoretic model of Earth System behaviour based on Milankovitch cycles and observations of temperature and sea level from the late Eemian up to the early Holocene. The late Holocene had exceptionally stable climate, temperatures and sea level compared to this previous period. The Earth System left this period of anomalous stability with an acceleration of Arctic warming from around 1980, as shown by surface and satellite measurements. The Arctic appears to be switching from a state with sea ice throughout the year to a state where there is very little sea ice by the end of summer and we show how weather extremes are becoming ever more severe as a result. Our model of Earth System behaviour can be used as a basis for restoration of the Earth System to its 1980 state or earlier, starting by cooling the Arctic using SRM (solar radiation management) since SRM techniques provide the most powerful cooling capability currently available. Research is urgently needed into optimum safe deployment of SRM, in the light of this model which predicts high risk of catastrophic climate change and sea level rise if powerful cooling action is not taken quickly.

Introduction

The current policy of CO2 emissions reduction, accepted by the majority of nations, is inadequate to address accelerating climate change and sea level rise. Urgent cooling intervention is required, particularly to refreeze the Arctic.

Sudden vast changes in climate and sea level have occurred in the past and could be happening again, triggered by global warming. Our objective is to show that an understanding of Earth System operation can point to practical and affordable SRM cooling techniques for quickly reversing climate change, but also slowing sea level rise and helping to restore the planet to a demonstrably safe and sustainable state in which future generations can prosper and biodiversity flourish. Cooling the Arctic is particularly urgent.

We are aware of a number of barriers to be overcome: firstly a huge and scientifically unwarranted stigma attached to these cooling techniques; secondly the resistance of the climate science community (and the governments who fund their research) to any change in policy; and thirdly the opposition of certain countries and industries to the refreezing of the Arctic. But perhaps the largest barrier is that of disbelief: people cannot reconcile the idea that intervention is required with their innate belief in the stability of the Earth System, as embodied in Mother Nature.

Milankovitch warming signals

The most important Milankovitch cycles are produced by variations in the distance of the Earth from the sun (100 kyr cycles of eccentricity), the angle of the Earth’s axis to its orbital plane (41 kyr cycles of obliquity with a maximum 24° in the Early Holocene), and the direction that this axis is pointing (26 kyr cycles of axial precession). These three independent cycles together produce variations of the total amount of insolation in the Northern Hemisphere (NH) summer. Periods of deglaciation coincide with peaks of this insolation. For the past million years they have been about 100k years apart until the Eemian which ended about 120 kya. The thermal maximum within the Holocene was around 8 kya and followed a peak Milankovitch warming signal in the NH summer.

Milankovitch signals and climate change

The Earth System (ES) is asymmetric with land around the South Pole and sea around the North Pole. This has been the case for the last 2.58 million years to the present day: a period known as the Quaternary. Snow more naturally settles on land, accumulating to form an ice sheet. There is naturally more ice in Antarctica than in the Arctic, and it is colder. This asymmetry has remained for the whole of the Quaternary. But within this time there have been alternating glacial and interglacial periods synchronised by Milankovitch signals. Entering a glacial period, the ice in the north greatly expands and sea levels fall. Entering an interglacial, the ice in the north contracts and sea levels rise. Between the glacial and interglacial maxima, temperatures vary by around 10C and sea levels by around 125 metres.

There is a sophisticated mechanism – a subsystem of the ES – which amplifies the Milankovitch signal (peak warming in NH summer) and warms the whole planet, melting ice everywhere and raising the sea level. Sometimes this is sufficient to take the planet firmly into an interglacial period. If so, the planet may move back into a glacial period when the warming signal subsides.

In our model of ES operation, the essential components of this mechanism include the Gulf Stream, the Atlantic Meridional Overturning Circulation (AMOC), the Greenland Ice Sheet (GIS) and the 6-banded structure of global atmospheric circulation (with three Hadley cells in each hemisphere). Evidence comes from pollen, ice cores, ice-rafted debris (IRD) and reverse modelling. IRD appears in the North Atlantic after NH temperatures have peaked, as recorded in pollen and Greenland ice cores. This shows that giant icebergs have been discharged from Arctic glaciers and have floated thousands of kilometres before completely melting. Reverse modelling, in which a climate model for the Arctic is run backwards to reconstruct the past, suggests that the Arctic Ocean became seasonally ice free during the Early Holocene, see below.

