

Celebration of Earth Day 2011

## What can we learn from past warm periods?\*

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**Resum.** Amb una limitada acció política per a controlar l'ús de combustibles fòssils i les emissions de gasos d'efecte d'hivernacle associats, cada vegada hi ha més interès a preparar el món envers els canvis climàtics inevitables. Però, per a quins canvis s'ha de preparar el món? Les simulacions proporcionen una orientació sobre escenaris de clima futur esperats, però també es pot aprendre de l'experiència passada. Encara que, en el passat, no hi ha episodis estrictament comparables amb el futur —que és un món en què el clima és modulat per les activitats humanes— sí que hi va haver períodes càlids que van ser el resultat d'altres factors de forçament. Hi ha algunes lliçons que podem aprendre dels registres paleoclimàtics sobre els episodis càlids i els canvis ambientals associats. Això és de particular importància ja que considerem els canvis futurs en la quantitat total de neu i gel al planeta i les conseqüències dels canvis globals en el nivell del mar. Actualment, més de cent milions de persones viuen a no més d'un metre sobre el nivell del mar i moltes ciutats importants són a la costa. Amb el creixement de la població i l'alta migració a les zones urbanes, aquesta imatge serà cada vegada més crítica. A aquesta preocupació s'afegeix l'augment esperat dels fenòmens climàtics extrems, especialment els huracans i les tempestes tropicals a les costes exposades. La major part dels països estan poc preparats per a un futur amb el nivell del mar molt més alt que l'actual, el que requerirà una planificació a llarg termini i grans inversions en infraestructures de protecció al llarg de moltes regions costaneres.

**Paraules clau:** paleoclimatologia · escalfament global · Grup Intergovernamental d'Experts sobre Canvi Climàtic (IPCC) · interglacial Riss-Würm · huracans · zones costaneres

The winter of 2010 was cold in Europe and in parts of Siberia, but for the year as a whole 2010 was exceptionally warm. In fact, according to the global temperature series produced by NASA,

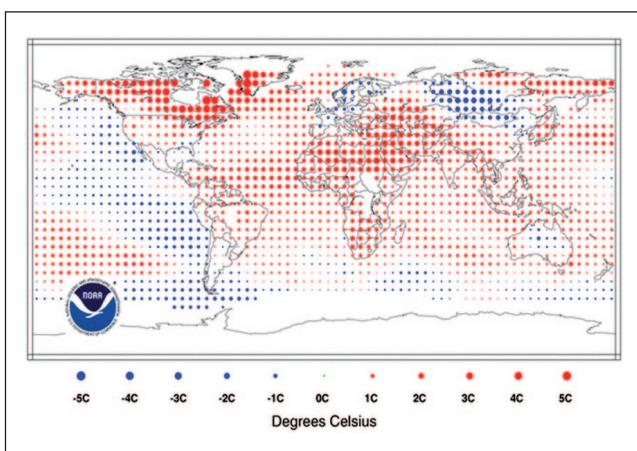
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**Abstract.** With limited political action to control fossil fuel use and associated greenhouse gas emissions, there is increasing emphasis on preparing for inevitable climate changes. But what changes should the world plan for? Model simulations provide some guidance about expected future climate scenarios, but we can also learn from past experience. Although there are no episodes in the past that are strictly comparable to the future, which is a world in which climate is modulated by human activities, there were warm periods in the past which resulted from other forcing factors. There are some lessons we can learn from paleoclimate records about those warm episodes, and the associated environmental changes. This is of particular relevance as we consider future changes in the total amount of snow and ice on the planet, and the consequences for global sea level changes. More than 100 million people currently live within 1m of sea-level, and many major cities are on the coast. With increased population growth and further migration to urban areas, this picture will only become more critical. Added to this concern is the expected increase in extreme weather events, particularly hurricanes and tropical storms, with their associated storm surges along exposed coastlines. Most countries are woefully unprepared for a future with sea-level much higher than today, which will require long-term planning and major investments in protective infrastructures along many coastal regions.

