European MARINE BOARD
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The ticking time bomb of climate change and sea-level rise:

Why human actions in the next 10 years can profoundly influence the next 10,000

In December 2015, political leaders from 195 countries attending the United Nations Climate Change Conference (COP21) in Paris, agreed to take action to address the causes and consequences of global climate change. Specifically, they committed to keeping the rise in average global air temperature by the end of this century to "well below 2°C above pre-industrial levels" (i.e. before 1750 and the advent of the industrial revolution).

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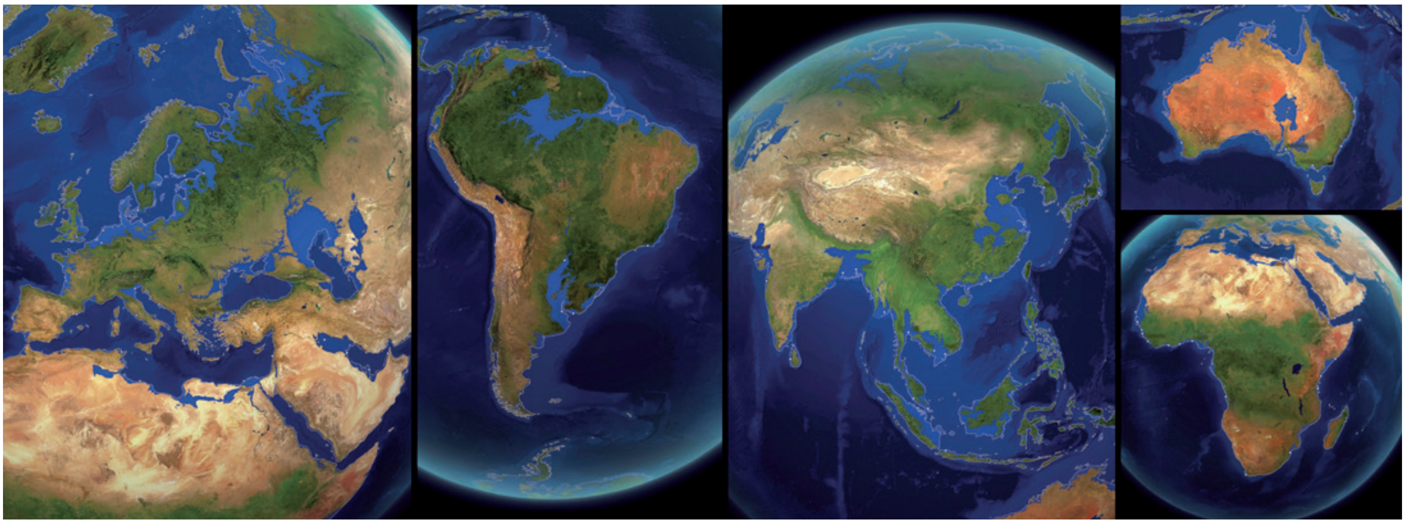
The 350-year window between 1750 and 2100 may seem like a long time in the context of human lifespans. However, in a seminal paper published in Nature Climate Change, Clark *et al.* (2016) have questioned the overemphasis in the global climate discussion on climate change as a 21st century only phenomenon, and on near-term impacts up to 2100. They argue that any increases in carbon dioxide (CO_2) from human activity will remain in the atmosphere and continue to affect Earth's climate for tens to hundreds of thousands of years.

Notwithstanding changes in air temperature, there is a time lag between rising CO_2 levels and the changes in sea levels that inevitably follow (see also DeConto and Pollard, 2016). To understand this, we need to look back, not 250 years, but at least 20,000 years. To properly consider the consequences, we need to look forward, not just to the end of this century, but to impacts of today's actions that will play out over millennia.