Amplifying and switch mechanism

The amplification of the Milankovitch signal is obtained primarily through melting of Arctic sea ice. This reduces albedo in the Arctic causing positive feedback: a vicious cycle of warming and melting known as “Arctic Amplification”. The warming also causes snow retreat and further positive albedo feedback. The climate forcing from albedo loss since 1979 may have reached as much as 1.0 W/m2, globally averaged.

The heat of the Milankovitch signal is absorbed by surface water flowing into the Arctic. The majority of surface water north of 50N flows into the Arctic: from the Atlantic, from the Pacific, and from large Canadian and Siberian rivers. A prime source is the Gulf Stream, which gets extra summer heat from insolation across the sub-tropics and beyond. The Gulf Stream sends a jet of warmed water across the North Atlantic towards the British Isles and Norway. This water acts like the jet in a liquid switch, switching the Arctic Ocean towards a seasonally ice-free state. Conversely any diversion, dilution, weakening or cooling of the jet has an amplified effect in the Arctic to restore perennial sea ice. This is a negative feedback to Arctic Amplification. For example, one such negative feedback is meltwater from the GIS – the spreading of meltwater over the North Atlantic in summer causes a huge “cold blob” over its surface and slows the retreat of sea ice.

There is strong evidence that, leading up to the Holocene thermal maximum, the Arctic Ocean became seasonally free of sea ice for a thousand years or more. This would have been the result of rapid warming as the Milankovitch signal approached its maximum. A decline in the signal, plus a large injection of cold freshwater into the North Atlantic or the Arctic Ocean itself, would have switched the Arctic Ocean back to the perennial state.

The past role of CO2

CO2 takes a subsidiary role in the coming and going of glacial periods (“ice ages”). Milankovitch cycles are the prime drivers for the major changes in the past, not CO2. Thus trying to correlate past temperatures with CO2 in order to determine the “climate sensitivity” of the planet is misguided. Certainly the CO2 level reacts to temperature: its concentration decreases as oceans cool and vice versa. But this is a reactive feedback rather than a driving effect. The CO2 level following temperature can be clearly seen in the Early Holocene records.

At the depth of glacial periods, oceans are cool and the CO2 level is at its minimum. One theory is that, at around 185 ppm, the decline was sufficient to produce die-off in forests and grasslands, releasing CO2 and methane into the atmosphere as a negative feedback to the cooling. The low temperature certainly resulted in arid conditions and more dust being blown onto the oceans, which increases productivity. Some dust would have landed on snow and ice, reducing albedo and warming the planet. According to one theory this effect would have been strong enough to take the planet out of a glacial maximum. It is well accepted that dust and ashes from super-volcanoes would have been sufficient to take the planet out of a snowball state. Currently we are seeing a dangerous reduction in Arctic albedo due to dust and soot from wildfires and tundra fires which have increased due to extremes of hot and dry weather. This is a strong positive feedback to Arctic amplification. The release of methane and exogenous heat from thawing permafrost is another.

At the last glacial maximum (LGM), 21 kya, the concentration of CO2 was about 185 ppm. A rise in concentration from 185 ppm to around 270 ppm took place prior to the start of the Holocene 11.7 kya. There was then a decline to 264 ppm by 9 kya followed by an increase to 280 ppm by around 1900, the baseline used by IPCC.

Since 1900, concentrations of CO2 have increased steadily and the forcing effect from this excess CO2 in the atmosphere is now around 2.0 W/m2. CO2 concentration at >415 ppm is now the major contributor to global warming with the other main greenhouse gases, methane >1908 ppb and nitrous oxide >334 ppb, together contributing over half as much forcing again.

Arctic amplification and sea level rise (SLR)

Over the course of the Quaternary period, the sea level has varied by about 125 metres almost totally due to varying quantities of ice on land. Ocean expansion and contraction only explain a few metres since global temperatures only varied by around 10°C.

Most of the variation in ice during the Quaternary occurred in the NH, with ice just reaching London in the UK during the last glacial period. At the LGM, 21 kya, the sea level was around 125 metres below today’s. The sea level rose 6-9 metres above today’s at or near the end of the Eemian, ~120 kya, due to a partial collapse of ice sheets in the Arctic and Antarctic, the latter contributing twice as much as the former. The maximum global temperature then was similar to today’s global temperature.

