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BREAKING THE 400 ppm BARRIER: PHYSICAL AND SOCIAL IMPLICATIONS OF THE RECENT CO_2 RISE

Sérgio H. Faria, Joseph V. Spadaro, and Anil Markandya

The past months have been particularly exciting for those involved in climate research: after nearly six years of work, the United Nations Intergovernmental Panel on Climate Change (IPCC) has released its fifth Assessment Report (AR5) on climate change since 1990. Formally composed of three parts plus a final Synthesis Report, the first part of AR5 was published in unedited form on 30 September 2013, under the title *Working Group 1 (WG1) The Physical Science Basis*. The remaining two parts (WG2 on impacts, adaptation and vulnerability, and WG3 on mitigation) are scheduled for the spring of 2014. The Synthesis Report of AR5 will be published in the autumn of 2014.

The objective of the IPCC Assessment Reports has not been to publish ground-breaking discoveries, but rather to consolidate those scientific results that have become well-founded and widely accepted by the climate research community* in recent years. As such, the IPCC Reports have been endorsed by a number of scientific academies worldwide and have become a major reference of the contemporary views of the scientific research community as a whole.

A key outcome of the new WG1-AR5 is the very high confidence assigned to the conclusion that *human influence has indeed been the dominant cause of modern climate change* (since the 1950s). The expression "extremely likely" used in this context (95–100% confidence, which is IPCC's highest degree of confidence after the rarely used "virtually certain") implies that a substantial human influence on climate is beyond doubt. This conclusion is supported by almost all *serious and unbiased climate researchers*.

Key Points

- ***The concentration of carbon dioxide (CO_2) in the atmosphere has achieved its highest levels in the last 800,000 years, and probably even in the last 2.1 million years, recently topping briefly the atmospheric concentration target of 400 ppm. Whereas this mark does not set Earth's climate in an apocalyptic mode, it does represent a grave global socio-political risk, because it highlights the inaction and indifference of government and society to our self-triggered climate changes and their consequences, especially for the poor and the weak.***
- ***Since pre-industrial times (i.e. since 1750), atmospheric CO_2 concentrations have increased by over 40%, primarily from fossil fuel emissions and secondarily from net land use change emissions, at a rate unprecedented in the last 22,000 years, reaching an average of 2 ppm/year in the last decade. About 30% of the emitted anthropogenic CO_2 has been absorbed by the ocean, causing ocean acidification that poses serious risks to marine ecosystems, resources, and services.***
- ***Ice core paleoclimate records teach us that, under typical conditions, global surface temperature never changes much in the long term (of centuries) without a corresponding change in atmospheric CO_2 concentration, and vice-versa. In order to explain the amount of warming observed in the temperature records, one must take into account the greenhouse effect caused by the corresponding Atmospheric CO_2 concentrations in that period. This does not preclude, however, the occurrence of short-term (decadal) climate variability, which can enhance or counteract the prevailing temperature trend (e.g. the current 15-year hiatus in global temperature rise).***
- ***In a business as usual scenario, atmospheric CO_2 concentrations by the middle of the 21st century would reach just over 500 ppm, a change of 25% above the present value, which would probably lead to an increase of more than 2ºC in the global mean surface temperature On the other hand, reducing emissions by 2% per year starting no later than 2020 would limit the global carbon dioxide concentration to below 450 ppm. Delaying emission cuts will only enhance the risks of dangerous, and potentially irreversible, climatic changes and increase the costs of future mitigation and adaptation measures.***

Another important outcome of the WG1-AR5 is related to the major drivers of human influence on Earth's climate system. As in previous Assessment Reports, the increased atmospheric concentration of carbon dioxide (CO_2), originating mainly from anthropogenic emissions, has been identified as the dominant agent of global mean surface temperature rise (so-called "global warming"). In the new WG1-AR5, this inference is corroborated by updated data, better understanding of physical processes, more complete numerical simulations, and a more realistic indicator of the eventual global mean temperature response, called "effective radiative forcing" (ERF). It is reported that *the atmospheric concentration of CO_2 has increased to levels unprecedented in the last 800,000 years* (Fig. 1), *and probably even in the last 2.1 million years.*¶

* Here we use the term "climate researcher" in a broad sense, including not only climatologists, but also related specialties, ranging from geosciences and mathematical modelling to ecology and environmental economics.