Over the next 10,000 years, the global mean sea-level rise that will inevitably result from even a modest emissions scenario will reach 25 m, causing inundation of many of the world's most densely populated coastal cities and regions, directly affecting 1.3 billion people or 19% of the global population (based on 2010 population figures). A higher, business-as-usual scenario will result in a global mean sea-level rise of 52 m, with even more devastating effects.

With this much longer timeframe in mind, Clark *et al.* stated that the real consequences of unchecked CO_2 emissions will be "large-scale and potentially catastrophic climate change." The authors also emphasize the magnitude and urgency of the response that is needed. We are presented with a narrow window of opportunity to avoid the worst of these impacts for future generations. The only effective response is to move as rapidly as possible towards the complete decarbonization of the world's energy systems by targeting net zero or negative carbon emissions.



Map demonstrating what the continental coastlines in different regions of the world (left to right, Europe, South America, Southern Asia, Australia and Africa) would look like if all the ice on land melted and drained into the sea, raising the sea level by 68.8 meters. (Credit: National Geographic)

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Why does it take so long for sea level to respond to increased levels of CO_2 in the atmosphere?

To understand this question, it is helpful to look back in time. There are two main drivers for sea-level rise: the loss of land ice and the expansion of the oceanic water column due to an increase in water temperature (thermal expansion). At the Last Glacial Maximum (LGM), which occurred around 21,000 years ago, the CO_2 concentration in air was approximately 190 ppm. This rose to about 270 ppm by the end of the last ice age 11,700 years ago and remained near this level until the onset of the industrial revolution in the mid-eighteenth century, when it started to rise to today's levels of just over 400 ppm. Palaeoclimate research has shown that the rise of 80 ppm in atmospheric CO_2 during the end of the last ice age resulted in a global mean air temperature increase (GMTI) of ~4°C during the same period. The same phenomenon also eventually led to a global mean sea-level (GMSL) rise of approximately 130 m. However, the rise in sea level was reached only ~6,000 years ago, or a delay of nearly 6,000 years compared to the rise in CO_2 level in the atmosphere and the corresponding rise in air temperature. So a key question arises: Why is the sea-level response so much slower than the air temperature response?

This long time lag of sea-level rise behind air-temperature rise largely reflects the slow response of ice sheets to a climate perturbation (also called response time). For a given temperature increase, it takes a long time for land ice to melt to a new steady state, with this response time increasing as the size of the ice mass increases. This response time can be reduced if warming triggers dynamic processes, such as sliding at the ice-sheet bed or unstable retreat of an ice sheet where its bed is below sea level.

The ocean responds slowly to a warming atmosphere on a shorter term than large ice sheets. The ocean is on average 4 km deep and the effect of increased CO_2 will be first to warm only the upper few hundred metres. Over a time period of centuries, the warming will eventually spread to greater depths. Because seawater expands at higher temperatures, the entire column of water will expand and as a direct consequence the sea level will rise.

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Human influence on sea-level rise and its impacts

Sea level can change as a result of several natural processes. However, by comparing the results of 14 climate models over the period 1900-2005, Slangen *et al.* (2016) concluded that the major part of the sea-level rise after 1950 was caused by anthropogenic greenhouse gas emissions and that this human contribution has been increasing. So there is a strong scientific basis to show that global warming and sea-level rise over the last 50 years are caused largely by human CO_2 and other greenhouse gas emissions.

Credit: Shutterstock

Looking at the near-term impacts, there are already alarming projections on the potential for ocean warming, ice melt, and sea-level rise by the end of the 21st century. The 2013 IPCC 5th Assessment Report projected warming of between 0.6°C and 2.0°C in the top 100 m of the ocean, and 0.3°C and 0.6°C at a depth of 1000 m. GMSL will likely rise by between 0.26 m and 0.55 m under the lowest emissions scenario examined, increasing to a range of between 0.52 m to 0.98 m under the highest emissions scenario, with greater amounts possible if parts of the Antarctic Ice Sheet become unstable. In other words, it is very possible that sea level could rise by at least 1 m in this century through a combination of thermal expansion of the oceans and melting of land ice.