Since the LGM there have been a number of rapid bursts of SLR known as meltwater pulses. At the end of the Younger Dryas 11.7 kya there was in increase in Arctic temperature of 7-10°C within 50 years, initiating 20m of SLR over 400 years: an average of 5cm per decade. This is salutary. Without cooling intervention global warming is liable to reach 2°C (above the IPCC baseline) by around 2045. Continued rapid Arctic warming could take its temperature to 8°C within the same period. This would make partial collapse of the GIS almost inevitable at some time this century.

Due to planetary dynamics, meltwater from the Arctic raises the sea level in Antarctica and conversely melt water from Antarctica raise the sea level in the Arctic. The speed of descent of a glacier ending in the sea is affected by changes in sea level at its termination. Thus a few metres of meltwater from GIS could trigger perhaps twice as much meltwater from Antarctica as happened at the end of the Eemian. Some major Antarctic glaciers may already be past their tipping points, so this triggering from GIS is a real threat. A partial collapse of the GIS could thus result in many metres of SLR within a very short period.

Several other factors affect the velocity of glacier descent, in particular the temperature of the water melting its termination and the quantity of meltwater lubricating its base. Thus both land and sea surface temperatures are critical in determining the future of SLR for the planet. For example GIS glaciers’ descent velocities are increasing due partly to warming of the Gulf Stream water licking at glacier terminations and partly due to high surface temperatures melting the surface of the ice, with meltwater descending through moulins to lubricate the descent of the glaciers.

Worldwide, glaciers have been losing ice mass over many decades, but since 1980 the rate of loss has been increasing, with one pause during the Pinatubo eruption. The contribution of glaciers to sea level rise is now overtaking the contribution from ocean expansion. Noting that 360 gigatonnes of meltwater raises the sea level by 1mm, the glacier contribution to SLR has approximately doubled from ~1 mm/yr to ~2 mm/yr over the past ten years. Continued doubling every ten years would give us 32 mm/yr by 2062 and around 90 cms of SLR in the next fifty years as a result of accelerated glacier and ice sheet meltwater discharge.

The glacier contribution is in addition to the contribution from ocean expansion. This was around 20 cms over the past 100 years when the average sea surface temperature was around 0.3°C; so if the average increases to 1.5°C this century we could expect a metre of SLR from ocean expansion alone. The IPCC has estimated a maximum of one metre SLR this century, so it appears that they are not taking the accelerating contribution from glaciers into account.

However, the IPCC and others have warned of tipping points being triggered at only 1.5°C of global warming, and the collapse of the GIS is one of these.

The immediate issue for small island states and low-lying populations is that flooding arises as a combination of SLR and storm surges. Over the next few decades the latter will dominate. The damage from storm surges is affected by the jet streams. A sticking jet stream can slow the movement of a storm making heavy rainfall last for longer. It can also block the movement of a storm in a certain direction. Hurricane Sandy is an example of where the jet stream blocked the passage of the hurricane up the east coast of USA and the hurricane turned westward towards New York causing huge damage. We discuss jet stream behaviour below.

The partial collapse of GIS may be highly unlikely in the next twenty years, but, if we take risk to mean the product of probability and impact, there is an argument that GIS collapse is the greatest risk as it would have a huge impact on coastal communities, agriculture and infrastructure around the world. It would be an existential threat to small island states and low-lying countries like Bangladesh and Vietnam.

There is an added risk for countries bordering the North Atlantic. The sudden collapse of major GIS glaciers could cause cascades of gigaton ice blocks descending at avalanche speeds into the sea, creating megatsunamis in the ocean as well as the sudden sea level rise affecting coastal regions around the world. It would be impossible to defend against such a catastrophe and the cost in lives and damage would be inestimable.

Minimising the risk of GIS collapse should be priority for climate action and by itself justifies urgent measures to cool the Arctic and the Gulf Stream water entering the Arctic on either side of Greenland. Proposals to slow glacier descent, e.g. by protecting terminations, should be considered as additional measures.