**Keywords:** paleoclimatology · global warming · Intergovernmental Panel on Climate Change (IPCC) · Eemian interglacial · hurricanes · coastal regions

it was the warmest for the entire period based on a network of two to three thousand stations around the world (Fig. 1). But 2010 was also very unusual in the context of the last 100–150 years (the instrumental period for which we have data from thermometers). If we reconstruct the temperature of the Northern Hemisphere for the past 1000 years based on various proxies of temperature such as tree rings, corals, ice cores, and historical records, we can see that average temperatures over the last 50 years were certainly warmer than anything that has occurred for at least 1000 years. It is in this context we will discuss the question of 'What can we learn from warm periods in the past?'



**Fig. 1.** Temperature anomalies January–December 2010 compared to 1971–2000 as the base period. Source: National Climatic Data Center/NESDIS/NOAA.

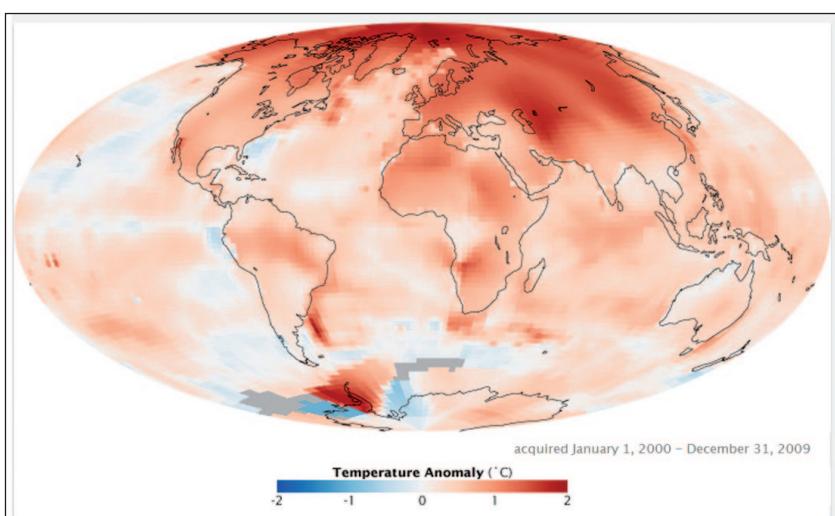
Figure 2 shows the geographical pattern of warming over the last decade. We see a characteristic geographical distribution where warming is greatest at high latitudes and a small portion of Antarctica. This is related to feedbacks in the atmosphere and the Earth system where, as temperatures rise, snow cover recedes, in turn producing changes in the albedo—the reflectivity of a given surface; sea ice in the oceans melts back, and warming is amplified.

What is the reason for the warming? Wherever we go on the globe, whether it is the North Pole, the South Pole or even the central Pacific, we see a relentless rise in CO<sub>2</sub> derived from the burning of fossil fuels. Carbon dioxide undergoes an annual cycle related to the growth of the biosphere, which removes CO<sub>2</sub> from the atmosphere during the summer months and returns it into the atmosphere during the winter months, but the underlying trend is increasing all around the globe. We know from the physics of CO<sub>2</sub> that it traps energy radiated from the surface of the earth. We would not have life on earth if we did not have CO<sub>2</sub> in the atmosphere, as well as water vapour and other greenhouse gases. But the increase in CO<sub>2</sub> has been very, very rapid since the Industrial Revolution 250 years ago. From mod-

el simulations, if we look at the effects on temperature anomalies of only natural factors, such as solar variations and volcanic forcing, we cannot simulate the changes that have taken place in the last 50 years. But if we use the same models and add CO<sub>2</sub> as a factor, then the observed temperatures are tracked very well by the models. In other words, the difference between the background forcing and the actual observed temperature is the result of the increase in greenhouse gases, especially over the last 50 years.

This led the Intergovernmental Panel on Climate Change (IPCC) to conclude in 2007 that “most of the observed increase in globally averaged temperatures since the mid-20th century is very likely (> 90 % probability) due to the observed increase in anthropogenic greenhouse gas concentrations.” [5] We currently emit about 8.5 billion metric tons of CO<sub>2</sub> per year and have a CO<sub>2</sub> level of approximately 390 ppm. If we compare it to the pre-industrial level of CO<sub>2</sub> in the atmosphere of 280 ppm, it means that by burning fossil fuels over the last 250 years we have increased the CO<sub>2</sub> concentration by 100 ppm or approximately 40 %. Now the question is, what does this lead to in the future?

