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The Response of Glaciers to Climate Change

A photograph of Dig Tsho, the moraine-dammed lake in the Everest region of Nepal. This breached in 1985 causing significant downstream damage, including the destruction of a newly-constructed hydropower facility. *(Courtesy of Matt Westoby, Northumbria University)*

Glaciers worldwide are shrinking because of global warming, which, since the latter half of the 20th century, has primarily been driven by carbon dioxide released by burning fossil fuels. Going further back in time, climate has always changed, albeit usually at a much slower rate than today, and glacier sizes have always fluctuated; knowledge of those past changes actually strengthens the scientific understanding that today's are primarily caused by humans, and could become much greater in the future.

The authors of this article are active scientists who have been working on climate and glaciological research for many decades, collectively just shy of a century. We have published some 500 peer-reviewed articles on these topics, which have been referenced about 24,000 times in other articles. We state this not to impress, simply to indicate that we have a deep understanding of the topics discussed and the current scientific consensus. This article does not represent the personal views of the authors. Our aim is to summarise this scientific understanding of past, present and future climate change and how it has, and will, impact glaciers around the world. It is not intended to be an exhaustive or comprehensive assessment and we

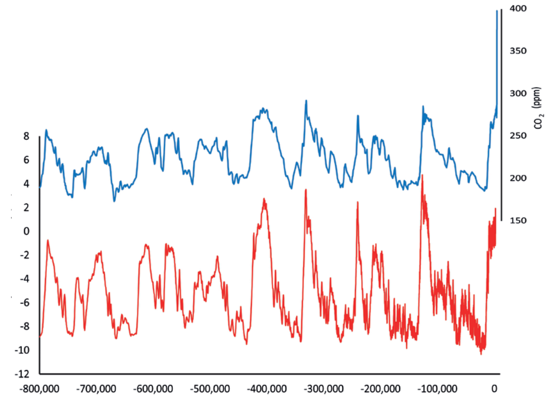
Jonathan Bamber, one of the authors of this article, on the White Spider, north face of the Eiger, August 1989. Today, the route is best climbed in November or spring, due to deterioration of the ice fields. *(Wil Hurford)*

have tried to avoid technical detail, which can be explored further in the references provided, many of which are subscription free. There are aspects of climate change research where open questions exist and a consensus is lacking. Here, however, we concentrate on what is well established and has high certainty.

The vast majority of glaciers worldwide are currently shrinking[1]. Careful monitoring programmes and satellite surveys confirm anecdotal evidence that mountain ranges are changing, affecting routes and creating hazards. In the summer of 2003, for example, local authorities, for the first time in the history of alpinism, 'closed' routes on Mont Blanc and the Matterhorn because of heightened rock fall hazards. Entire icefalls and crevasse fields have disappeared as their glaciers melted away. Landslides are increasing in some places as permafrost melts, and as shrinking glaciers no longer buttress steep valley walls. In other places, glacier retreat has left lakes behind unstable moraine dams, raising the danger of outburst floods[2].

1. D G Vaughan et al, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T F Stocker et al (eds), Cambridge & New York, Cambridge University Press, 2013, pp317-82.
2. S J Cook et al, 'Glacier Change and Glacial Lake Outburst Flood Risk in Bolivian Andes', *The Cryosphere* **10**, 2016, pp2399-413.

Figure 1 Past CO_2 concentrations (blue solid line) and temperature (red line) recorded in an Antarctic ice core, going back 800,000 years. Also shown are recent observations of atmospheric CO_2 concentrations and the current atmospheric CO_2 concentration (c400ppm) measured since the 1950s from the Mauna Loa Observatory, Hawaii, often called the Keeling Curve. *(Data courtesy of NOAA National Climatic data Center, USA)*



The photograph opposite was taken almost 30 years ago, in August 1989, from one of the most famous and iconic mountaineering routes in the world: the Eigerwand. The White Spider looks nothing like this today; the ice fields are so depleted and have deteriorated so much in just three decades that the route is best climbed in November or in spring. Is this due to natural variations in the climate system, or human-induced climate change? Glaciers have changed in the past, but what contribution, if any, are humans making? Here, we summarize some of the evidence on the long but clear scientific path leading from the observation of glacier shrinkage to the confident statement that humans are primarily responsible for current trends[3]. This path takes us through our understanding of glaciers, the physics of the climate system, computer climate models, recent observations, and much more.