¶ After CO_2, the well-mixed greenhouse gases (WMGHG) identified by AR5 as the largest contributors to radiative forcing are methane (CH_4) and nitrous oxide (N_2O). Their atmospheric concentrations have also reached unprecedented levels in the last 800,000 years, according to ice core records. Thanks to the phase-out of hydrocarbon emissions under the Montreal Protocol, N_2O has now replaced CFC-12 as the third largest WMGHG contributor to radiative forcing.

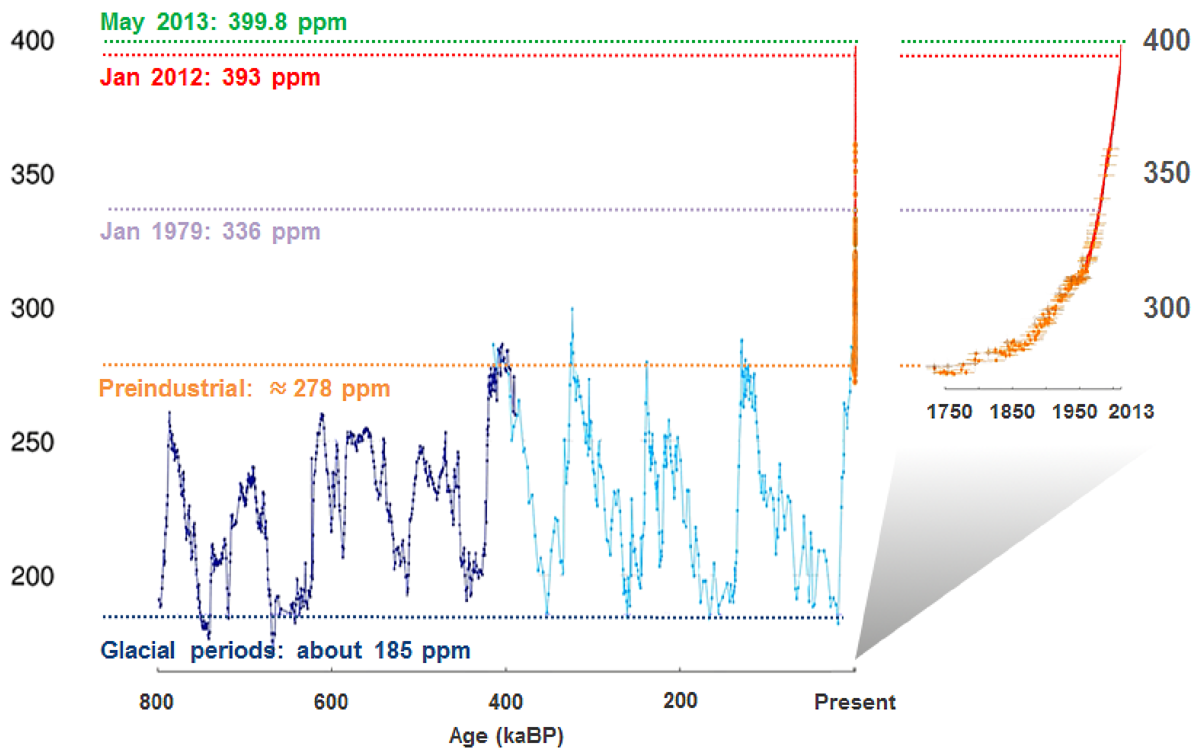

Figure 1: Historical record of atmospheric CO_2 concentrations back to circa 800,000 years ago. Vertical axis: atmospheric CO_2 concentration in parts per million (ppm). Horizontal axis: age of the record in thousands of years before present (kaBP). Red: Mauna Loa data, Hawaii (1958 to present). Orange: Law Dome Ice Core, Antarctica (last 1,000 years; a few data points from Siple Dome Ice Core, Antarctica, are also included). Light blue: Vostok Ice Core, Antarctica (last 420,000 years). Dark blue: EPICA Dome C Ice Core, Antarctica (last 800,000 years). Historical milestones in the atmospheric CO_2 concentration, averaged over defined periods, are indicated on the left. Very low CO_2 concentrations coincide with glacial periods (colloquially called “ice ages”), which occur with a frequency of more or less 100,000 years (in accordance with Milankovitch’s 100 ka orbital cycle; eight glacial periods can therefore be identified in the full 800 ka record). The highest monthly-averaged CO_2 concentration ever recorded in human history is marked in green. The top-right panel shows a magnification of the same record for the current Industrial Era. All this data is available at the NOAA Mauna Loa website: http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html. This figure is an adaptation of a very instructive and highly recommended 3.6 min animation available at the NOAA website: http://www.esrl.noaa.gov/gmd/ccgg/trends/history.html.