We do not know what our future energy consumption pattern will look like: how many nuclear power plants will there be—and after the Fukushima Daiichi nuclear disaster in 2011 maybe not so many—or how many green vehicles will people use, or how many people will there be on the planet? These are very uncertain issues. And so the IPCC presented a series of possible scenarios with outcomes for the year 2100, ranging from a strong continued increase in emissions to a more optimistic view in which emissions will increase for the next 40 or 50 years and then begin to decline, based on the United Nations’ estimates that world population will also peak in the mid-century and then begin to decline. Looking at these two scenarios, if emissions continue to rise, then by the end of the century we may have CO<sub>2</sub> levels more than ~2.5 times what they are today, approximately 940 ppm. If we take the more optimistic scenario, in which emissions rise somewhat but then decline by the end of the century, CO<sub>2</sub> levels will be around 550 ppm.



**Fig. 2.** Global average temperature anomalies from 2000 to 2009. Source: NASA Earth Observatory.

Why will not CO<sub>2</sub> levels be less by the end of the century if there is a drop in emissions? It is logical to think that if we reduce our emissions, the total CO<sub>2</sub> in the atmosphere would be lower. The problem is that the processes by which CO<sub>2</sub> is removed from the atmosphere (the ‘sinks’) are not as effective and they are much slower than the production rate that we are now engaged in. And so, even if we reduce our emissions to what they might have been 30 or 40 years ago, by the end of the century CO<sub>2</sub> levels are still going to be higher. And so studies suggest that there is a high probability (approximately 50 %) that the post-industrial era has most likely committed the world to a warming of ~2.4°C (1.4–4.3°C) above the pre-industrial surface temperatures [10].

If that is the case, what can we learn from periods in the past that were warmer? What happened to the environment during those periods? Were there warm periods in the geologically recent past (when the world geography was similar, so taking into account just the last few hundred thousand years) that can inform us about potential environmental changes we may face in the near future?

## Studies of past warm periods

Interestingly, studies of warm periods in the past began in the Netherlands. In 1875, Professor P. Harting was digging in the mud of the river Eem, near Amersfoort. There he found fossils that indicated that summer temperatures in the region had been several degrees warmer than today, with the absence of severe or long-lasting winter frosts. He found fossils of hippopotamus, wildebeest, and several amphibians, i.e. animals that cannot survive in freezing temperatures. That is a very different condition from what you might expect to find in the Netherlands today. And so he concluded that, in the past, conditions in the Netherlands were very different. Summers must have been warmer and winters much milder. Moreover, because this area of the river had been covered by marine sediments and Harting found marine fossils there, he also concluded that the sea level was thus higher, flooding these low-lying areas [3]. But he did not know how much higher the sea level had been, neither did he know exactly when this had happened, nor did he know why it had happened.

Today we have a lot more information about this period, which is referred to as the ‘Eemian,’ after the river Eem. It took place 120–130,000 years ago, and it was one of the many interglacial periods, such as the one we are currently experiencing. Carbon dioxide levels were not higher, they were actually lower than they are today (~280 ppm). The higher temperatures were caused by higher amounts of energy being received from the Sun during the Northern Hemisphere summers, with other feedbacks and processes within the climate system amplifying this change. In addition, polar ice sheets were smaller, which meant that water that is now locked up in Greenland and Antarctica entered the oceans, thus raising the sea level so that it was approximately 6 m higher than it is today.

Let us just step back for a minute and remember how the world has changed in the past. Thirty thousand ago

there were large ice sheets over North America that completely covered the land, all the way down to New York and Illinois; there were smaller ice sheets over Scandinavia and Great Britain, and ice caps in the Alps, the Pyrenees, in Tibet, and in parts of Siberia [1]. These ice sheets and ice caps grew because water was taken from the oceans and stored on the land. At the height of the Last Glacial Maximum, the sea level fell 130 m below the present day level. The evaporation of that water from the oceans and the deposition of water on the continents as snow altered the isotopic composition of the ocean water. The foraminifera that lived in the ocean captured that chemical signal in their structure, in the calcium carbonate of their shells, or tests, as we call them. And so, if we take a sediment core from the ocean and look at the isotopic composition of the calcium carbonate in these foraminifera, we can see a back and forth cycling that reflects the changes in the chemical composition of the ocean throughout glacial and interglacial periods.