First, it is useful to restate the difference between climate and weather. The latter is what happens in a particular day, month or season. Weather is inherently noisy and variable. Climate is the average state over a longer time period, often taken as 30 years by meteorologists. The idea is that taking the average over this period reduces the effects of variations in weather so that long-term trends can be identified. Glacier length variations act as natural thermometers for measuring changing *climate*, as discussed later, because they tend to average out year-to-year fluctuations due to weather and respond on timescales of tens to hundreds of years depending on their size and climatic setting[4]. The surface of a glacier can rise and fall in response to 'weather' (for example between the winter accumulation and summer melt seasons) but changes in extent are more gradual as the average glacier motion adjusts slowly to changes in climate. Typical Alpine glaciers have average speeds of about 100m per year.

3. Intergovernmental Panel on Climate Change, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T F Stocker et al (eds), Cambridge & New York, Cambridge University Press, 2013, pp1-30.
4. W S B Paterson, *The Physics of Glaciers*, 3rd edn, Oxford, Pergamon, 1994, p480.

Climate and glaciers, including the great ice sheets that cover Greenland and Antarctica, have changed in the past, long before humans influenced climate, indeed, long before humans even existed (see *Figure 2*), but a 'four-legged stool' of evidence supports the understanding that recent warming, over the last few decades, and glacier shrinkage are primarily human-caused; these lines of evidence include physics, past climate and ice changes, recent observational data, and computer climate and ice models.

We'll now consider these four 'legs' of evidence, before addressing what they mean for future glacier and ice sheet changes.

The first leg: physics

Extracting and burning carbon-rich material such as coal, oil and gas increases carbon dioxide (CO_2) concentrations in the atmosphere. The human source is roughly one hundred times the natural volcanic source, and CO_2 concentrations in the atmosphere are currently increasing rapidly. Concentrations now exceed 400ppm, meaning that for every one million molecules in the atmosphere, 400 of them are CO_2 (see *Figure 1*). This is greater than at any time over about the last three million years[5]. The warming influence from this (i.e. the 'greenhouse effect') was first calculated by the Swedish chemist Arrhenius in 1896 and physics tells us that there is simply no known way to increase CO_2 concentrations and not have a warming influence, a signal that is routinely observed by satellites and terrestrial data, and also seen in ice cores drilled in Antarctica which go back 800,000 years (*Figure 1*). Without this warming effect of CO_2 and other greenhouse gases, simple physics tells us that our planet would be in a 'snowball' state, with temperatures about 30°C cooler than they are today.

The physics of glaciers is also well understood. Glaciers can change for many reasons, but they are most sensitive to temperature. Warming increases the melt rate on the warmest days and lengthens the melt season, and shifts the snowline higher to include more of the glacier in the zone of melting. It also switches some snowfall to rain. Conversely, warmer air can deliver more moisture when snowing, by roughly 7% per degree C, leading to occasionally heard speculation that warming should instead grow ice. However, across multiple glaciers, loss of ice due to melting increases about 35% per degree C, with some variations[6], meaning that the loss due to warming clearly dominates. In rare cases, changes in debris cover, or in supply of snow by avalanches, or other factors can cause a glacier to grow in a warming climate, and the tendency of some glaciers to surge or otherwise vary for internal reasons means you may need to monitor a glacier for a while to know what it is really doing. However, the great majority of glaciers shrink with warming, and glaciers are actually quite accurate thermometers for past climate, as discussed above[7].