Atmospheric CO_2 concentrations have increased by over 40% since pre-industrial times (from 278 ppm[§] in 1750 to a global average value of 394 ppm in 2012), primarily driven by fossil fuel emissions, which account for two-thirds of the 545 GtC cumulate emissions released to the atmosphere, and secondarily from land use change, mainly due to deforestation.[†] In 2010, fossil fuel emissions exceeded land use changes by a factor of ten.[‡] Most historical emissions are still stored in the atmosphere (about 44%, or 240 GtC), while natural terrestrial ecosystems have accumulated 150 GtC. The oceans have absorbed about 30% of the emitted anthropogenic CO_2, with serious consequences for marine ecosystems from the resulting acidification of surface sea waters (cf. Inter-Academy Panel Statement on Ocean Acidification, 2009).

Estimates of future atmospheric and oceanic CO_2 concentrations indicate that by 2100 the average surface ocean pH could be lower than it has been for more than 50 million years (WG1-AR5). Reduction of sea water pH renders oceans increasingly corrosive to different forms of calcium carbonate ($CaCO_3$), such as calcite and aragonite, which are vital for a large variety of marine calcifying organisms that provide coastal protection, habitat for marine life, and are at the base of the food webs. Consequently, ocean acidification constitutes a serious hazard to marine resources and ecosystem services, ranging from fisheries to coastal infrastructure and tourism. For instance, coral reefs are highly vulnerable to changes in pH and warming ocean temperatures, which are estimated to cause losses of reef-building corals at a rate of 1–2% per year. Such a loss adversely affects marine diversity, contributes to loss of economic activity, and increases the vulnerability of man-made infrastructures, natural landscape, and the human health of coastal populations to increasing sea level rise and related extreme events, like storm surges.[&] Recent studies also

[§] The concentration unit “ppm” (= µmol/mol) stands for parts per million, which in this context means 278 CO_2 molecules per 1 million molecules of dry air. One ppm of CO_2 is equivalent to 2.12 GtC, or 7.77 $GtCO_2$.

[†] From 1750 to 2011 the air concentration of methane (CH_4) has increased by a factor of 2.5 to 1.80 ppm, while the concentration of nitrous oxide (N_2O) incremented by 20% to 0.32 ppm within the same period. Anthropogenic emissions and changes in the nitrogen cycle have contributed to the accumulation of these non-CO_2 species in the atmosphere. Unlike CO_2, the atmospheric lifetimes of these pollutants are much shorter, 12 years for CH_4 and 120 years for N_2O. In contrast, emissions of carbon dioxide can remain in the atmosphere for many centuries.

[‡] Estimates of deforestation carbon are more uncertain than fossil fuel emissions, but could potentially be offset on a time scale of a century by forest regrowth and improved management of agricultural and forestry practices.

[&] Circa 23% of the world population lives within 100 km of the coast, and less than 100 m above sea level. In most common cases, one meter rise in sea level may cause a mean horizontal shoreline retreat from tens to hundreds of meters, or even a few kilometres depending on the coastal topography. In this sense, global sea level rise is already increasing human vulnerability to coastal extreme events by enhancing the severity of potential floods, regardless of the impact of climate change on the frequency and intensity of such extreme events.

suggest that ocean acidification may produce a positive feedback to global warming, through associated reductions in the release of cloud-forming compounds by phytoplankton.[#]

The high CO_2 concentrations already present in the atmosphere, and their associated climate impacts, will persist for many centuries even if anthropogenic emissions could be fully stopped. This is supported by recent paleoclimatic evidence of the very long timescales for natural recovery from large CO_2 emission pulses. All the facts discussed here represent (quoting WG1-AR5) *"a substantial multi-century climate change commitment created by past, present, and future emissions of CO_2."*

Is CO_2 really the main "control knob" of global warming?