The Earth has experienced many glacial periods, when ice sheets have formed and then melted, and each time this sequence of events is recorded in the chemistry of the world ocean. If we call sea level today ‘zero’ and compare it to the Eemian, there was a slightly different chemical composition of the ocean at that time, which reflects the fact that most of the water that is now on the land was in the ocean during that period. Sea level during the Eemian is calculated to have been somewhere between 6.6 and 9.4 m above the present day level [6]. On a time scale of a million years, the sea level today is unusually high. If we look at the averages, sea level was 60 m below what it is today and at the extreme, 130 m lower. Over this period, the geography of the world has changed; interestingly, however, there were a few periods in the past when sea level was higher than it is today, meaning less ice on the continent. Why did that happen?

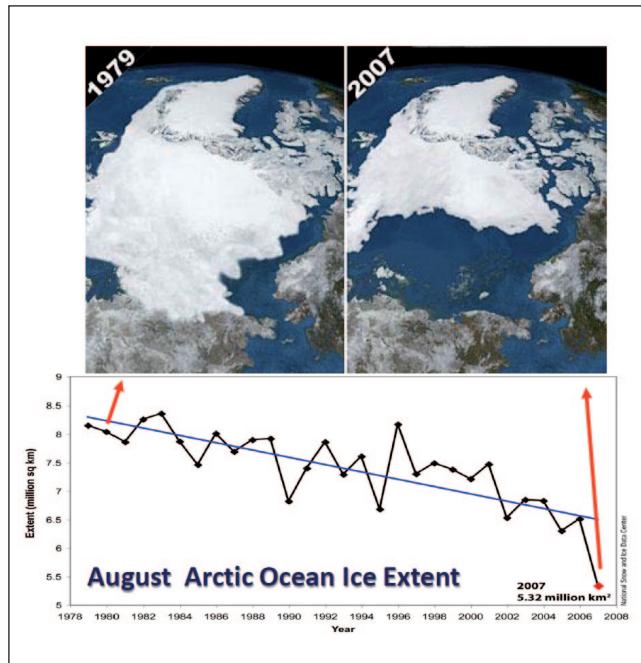
We know that this is not directly related to greenhouse gases but instead to the so-called Milankovitch cycles, in which the Earth’s position relative to the Sun changes periodically. The Earth’s tilt, or obliquity, changes between 22.1° and 24.5° on a 41,000-year cycle: today it is 23.5° and decreasing; the Earth completes one full cycle of precession (a change in the seasonal timing of the perihelion during the Earth’s orbital path around the sun) every 19–23,000 years; and the Earth’s orbital shape, or eccentricity, with a cycle between 100,000 and 413,000 years, has changed so that is nearly circular today. It is important to note that during the previous interglacial periods the Earth’s orbit was more eccentric, and the timing of when the Earth was closest to the Sun coincided with the Northern Hemisphere summer. If the Earth’s orbit was perfectly circular then the time of the Northern Hemisphere’s summer would not matter, but if the summer position of the Northern Hemisphere is when the Earth is close to the Sun, then this has a large effect on the energy being received by this hemisphere. Today we are closest to the sun in January, i.e., in the Northern Hemisphere winter. Eleven thousand years ago, we were closest to the Sun in July, and that had a large effect in terms of the energy being received in the Northern Hemisphere, as it did during the previous interglacials.

Interglacials occurred because there was more energy being received at the surface. But from the ice cores that have been recovered from places in Antarctica it is clear that this process was amplified by greenhouse gases. As snow accumulates in ice cores, it traps small bubbles of gas, which contain small samples of the atmosphere. If we look at the CO<sub>2</sub> corresponding to the last 800,000 years, we can see that CO<sub>2</sub> levels have gone up and down, being lower during the glacial periods and higher during interglacials. There was a feedback or a reinforcing effect of the greenhouse gases that corresponded to orbital changes. But in all of the glacial periods, CO<sub>2</sub> never fell below about 180 ppm and it rarely went above 280 ppm. Today, CO<sub>2</sub> levels are 390 ppm, which means that we are certainly far outside the range experienced during the recent geological history of the Earth. In the past, warming was the result of orbital changes, reinforced by the oscillations of greenhouse gases; today, warming of the Earth is the result of greenhouse gases.