5. M Pagani et al, 'High Earth-system Climate Sensitivity Determined from Pliocene Carbon Dioxide Concentrations', *Nature Geoscience* **3**, 2010, pp27-30.
6. J Oerlemans and B K Reichert, 'Relating Glacier Mass Balance to Meteorological Data by Using a Seasonal Sensitivity Characteristic', *Journal of Glaciololgy* **46**, 2000, pp1-6.
7. J Oerlemans, 'Extracting a Climate Signal from 169 Glacier Records', *Science* **308**, 2005, pp675-7.

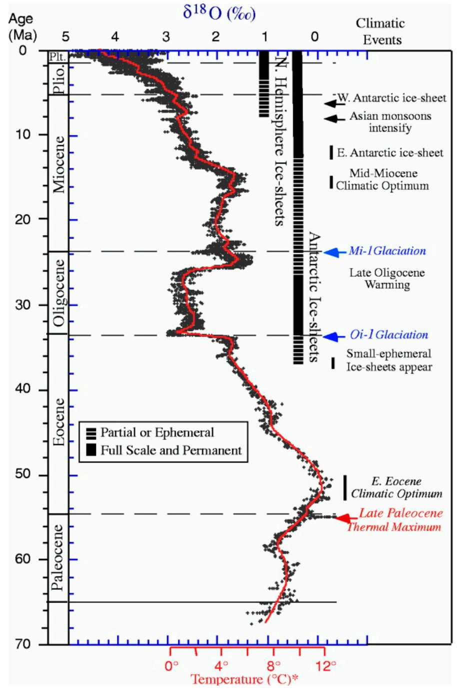


Figure 2 Global ocean oxygen isotope compilation from more than 40 ocean sediment cores shows several major climate transitions. Note the shift from 'greenhouse to icehouse' conditions at 34 Ma BP[8].

The second leg: past climate and ice changes

What about the big changes in climate and ice cover further in the past? These happened with no help from humans. However, as we shall see, they ultimately help confirm our understanding that human-induced climate change is important and becoming more important.

There are many ways of reconstructing past climate and ice changes. One of these is by examining the ratio of two isotopes of oxygen, with atomic mass of 18 versus 16, or ^{18}O and ^{16}O, found in the shells of ancient fossils layered in the sediment at the bottom of the ocean. These we can extract by drilling cores into the ocean floor. Tiny sea creatures called foraminifera live in the lowest layers of the ocean and their shells are made of calcium carbonate ($CaCO_3$). Next time you go climbing in Pembroke, the Dolomites or Julian Alps, remember those cliffs were all underwater millions of years ago and what you're hanging off are dead microfossils. The oxygen isotope ratio, $\partial^{18}O$, depends on the temperature of the oceans and the volume of ice on land and can be used as a 'paleo-thermometer'. Figure 2 shows this paleo-thermometer record for the last 65 million years, since the extinction of the dinosaurs, obtained from multiple ocean sediment cores[8]. About 35 million years ago, or 35Ma BP, there was a change from 'greenhouse to icehouse', or more formally the Eocene-Oligocene transition, when a relatively abrupt cooling of about 4°C took place. This is when extensive ice fields first started forming in Antarctica, at the same time as a decrease in atmospheric CO_2 and while South America and Australia were moving away from Antarctica, forming the Drake Passage and the Antarctic continent we know today (not as erroneously stated in *AJ* 2016, at 1Ma BP[9]). Extensive ice cover in Greenland is more recent, starting around 3.5Ma BP, with large fluctuations in extent since then[10].

8. J Zachos et al, 'Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present', *Science* **292**, 2001, pp686-93.
9. E Mearns and A Milne, 'The Shrinking Glacier Conundrum', *Alpine Journal*, 2016, pp195-207.
10. R B Alley et al, 'History of the Greenland Ice Sheet: Paleoclimatic Insights', *Quaternary Science Reviews* **29**, 2010, pp1728-56.

Clearly there have been dramatic shifts and transitions in the climate conditions of the planet in the past. We believe that these are driven primarily by changes in atmospheric CO_2[11 12], with contributions also from changes in the paleo-geography, the positions of the continents, variations in solar radiation reaching the Earth due to fluctuations of the Earth's rotation and orbit around the sun, and complex feedbacks between these and other parts of the climate system[8]. It is important to note, however, that the changes shown in *Figure 2* were slow compared to human timescales. The E-O transition, for example, took place in two stages over about 500,000 years. That is about two thousand times longer than the time since the start of the Industrial Revolution.