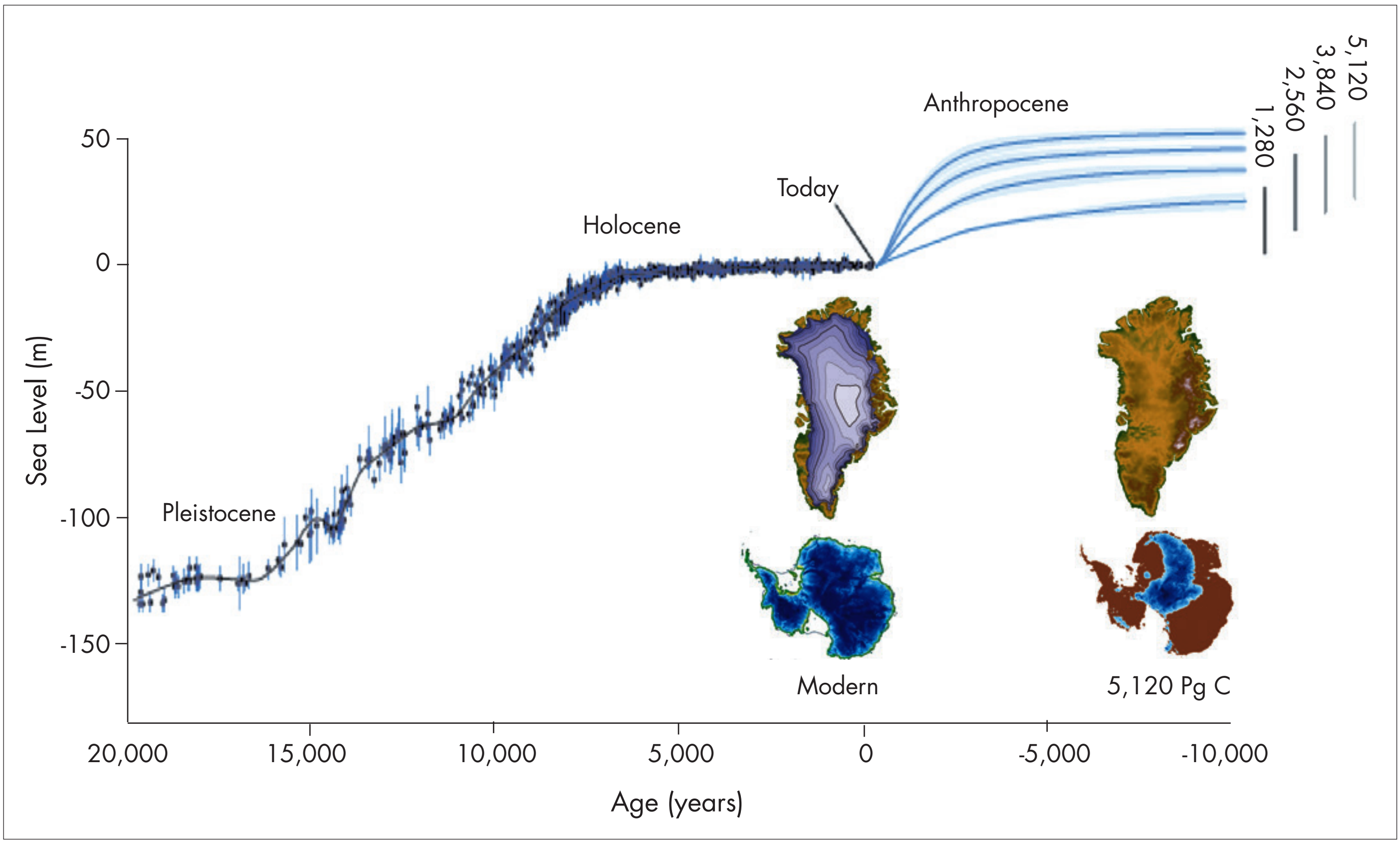
Substantially extending the time horizon, Clark *et al.* examined the likely effects over the next 10,000 years of four different scenarios of total CO_2 emissions ranging from 1,280 to 5,120 Pg C. For reference, between 1750 and 2000, human activity has emitted approximately 580 Pg C into the atmosphere, and at current annual emission rates of ~10 Pg C, we are rapidly approaching the low-end 1,280 Pg C emissions scenario.