There are now many studies of the temperature conditions during the last interglacial. These studies have shown that it was much warmer during the Eemian period. In fact, a number of authors have tried to look at the relationship between global and Arctic temperatures, during glacial periods, during interglacials, during the early Holocene (8000–10,000 years ago), and during medieval times. The results consistently show that the greatest warming in all these periods was at higher latitudes, where there is a reinforcing effect of melting snow and ice on the land and in the ocean. The estimates suggest that if global temperatures rise, Arctic temperatures rise 3–4 times faster or greater, meaning that if we have a global warming of 2°C, the geological and the palaeoclimatic evidence suggest that the Arctic will warm by 6–7°C [7]. And in fact, this is reproduced in computer models, which show a much greater rise in temperature in higher latitudes than in the tropics, and that temperatures variations in the Arctic tend to be 2–3 times greater than at lower latitudes [4]. This polar amplification, or positive feedback of temperature, is due to a retreat of the snow cover and a loss of Arctic sea ice.

## What evidence do we have today?

Warming is taking place at higher latitudes, and the consequence is that we are seeing a very dramatic loss in Arctic sea ice. Figure 3 shows satellite images taken some 30 years ago and very recently. Clearly, there has been a systematic decline in sea ice, with the lowest level recorded in 2007 [Note added in proof: Sea ice extent at the end of the summer in 2012 was even lower than in 2007, and melting on the Greenland ice cap was extensive, all the way to the summit]. The problem is that not only is the ice cover less but it is also getting thinner. There is now only very little thick ice left in the Arctic Ocean, meaning that the process of removal each year is that much quicker. Similarly, on the continents, such as Greenland, between 1992 and 2007 the total melt area increased, and a pattern of higher melting around the margins was observed [8]. These are very hard measurements to make, and there is a lot of variability in the estimates of melting between years, but there appears to



**Fig. 3.** Satellite images of the decline in Arctic Sea ice and the extent of Arctic Ocean in August (1978–2008). Source: NSIDC.

be a systematic increase. Satellite estimates of the gravitational mass of the ice going back just to the last decade or so confirm this systematic decline of the Greenland ice sheet [12]. By melting, this water is being removed from the continent and re-entering the oceans.

Table 1 compares forcing, CO<sub>2</sub> levels, and positive and negative feedbacks during interglacials and as predicted for our

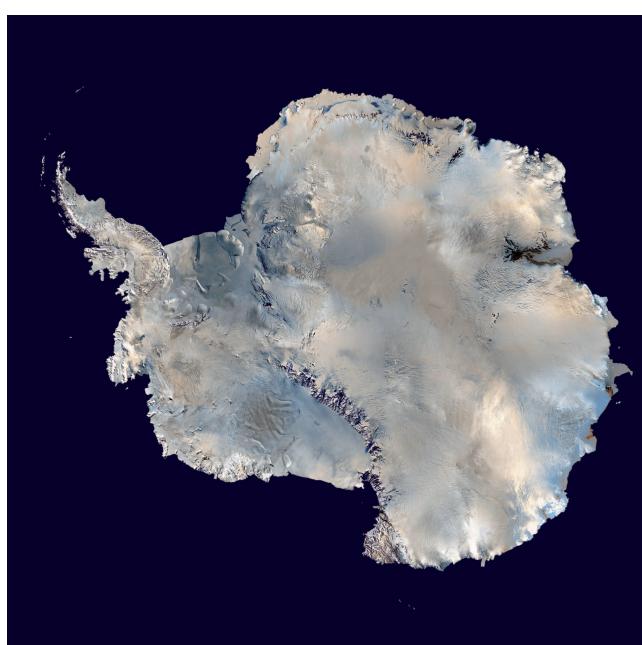
**Table 1.** Comparison of forcing, CO<sub>2</sub> levels, and positive and negative feedbacks of previous interglacials and during the 21st century