Arctic amplification and extreme weather

An understanding of the effect of Arctic amplification on jet stream behaviour is fundamental to understanding extreme weather. Arctic amplification means that the Arctic is warming faster than the global average. The IPCC typically gives a factor of two, but this is averaged over a century or so. Recent observations suggest that Arctic temperatures have been rising about four times faster than average global temperatures. This means that the temperature gradient between the Arctic and tropics has been reducing which is disrupting jet stream behaviour causing increasing extremes of weather and climate, as explained below.

The banded structure of global atmospheric circulation, known as Hadley cells, is formed because of a combination of the Earth’s circulation and the heat differential between tropics and poles. There are three cells in each hemisphere: easterly winds are associated with the subtropical cell; westerlies with the mid-latitude cell; and easterly with the polar cell or “polar vortex”. Jet streams form at the boundaries between the subtropical cell, mid-latitude cell and polar vortex in each hemisphere. The jet streams oscillate to north and south in what are known as Rossby waves. These circle the planet, moving in an easterly direction. The energy which drives these waves in the NH has been diminishing as the temperature gradient between Arctic and tropics has diminished over the past forty years of Arctic amplification. This reduced energy has led to two trends in the Rossby waves: they meander further to north and south; and they tend to get stuck in blocking patterns. The meandering means there is a trend towards greater extremes of heat in the north and cold in the south. The blocking patterns means that weather stays in one place for longer times, giving the “stuck weather” syndrome so commonly experienced recently. Where the weather is stuck in a hot dry spell, a heat dome can build up producing extremes of heat and drought (as seen in the Pacific North West); where the weather is stuck in a rainy spell (e.g. from a hurricane) it can cause extreme flooding; and likewise for cold spells and blizzards.

Global warming has generally increased the heat of hot spells and the precipitation in wet spells. We suspect that the majority of weather extremes which have occurred in the Northern Hemisphere over the past two or three decades can be attributed to a combination of global warming and the jet stream disruption from Arctic amplification. The disruption of the jet stream has been plain to see, and the consequences obvious. The argument that Arctic amplification disrupts the jet stream to cause weather extremes, as proposed by Jennifer Francis a decade or more ago, is difficult to dispute.

Immediate emergency climate action

The implications for climate action are hugely significant. The risk of GIS disintegration will grow as the Arctic warms. Extremes of weather and climate will get more severe while Arctic amplification continues. The only possible action to reverse these trends is through reducing the temperature in the Arctic, effectively refreezing it to some extent. This necessarily involves some kind of solar radiation management (SRM). IPCC’s current strategy of emissions reduction is totally inadequate to deal with the situation. Indeed the IPCC has confined SRM to long-term research, with no advocacy for field trials. A new strategy is required where the top priority is to lower the Arctic temperature using the most powerful SRM techniques available. This will be resisted by organisations, including the US government, wishing to exploit a warmer Arctic for its resources and/or sea routes. But the damage to even the wealthiest countries from the effects of unabated Arctic warming should outweigh any advantages from its exploitation. A realistic cost-benefit analysis is required to establish this.

Refreezing the Arctic

A vicious cycle of warming and melting has built up in the Arctic, partly due to albedo positive feedback but also aggravated by the entry of warm Atlantic and Pacific waters into the Arctic Ocean. The cycle has to be broken and waters cooled before the Arctic can be refrozen. Our group, PRAG, has already produced a review of methods for refreezing the Arctic which was presented at AGU 2020. Since then our focus has been on the two most powerful methods: marine cloud brightening (MCB) using seawater to create cloud condensation nuclei; and stratospheric aerosol injection (SAI) using SO2 to create a reflective aerosol haze. MCB is known to work because of ship trails. But the technology now being developed relies on the production of droplets in a certain critical size range, and the technology to produce them is yet to be demonstrated on a sufficient scale to brighten clouds. The potential is to provide local cooling but there is dependency on suitable marine cloud availability over large enough areas to cool the Arctic and surface water flowing into the Arctic. On the other hand SAI has the prime exemplar of large volcanic eruptions producing SO2 in the stratosphere which can be monitored for cooling effect. The spreading of the SO2 by stratospheric circulation produces a blanket cooling effect suitable for cooling the whole planet or just the poles. There is no problem of scalability as enough SO2 can be supplied to produce whatever blanket cooling is required. MCB can be added for local cooling. Deployment costs are estimated to be in the tens of billions of dollars per year, whereas the costs in the absence of such cooling run into trillions of dollars per year and millions of lives.