Once the ice began growing in the high latitudes and altitudes, it has waxed and waned, especially in the Northern Hemisphere, for reasons that at first had nothing to do with CO_2. Features of Earth's orbit and axis of rotation result in subtle shifts of sunlight around the planet, pole-wards or equator-wards, later in spring or later in autumn. For example, the North Pole does not point straight up from the plane in which the Earth orbits the sun, being tilted at about 23°, and as a result, the summer sun warms the pole. This 'obliquity' changes slightly over time, as the gravitational pull of other objects in the solar system tug at the Earth and cause the tilt to change, on a cycle of about 41,000 years. Higher obliquity – more tilt – allows relatively more sunlight at the poles, and relatively less at the equator. In addition, the direction that the North Pole points towards, known as the 'North Star' (currently Polaris), changes over 19,000 to 23,000 years. The 'North Star' was Vega 14,000 years ago. The shape of Earth's orbit becomes more and less elliptical over about 100,000 years as Jupiter tugs on us every time we pass it in the orbit. The great mathematician-astronomer Milutin Milankovitch calculated these changes in the early 20th century, predicting they would show up in ice-age records when geologists finally assembled good enough records.

And he was right! The Swiss-American scientist Louis Agassiz consolidated the idea of cycles in glacier retreat and advance. He noticed large rocks, known as erratics, like those used for bouldering throughout the Chamonix valley, that could only have been transported to where they were by glaciers that were no longer present. Thus developed the idea of ice ages, or glacial-interglacial cycles. During periods when summer sunlight has been relatively weak in the far north, ice has grown, whereas during periods when summer sunlight has been relatively strong, ice has melted. The Southern Hemisphere is less important for causing variations in ice sheets; ice has sat on Antarctica for tens of millions of years, and there isn't much land nearby for southern ice to grow, so the big northern landmasses have dominated. In addition, the vast ice sheets in the Northern Hemisphere

11. R M DeConto and D Pollard, 'Rapid Cenozoic Glaciation of Antarctica Induced by Declining Atmospheric CO_2', *Nature* **421**, 2003, pp245-9.
12. D J Lunt et al, 'Late Pliocene Greenland Glaciation Controlled by a Decline in Atmospheric CO_2 Levels', *Nature* **454**, 2008, pp1102-5.

during cold ice-age 'glacial' periods changed many other things in the climate. Sea level dropped over 100m, winds shifted, desert dust was blown around in different patterns, ocean currents rearranged – and some CO_2 shifted from the atmosphere into the deep ocean. During glacials, not only did the ice sheets covering Antarctica and Greenland expand but there were also ice sheets covering Eurasia and North America: the latter called the Laurentide Ice Sheet. At the Last Glacial Maximum, around 21,000 years ago, global average sea level was some 120m lower than the present day[13]. There isn't a single factor responsible for these dramatic shifts in ice cover, but many processes clearly contributed, and the evidence of the CO_2 decrease is very clear (see *Figure 1*). Furthermore, our computer climate models (the fourth leg of the stool) cannot reproduce the cold temperatures of the glacial periods without including the effect of decreased CO_2. Essentially the whole world cooled when sunshine dropped in the far north, and warmed when northern sunshine rose over ice-age cycles, even though large areas of the world had opposite trends in sunshine; the regions that cooled with rising sunshine and warmed with falling sunshine are explained by the trends in CO_2, and not explained otherwise.

The third leg: recent observational data

The last of the major deglaciations started after the Last Glacial Maximum, 21,000 years ago. The interglacial (i.e. relatively warm) period we are now experiencing began about 12,000 BP and is called the Holocene. It is during this period that civilisations and arable farming practices developed and it is characterised by a relatively stable climate compared to past glacials and interglacials. Nonetheless, there have been a number of periods of slight warming, such as the Medieval Climate Anomaly and cooling such as the Little Ice Age, both of which lasted several hundred years[14] (*Figure 3* overleaf). Cooling from the sun-blocking effect of particles from large volcanic eruptions, and temperature changes from slight changes in the brightness of the sun, were instrumental in these small climate changes.