	Interglacials	21st century
Forcing	Solar radiation season forcing: mainly over the Northern Hemisphere and in summer	Greenhouse gas forcing: year-round and global
CO <sub>2</sub> levels	~ 280 ppm	> 450 ppm? (very likely in the next 20 years or so)
Positive feedbacks	Less Arctic sea-ice Less snow cover in the Northern Hemisphere Less permafrost → More wetland CH <sub>4</sub>	Less Arctic sea ice Less snow cover in the northern hemisphere Less permafrost → More wetland CH <sub>4</sub> ? Less forests (reduced CO <sub>2</sub> sink)
Negative feedbacks	More forests (CO <sub>2</sub> sink)	

future. While similar things are happening and the pattern of change is very similar, the causes are very different.

If we think about the Eemian again, when sea level was 6–9 m higher than it is today, where did that water come from? Because we have drilled through the Greenland ice sheet in several locations, we know that in at least three or four places, at the bottom of the ice sheet there is Eemian ice, meaning that the ice core extends back in time all the way to the Eemian period and that there was still some ice, at least in central and northern Greenland, at the time [8]. The current thinking is that the southern part of Greenland was ice-free, and perhaps the margins were shrinking. During the Eemian, 2–3.5 m of that 6- to 9-m rise in sea level likely came from Greenland. If all the other smaller ice caps, the glaciers in the Alps, and those in other parts of the world melted, this would amount to less than 50 cm. So, to explain changes in sea level it is really Greenland and Antarctica that hold the answers.

So what about Antarctica? If we look at the Antarctic ice sheet today, we see a very large volume of ice on the east Antarctica sheet, separated by the Transantarctic mountains from the West Antarctic ice sheet (Fig. 4). The difference between these two ice sheets is that the West Antarctic ice sheet extends into the ocean as ice shelves, which are floating. And these ice shelves are considered to be vulnerable; they extend out and away from the ice sheet and are pinned by the shallow rocks that support the ice sheet in the interior. Fear has been expressed that if the sea level rises it will basically destabilize and decouple the ice shelves from the pinning point. So, right now the ice sheet is balanced but with a rise in sea level it may simply give way. Estimates of how much water could be released from the West Antarctic ice sheet if this happened are approximately 3–4 m, enough to explain half of the total Eemian sea level rise.



**Fig. 4.** Satellite composite image of Antarctica generated from NASA's Blue Marble data set. Credit: Dave Pape.

**Table 2.** Summary of the main characteristics of the last interglacial

Polar amplification	Global temperatures of +1–2°C and of +3–6°C in polar regions of the northern hemisphere
Sea-level	+6 m (and possibly up to 9 m) above present levels
Rate of sea-level rise	5–6 mm/year or approximately 5.6 m in 1000 years
Evidence of a two-step sea-level rise	1. Greenland 2. West Antarctica?

It turns out that if we look at the Eemian sea level rise very carefully, two increments can be distinguished. The first was the result of Greenland melting, accounting for maybe 3 m, and the second contributed another 3 m. The suggestion is that warming started in the Northern Hemisphere, led to the melting of Greenland, thus causing a rise in sea level, and in turn affecting the West Antarctica ice sheet so that it collapsed during the last interglacial. Table 2 summarizes the changes that took place during the last interglacial.

Where are we today? Sea level has been rising rather slowly, but it is accelerating. The latest projections suggest that by the end of the century, and assuming no major West Antarctic ice shelf collapse, sea level will be  $1-1.25 \pm 0.05$  m higher than it is today [9]. The Dutch Delta Commission recently made their own estimates, one of which extends two centuries ahead, to 2200. They estimate a rise in sea level of 1.5–3.5 m. According to more recent studies, by the end of the century there could be a rise in sea level of as much as 2 m. So it seems that as the science improves, estimates of the sea level increase. Within the next century, we should expect at least 1 m and perhaps as much as 2 m.