The Pinatubo eruption in June 1991 produced about 0.5°C of global cooling over two years. On the downside it produced some ozone depletion. A recent research study suggests that SAI with injection poleward of 60° could cool the poles by 2°C with only a small manageable risk from ozone depletion. The injection would be during late spring and early summer such that almost all the aerosol would leave the stratosphere within two or three months due to Brewer-Dobson circulation. This should almost entirely avoid ozone depletion since the reaction that causes the ozone hole is a cold temperature reaction which occurs at the end of winter when the upper stratosphere is coldest. The objective would be a blanket cooling over the whole polar region: this would increase the pole-to-tropics temperature gradient thereby reducing extremes of weather and climate produced by Arctic amplification. Injection poleward of a lower latitude, e.g. 50° rather than 60°, would do more to cool the sub-polar regions, stabilise the GIS, and slow release of methane from permafrost.

Hitherto, the idea of SAI has been met with extreme scepticism by the scientific community. Our examination of the evidence finds that SAI is potentially benign. A realistic reassessment is urgently required, since calculations may find that SAI is the only cooling technique with enough power to refreeze the Arctic.

There is much scientific work still to be done with no time to lose: in assessing cooling power requirements, in validating the expected Brewer-Dobson circulation at high latitudes, in modelling to assess optimum deployment, in designing trials, in monitoring, and in ensuring early detection of side-effects.

Redressing the Earth's energy imbalance

There is an energy imbalance in the ES of around 1.7 W/m2 according to some estimates, but this does not include Arctic albedo loss which could add another 0.5 – 1.0 W/m2. The result of this imbalance is a global heating of ~0.25°C per decade and ~1.0°C per decade in the Arctic. As a result of reduced cooling from SO2 emissions, the global heating rate could double to ~0.5°C per decade and Arctic heating rate double to ~2°C per decade. The retreat of non-polar glaciers is already causing severe water shortages in some countries. Continued heating of the ocean, which absorbs over 90% of the energy balance, is contributing to SLR through ocean expansion and contributing to flood events in low-lying areas of the planet through increased storm intensity. The behaviour of the El Niño Southern Oscillation (ENSO) has been disrupted, causing changes in the timing of monsoons in south-east Asia and the patterns of weather in Australasia.

In order to avoid further hardship and damage, especially in the Global South, global cooling is required on a much shorter timescale than can be produced by emissions reduction, even with CDR. Thus the priority for international climate action after reducing Arctic temperatures is to reduce the global mean temperature. A suggested target is to cool the planet to below 0.5°C by 2050, enough to slow sea level rise significantly and allow non-polar glaciers to advance. Again MCB and SAI are prime candidates for cooling on the necessary scale.

Planetary restoration

The mission of PRAG is to restore the planet to a safe, sustainable and productive state. Ideally the Sustainable Development Goals (SDGs) would be achieved at the same time. Cooling the poles and then the whole planet will have multiple benefits, including the restoration of many at-risk habitats. But, for sustainability, it must be possible to phase out SRM. Therefore there is a long-term requirement to reduce the levels of GHGs in the atmosphere towards their pre-industrial levels. This should be done in such a way as to improve land and ocean productivity while safe-guarding biodiversity. Carbon can be sequestered in soils using methods such as biochar which reduces requirements for artificial fertilizers and intensive irrigation where they are necessary. Carbon can also be sequestered in the oceans in ways which boost the marine food chain, improving the lives of 20% of the world's population which rely on fish for their protein. We believe that a target of substantial planetary restoration by 2050 is feasible.

Since Arctic warming started to accelerate around 1980, an ideal target for planetary restoration would be something better than the state of planet in 1980: with the Arctic safely refrozen; with CO2e safely below 380 ppm; with global mean temperature safely below 0.5°; and with SDGs met.

Conclusion

Our vision is of the Arctic refrozen, climate change reversed, sea level rise slowed and the whole planet restored to a healthy state by 2050. Through an understanding of Earth system operation and the efficacy of cooling technology, we believe such restoration is possible and should be demanded by the scientific community. Such an ambitious endeavour will require unprecedented global collaboration. But a safe, sustainable and productive planet is what everyone must want for their children and grand-children.

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