The average global temperature difference between these two events is estimated to be 0.24°C[14] but the effect in the Northern Hemisphere climate was more dramatic. In Europe, the Little Ice Age ended around 1850 and this roughly coincides with the Holocene maximum extent of glaciers in the Alps and elsewhere in the Northern Hemisphere. Since the late 19th century these glaciers have been receding in response to warmer temperatures. *Figure 3* shows the temperature anomalies, deviations from the average, for the last two thousand years for the Northern Hemisphere based on multiple indirect (e.g. tree rings) and instrumental records[15]. All these records show a marked warming trend at the beginning of the 20th century,

13. E Bard et al, 'Deglacial Sea-level Record from Tahiti Corals and the Timing of Global Meltwater Discharge', *Nature* **382**, 1996, pp241-4.
14. M E Mann et al, 'Global Signatures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly' *Science* **326**, 2009, pp1256-60.
15. V Masson-Delmotte et al, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* T F Stocker et al (eds), Cambridge & New York, Cambridge University Press, 2013, pp383–464.

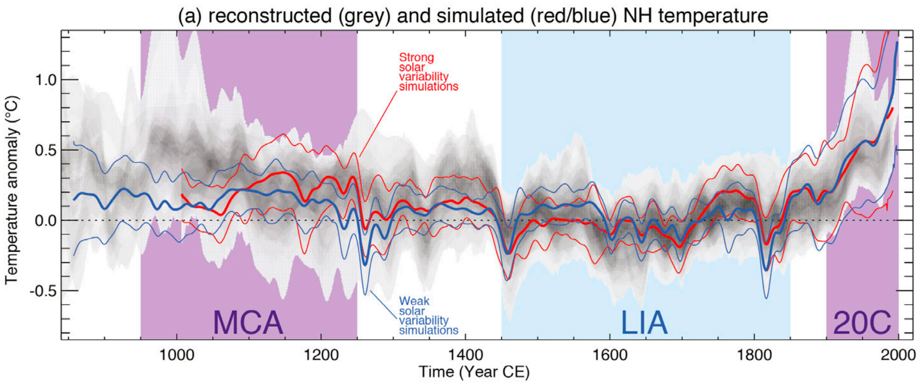


Figure 3 Reconstructed and modelled temperature variations for the Northern Hemisphere over the last millennium, adapted from Fig 5.8 of the IPCC Fifth Assessment Report, Chapter 5[15]. The grey cloud shows the spread of reconstructions from different 'paleo-proxies' such as tree rings, glacier length records, borehole temperatures etc. The thick red and blue lines represent multi-model mean reconstructions using natural (volcanic and solar activity) and human (greenhouse gases) with strong and weak solar variations. The relative warmth of the Medieval Climate Anomaly and cooling of the Little Ice Age can be compared to the warming of the 20th century.

on top of a less intense warming coming out of the Little Ice Age. Not surprisingly, glaciers responded to that warming. It is apparent that the rate and magnitude of warming is unprecedented during the last two thousand years. Interestingly, the rate of sea level rise over the same time period shows a similar trend[16] and the rate over the last 25 years of 3.2mm per year is around twice the value for the 20th century[17]. Warming since the pre-industrial era, defined as pre-1880 when CO_2 concentrations in the atmosphere were around 280ppm, is 0.85°C, equivalent to over three times the contrast between the Medieval Climate Anomaly and the Little Ice Age[18]. Atmospheric CO_2 levels now exceed 400ppm (*Figure 1*).