There is one other threat that accompanies the rising temperatures: more intense tropical storms. Sea surface temperatures are the fuel for hurricanes and tropical storms, and models suggest that there may not be many more storms, but those that do occur will be more severe, more intense. Most of the damage from tropical storms, apart from the wind, is flooding due to the storm's surge. Even if the sea level does not change, flooding can occur at many meters above sea level. If we add 1–2 m of static sea level rise on top of that then flooding will be even worse. In the Boston, Massachusetts area there is a very interesting lake that happens to have sea water at its bottom. As the sediments are carried into the lake from the surrounding land, they form layers, providing a record so perfect that you can count back the layers year by year over a thousand years. When a hurricane passes, sediment deposition increases because of the heavy rain, and so the layers in the lake show thick sediment pulses related to the hurricanes that tell us their frequency in this part of Massachusetts for the past 1000 years. A thousand years ago, often referred to as the Medieval Warm Period, an average of one hurricane struck this

area every 12 years, whereas during the Little Ice Age this happened maybe once every 50 years. So, in this region at least, there were more hurricanes during the warmer episode and fewer hurricanes during the cold period in the last thousand years. This is one line of evidence that suggests that hurricane frequency has indeed changed and might change in the future with warmer conditions.

What would be the consequence of this? Many major cities around the world are within 1 m of sea level, including several airports, such as JFK; if we had a storm surge, much larger areas would be flooded. Most of greater Catalonia is going to be impacted, and there are many parts of Europe that are also vulnerable, especially the coast of Southern France, the Netherlands, and of course, the poster child of this problem, Venice, where we have a perfect microcosm of the problems we will all face in the future. Venice has experienced more than a meter of sea level rise. This is not because of global sea level rise, but because the city itself has been sinking—partly because it is built on peat but also because water is being extracted from the aquifers for industrial plants located all around the edge of the city. Most coastal cities are built on deltas and these are also sinking, as water is being moved from the land and transferred back into the ocean. In today's Venice, we can see the problem that every coastal city will soon face. And in that sense we are all Venetians.

As a solution, a system called MOSE (*Modulo Sperimentale Elettromeccanico*) has been proposed, in which a set of barriers will lie flat at the bottom of the sea in the Venetian Lagoon. When the *acqua alta* comes, they are emptied of water by the introduction of compressed air so that they rise, protecting the lagoon from the sea and stopping the tidal flow. MOSE has been the subject of great controversy. The deputy mayor of the city, Gianfranco Bettin, called this project “expensive, hazardous, and probably useless” and the cost is in the tens of billions of euros. The main problem is that it is being designed for a sea level rise of 110 cm above the present-day level and that is nowhere near enough if sea level is going to rise more than a meter this century.

The Netherlands has a bigger problem of course. Most of the Netherlands is close to or below sea level and there are major rivers that pass through the country. So it is not just a matter of blocking the coast, water must exit too. In 2009, the Delta Commission, a well-qualified panel, estimated that the cost of the Delta Programme to raise the levees and the barriers on the coast “would be 1.6 billion Euros per year until the year 2050, when the cost is anticipated to drop to a minimum of 900 million Euros per year, not including maintenance and management costs, which could add an additional 1.2 billion Euros per year...” [11] And this calculation is for only 350 km of coast, which amounts to not even half of the coast of Florida. The costs of protecting the coasts in Europe, North America, Japan, India, and so on are obviously enormous. If we think about every major city around the world that is on the coast—currently over 100 million people live within 1 m of the present sea level—the consequences of global sea level rising are shocking and they are not being adequately considered when we think about climate change.

## Coda

Warm periods of the past provide insights into future conditions, even if the underlying causes were very different. A rise in global temperatures of 2°C (this is the EU's most optimistic target, which will probably not be achieved) will be amplified at high latitudes, leading to the melting and eventual collapse of the West Antarctic ice sheets. Estimates for the most positive scenarios predict a rise in sea level by at least 1 m this century, more in some places. Once the West Antarctic ice sheet begins to collapse, the process will be unstoppable. Major coastal cities around the world will be affected and more severe tropical storms will exacerbate the problem. Accordingly, plans must be developed now for the protection of coastal areas against an increased frequency of flooding.

When we talk about global warming, we tend to think only about global temperatures rising 1–2°C, but we also have to consider the consequences and start planning now for what will inevitably happen within the next few decades. This is probably the biggest economic challenge we have to deal with in global warming issues. Even though we are in an interglacial today, we still have ice on the land. Perhaps our future will be a ‘super interglacial’, with no ice and higher sea levels, higher than anything that has occurred for many millions of years.

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