Anthropogenic emissions of greenhouse gases, primarily CO_2, have contributed to an increase in surface temperature that is likely (66% to 100% probability, according to WG1-AR5) to be between 0.5ºC and 1.3ºC. Other human-caused forcings related to ambient concentration changes of aerosols, tropospheric ozone, and albedo-altering black carbon have likely contributed to between −0.6ºC and 0.1ºC. Natural climate forcings due to decadal scale changes in solar output and arising from the cooling aftermath of volcanic eruptions have likely contributed to between −0.1ºC and 0.1ºC. Together these effects have contributed to an increase in the global mean surface temperature consistent with observations of +0.6ºC warming. The WG1-AR5 report concludes that *"... more than half of the observed increase in global average surface temperature from 1951 to 2010 is very likely* (confidence greater than 90%) *due to the observed anthropogenic increase in greenhouse gas concentrations."*

In his Bjerknes Lecture to the 2009 American Geophysical Union Meeting, geologist Richard Alley (one of the Lead Authors of IPCC's AR4) reviewed the geological evidences of the role of carbon dioxide in Earth's climate history.[**] He concluded that if higher atmospheric concentrations of CO_2 cause mean surface warming, then Earth's climate history makes sense —in particular a number of peculiar warming events, like the End-Permian Mass Extinction, the Mid-Cretaceous Warming, the Palaeocene–Eocene Thermal Maximum, and many others— with CO_2 having *caused or amplified* the observed warming with a climate sensitivity comparable to the values adopted in modern models (roughly 3ºC warming for doubled CO_2 concentration). On the other hand, *"if higher CO_2 does not warm,"* Alley affirms, then *"we must explain how radiation physicists are so wrong, and how a lot of really inexplicable climate events happened over Earth's history."*

It must be emphasized that not *every* warming event is *triggered* by higher atmospheric CO_2 concentrations. The most obvious examples are the terminations of glacial periods (colloquially called "ice ages" in the popular culture), which are set off by orbital variations (viz. Milankovitch cycles; see Fig. 2). Notwithstanding, when carbon dioxide does not trigger the warming, it follows and amplifies it through a feedback effect. This means that there have been events in the climate history of Earth where temperature changes lagged those of CO_2, and other events where the opposite occurred (Fig. 3).

Accordingly, transient divergences between temperature and carbon dioxide responses can occasionally take place. For instance, recent high-resolution paleoclimate studies demonstrate (see WG1-AR5 and references therein) that when an increase of atmospheric CO_2 concentration precedes global surface mean temperature response, there still may occur short periods (on the order of a decade) during which the global temperature rise is flat. One example is the current 15-year moderation in global temperature rise: 0.05ºC increase per decade since 1998, instead of the long-term trend of 0.12ºC per decade since 1951. This recent warming hiatus is a particular manifestation of short-term climate variability combined with changes in the effective radiative forcing, which can enhance or counteract the prevailing temperature trend. According to WG1-AR5, a decline in natural forcing attributable to a reduction in solar irradiance and increased stratospheric aerosol loading after 2000 by enhanced volcanic activity would explain about half of the observed decrease in temperature rise over the period 1998–2011 against 1951–2011. Ocean heat uptake has also contributed to the slowing down of temperature change. In any case, what really matters in projecting future climates is the