The fourth leg: computer climate and ice models

So how much of the observed warming and glacier shrinking is due to natural variability in the climate system and how much is due to human-induced warming as a consequence of the increased concentrations of greenhouse gases? The most comprehensive synthesis of evidence addressing this question was undertaken by the Intergovernmental Panel on Climate

16. R E Kopp et al, 'Temperature-driven Global Sea-level Variability in the Common Era' *Proceedings of the National Academy of Sciences* **113**, 2016, E1434-41.
17. J A Church et al, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T F Stocker et al (eds), Cambridge & New York, Cambridge University Press, 2013, pp1137-1216.
18. D L Hartmann et al, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T F Stocker et al (eds), Cambridge & New York, Cambridge University Press, 2013, pp159-254.

Change (IPCC) and published in their Fifth Assessment Report (AR5)[19]. Electronic copies of individual chapters are freely available from the IPCC website: *https://www.ipcc.ch/report/ar5/wg1/*.

Their conclusions concerning the causes of recent warming were primarily based on comparing the results of computer climate models (known as General Circulation Models, or GCMs) with observations (*Figure 3*). GCMs encapsulate our understanding of physics in a numerical form, which can be solved on a computer. They produce remarkably accurate simulations of the Earth's climate, with storms riding the prevailing westerlies, a Gulf Stream in the Atlantic, a realistic Indian monsoon, El Niño events, and the other major features of our climate system that we know. These GCMs are used for weather forecasting as well as climate science, often the same model for both.

The AR5 was written by several hundred climate scientists, synthesising the results of several thousand publications and studies. We will not replicate that effort here! In summary, if the recent increase in CO_2 concentrations is 'turned off' in the models, then the simulated climate no longer matches reality, with observed recent warming no longer simulated by the model, contrary to observations. Applying GCMs to help understand the data shows humanity's fingerprint on recent changes[20].

The IPCC concluded from synthesising multiple studies that 'more than half of the observed increase in global mean surface temperature from 1951 to 2010 is very likely due to the observed anthropogenic [human-induced] increase in greenhouse gas concentrations.'[19] In this context, very likely means 90-100% confidence. There are other important conclusions in this and other chapters that are well worth exploring including a discussion of the role of solar forcing, the change in the average amount of solar energy absorbed per square metre of the Earth's area, on past and recent climate.

As well as climate models, there are also ice sheet and glacier computer models, which can similarly address the question of how natural versus human-induced warming has affected glaciers around the world, particularly over the last few decades? One thorough assessment of this question was undertaken in a recent study by Ben Marzeion at the University of Innsbruck and colleagues[20] in which they compared modelled and observed glacier mass balance, the balance between losses by melting and gains by precipitation, for both natural and 'full' (i.e. natural plus human) forcing (*Figure 4* overleaf).

The graphs in *Figure 4* are a little complicated but the key message is in panel C, which shows the proportion of glacier mass loss that is due to human-induced versus natural changes. In 1850 the percentage is close to zero, although human forcing had started, it was quite small compared to today. The year-to-year variations are large and noisy, but when smoothed

19. N L Bindoff et al, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T F Stocker et al (eds), Cambridge & New York, Cambridge University Press, 2013, pp159-254.
20. B Marzeion et al, 'Attribution of Global Glacier Mass Loss to Anthropogenic and Natural Causes', *Science* **345**, 2014, pp919-21.