The authors calculate that during the next 10,000 years, GMSL will rise by between 25 m and 52 m from the lowest to highest of these emissions scenarios. Such a magnitude of sea-level rise will render all traditional measures of coastal protection, including dikes and storm surge barriers, entirely inadequate. Since many of the world's megacities such as New York, London, Tokyo, Jakarta, and the Dutch 'Randstad' are located in low-lying coastal areas vulnerable to this sea-level rise, this will lead to a massive loss of infrastructure and mass migration of hundreds of millions of people to higher areas with devastating economic and human consequences.

Ppm = Parts per million or milligrams per kilogram

Pg C = Petagrammes of Carbon. 1 Pg = 10^{15} grammes = 10^9 tonnes = 1 billion tonnes. 1Pg C = 3.664 Pg CO_2

Past and future changes in global mean sea level



Long-term global mean sea-level change for the past 20,000 years (black line) based on palaeo sea level records (black dots with depth uncertainties shown by blue vertical lines) and projections for the next 10,000 years for four emissions scenarios (1,280, 2,560, 3,840, and 5,120 Pg C). Vertical grey bars show range of long-term sea-level rise for each emission scenario. Images show reconstructions of the Greenland (top) and Antarctic (bottom) ice sheets for today (left) and for the 5,120 Pg C emission scenario (right). (Figure adapted from Clark *et al,* 2016).

Zero carbon by 2030? There is no other option

Global climate discussions and scientific assessments have generally placed a predominant focus on the near-term impacts of climate change, with the year 2100 most commonly used as the end point of the current projections. This artificial target is a legacy of the limitations of early climate models to forecast beyond this time frame. However, the extent of potential sea-level rise projected by Clark *et al.* for the much longer time frame of 10,000 years is orders of magnitude greater than that projected for the year 2100 in the IPCC 5th Assessment Report. The authors argue that this focus on near-term impacts has given a falsely reassuring impression that the effects beyond 2100 are of lesser importance and that it may be possible to reverse the effects through later emissions reductions.

It is imperative that future global climate policy discussions are underpinned by a clear understanding that we are already committed to significant global warming and sea-level rise that will have profound impacts on future generations and on Earth's ecosystems. Moreover, that continued emissions, even if reduced, will commit us to further warming and sea-level rise. The policy discussions must also recognise and support the critical role of climate and ocean science in ensuring an appropriate, evidence based response to the changes to come. The only option to avoid catastrophic climate change is to make rapid and fundamental changes to our energy, industrial and agricultural systems such that we move towards net-zero or negative carbon emissions within 20-30 years. This may sound dramatic, but compared to the potential human cost, it is basic common sense.

Credit: Shutterstock

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Peter U. Clark, Jeremy D. Shakun, Shaun A. Marcott, Alan C. Mix, Michael Eby, Scott Kulp, Anders Levermann, Glenn A. Milne, Patrik L. Pfister, Benjamin D. Santer, Daniel P. Schrag, Susan Solomon, Thomas F. Stocker, Benjamin H. Strauss, Andrew J. Weaver, Ricarda Winkelmann, David Archer, Edouard Bard, Aaron Goldner, Kurt Lambeck, Raymond T. Pierrehumbert and Gian-Kasper Plattner (2016). Consequences of twenty-first century policy for multi-millennial climate and sea-level change. Perspective article in Nature Climate Change 6: 360-369. DOI:10.1038/nclimate2923.

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