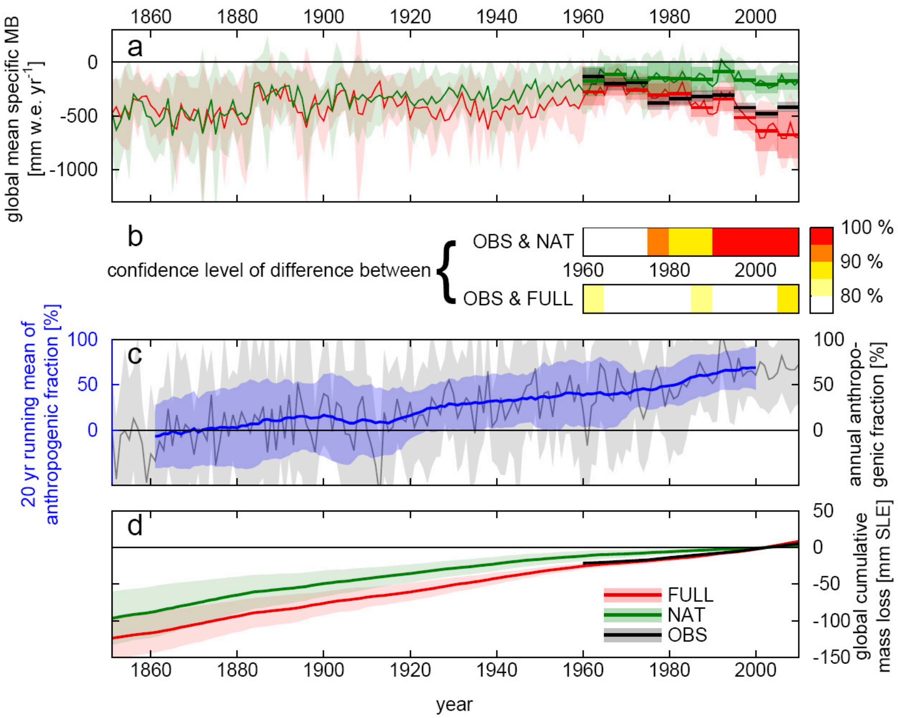


Figure 4 Attribution of glacier mass loss to natural and anthropogenic causes. Panel C shows the percentage of mass loss associated with human-induced climate change as a proportion of the total, while the top panel shows changes in the mass, and by inference volume, of glaciers around the world excluding the great ice sheets. The bars from 1960 represent five-year average values from direct and satellite-derived observations in black, modelled (natural and human) in red and modelled (natural only) in green. From about 1985 these two simulations diverge with 'natural only' being unable to reproduce the observations.

over twenty years, the solid blue line, a clear trend emerges. Over the whole period 1851-2010, 25% of glacier loss is due to humans. From 1991-2010, however, that fraction has increased to 69%[20]. So, while it is true to say that 'there is absolutely nothing unusual about glaciers melting during inter-glacials'[9], this statement is extremely misleading. What is 'unusual' in recent decades, are both the rate and the cause. As such, we think a more helpful statement is that 'there is absolutely nothing unusual about glaciers melting during inter-glacials, but the current rate (fast) and cause (human) is unprecedented in the entire period for which we have reliable observations.'

The future for glaciers and ice sheets?

So, that concludes the four-legged stool. What about the future of ice on the planet? Let's look briefly at some projections of glacier mass change over the next century based on several future climate scenarios produced

by the IPCC. Again, the most authoritative and comprehensive synthesis of projected climate change can be found in the IPCC report itself. Chapter 12 (*https://www.ipcc.ch/report/ar5/wg1/*) focuses on CO_2 scenarios and the response of parts of the climate system to these scenarios[21] while the reaction of glaciers and ice sheets is discussed in the subsequent chapter on sea level.

The choices we make now, and the effectiveness of climate action policy such as the Paris COP21 agreement will influence our future climate. There are several different pathways we, as a species, can follow. Which one we take will determine how the climate will evolve and the associated impacts. Various future emission scenarios were defined by the IPCC to explore how the climate system will evolve, called Representative Concentration Pathways (RCPs): the higher the number for the RCP, the greater the amount of CO_2 entering the atmosphere. The most pessimistic trajectory used was RCP8.5, which crudely equates to a business-as-usual scenario with emissions rising throughout the 21st century as a consequence of economic growth and minimal climate policy. For this pathway, the projections suggest that, by 2100, glaciers will have largely disappeared from central Europe, western Canada and the US, Svalbard, Caucasus, low-latitude areas and New Zealand. Other areas will experience significant volume losses but not as complete as these regions[22]. Whether this is a good or bad outcome of human-induced warming depends on what it is you're interested in. If you enjoy Alpine climbing or skiing the outlook is definitely bad for the European Alps[23]. Climate model simulations for the end of century indicate as much as a 50% reduction of snow cover even above 3,000m elevation. Remember also that, following a temperature increase, glaciers take a while to come into balance. If temperature were stabilized after warming, additional ice loss would occur for years to decades. We already are committed to more ice loss than has occurred, and similarly the warming projected by 2100 would cause additional mass loss beyond that date.

The IPCC, among many other organisations, summarised the strong scholarship that the negative consequences greatly outweigh the positive. (See IPCC Working Group 2 on impacts: *http://www.ipcc-wg2.awi.de/*) One particularly serious consequence of global warming is sea-level rise. Some 200 million people are at risk from a sea level rise of one metre, which for RCP8.5 could be achieved by the year 2100[24]. The Syrian refugee crisis that has so strained political stability and tolerance in Europe is 'only' about five million. Sea-level rise of this magnitude would be truly catastrophic. In a warming world, sea level increases through the dual effects of thermal

21. M Collins et al, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. T F Stocker et al (eds), Cambridge & New York, Cambridge University Press, 2013, pp1029-136.
22. B Marzeion, A H Jarosch, M Hofer, 'Past and Future Sea-level Change from the Surface Mass Balance of Glaciers', *The Cryosphere* **6**, 2012, pp1295-1322.
23. C Marty et al, 'How Much Can We Save? Impact of Different Emission Scenarios on Future Snow Cover in the Alps', *The Cryosphere* **11**, 2017, pp517-29.
24. J L Bamber and W P Aspinall, 'An Expert Judgement Assessment of Future Sea Level Rise from the Ice Sheets, *Nature Climate Change* **3**, 2013, pp424-27.

expansion of the oceans and melting of land ice. During the last interglacial, called the Eemian, global average sea level was 6-9m higher than present[25], at a time when global ocean temperatures were 0.5°C warmer than pre-industrial and similar to the average for 1994-2014[26].

The Antarctic and Greenland ice sheets are huge. Anyone who has been to Antarctica will know how vast and humbling a landscape it is. These ice sheets contain enough water locked on land, to raise global mean sea level by 58m and 7.4m, respectively[1]. Antarctica covers an area larger than the lower 48 states of the US; the thickest ice is almost 5km thick in the interior. These are the 'super-tankers' of the climate system. In their slow-moving interior it can take thousands of years or longer to fully respond to changes in climate[4]. Around the edges, where the ice flows faster and, in particular, where it is in direct contact with the ocean, the response can be much faster. Once they have changed course, it will take a very long time to steer them in a different direction.

Projecting the response of these ice sheets to climate change is challenging because of complex linkages between the atmosphere, oceans and the ice and difficulties in observing and modelling processes that take place underneath 5km of ice. Nonetheless, observations from satellite data since 1992 indicate accelerating mass loss from both Greenland and the West Antarctic Ice Sheet[1], such that they are now contributing more than 1mm per year to sea-level rise. This may not sounds like much, but if the acceleration in mass loss continues it could soon become a serious threat to the stability of modern civilisation. The West Antarctic Ice Sheet, for example, is considered to be particularly vulnerable to changes in oceanic warming and has the potential to raise sea level by over 3m on its own[27]. Recent studies suggest it may have already passed the point of no return[28]. Other irreversible thresholds exist in the climate system and time is rapidly running out for us to implement affordable and palatable mitigation strategies[29]. We all have choices. Our future on the planet depends on those choices.

Note: The numbers presented in this article all have an error associated with them and, to aid readability, we have not included this error but note that they are all statistically significant to one standard deviation of the quoted uncertainty in the original manuscript.

25. R E Kopp et al, 'Probabilistic Assessment of Sea Level During the Last Interglacial Stage', *Nature* **462**, 2009, pp863-U851.
26. J S Hoffman et al, 'Regional and Global Sea-surface Temperatures During the Last Interglaciation', *Science* **355**, 2017, pp276-9.
27. J L Bamber et al, 'Reassessment of the Potential Sea-Level Rise from a Collapse of the West Antarctic Ice Sheet', *Science* **324**, 2009, pp901-3.
28. I Joughin, B E Smith, B Medley, 'Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica', *Science* **344**, 2014, pp735-8.
29. N Stern, *The Economics of Climate Change: The Stern Review*, Cambridge, Cambridge University Press, 2007.