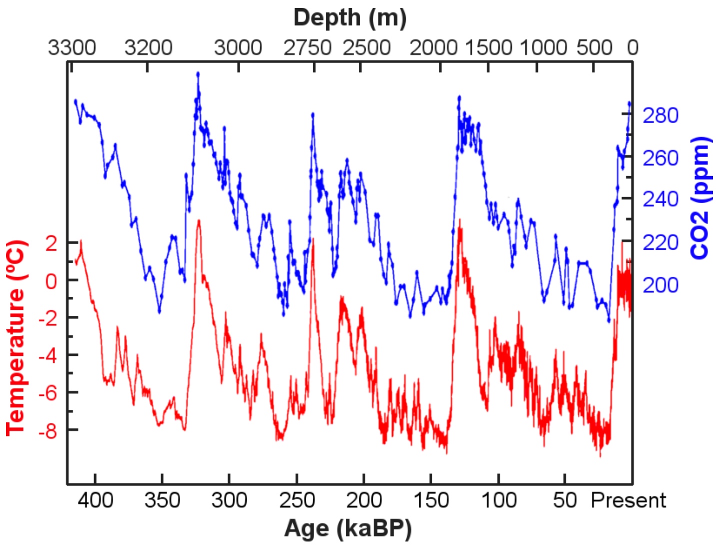

Figure 2: Vostok (Antarctica) deep ice core record of atmospheric CO_2 concentrations and Antarctic temperature back to circa 420,000 years ago.[¶¶] Left vertical axis (red curve): surface temperature variation from present value. Right vertical axis (blue curve): atmospheric CO_2 concentration in parts per million (ppm). Bottom horizontal axis: age of the record in thousands of years before present (kaBP). Top horizontal axis: depth from which the respective ice sample was extracted (the ice sheet at Vostok is more than 3.7 km thick). Four glacial periods can be clearly recognized, characterized by slow initial cooling and rapid warming at their terminations. The correlation of temperatures and CO_2 concentrations is striking.

[#] Barford, E. (2013) "Rising ocean acidity will exacerbate global warming." *Nature News,* 25 August 2013. http://dx.doi.org/10.1038/nature.2013.13602

[**] Alley, R.B. (2009) "The Biggest Control Knob." http://www.agu.org/meetings/fm09/lectures/lecture_videos/A23A.shtml

[¶¶] After Pettit et al. (1999) "Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica." *Nature* **399**, 429–436.

long-term trend, rather than variability over the short term. In this regard, current climate modelling simulations are consistent with historical climate observations. Indeed, even with the current "flattening" in the global temperature trend, the decade of the 2000s has been the warmest in the history of instrumental records and 2013 is on course to be among the ten hottest years ever recorded.§§

The lesson to be learned here is that, under typical conditions, global surface temperature never changes much without a corresponding change in atmospheric CO_2 concentration, *and vice-versa*. Ice core paleoclimate records are unambiguous in this respect, showing a striking correlation between CO_2 and temperature on the millennial scale, which is not only qualitative, but also quantitative (Fig. 2). This means that, in order to explain the amount of warming observed in the temperature records, one *must* take into account the greenhouse effect of the corresponding CO_2 concentrations recorded in that particular period. Thus, the question whether carbon dioxide has historically been a driver or a feedback of climate change is essentially irrelevant, as long as one understands that higher CO_2 concentrations *do warm* Earth's atmosphere.

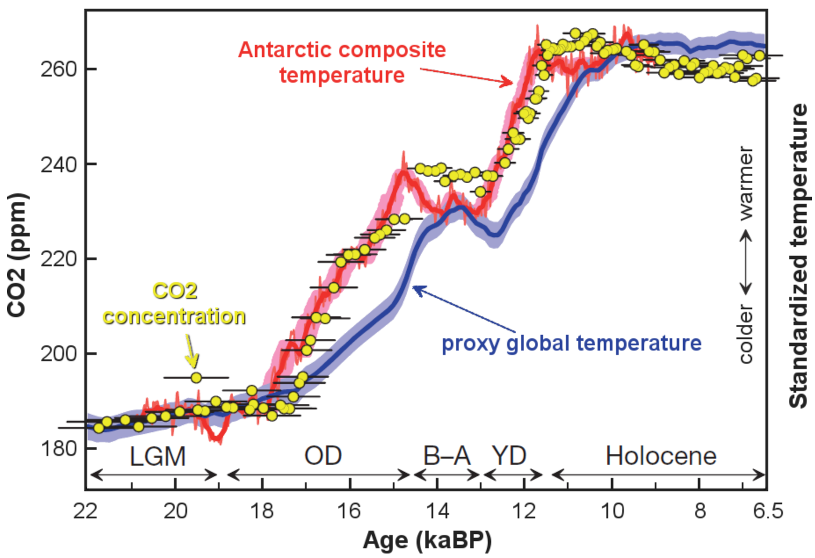

Figure 3: Variations in atmospheric CO_2 concentration, Antarctic and global temperatures during the last deglaciation†† (22,000–6,500 years before present). The global proxy temperature stack (blue) and the Antarctic ice-core composite temperature record (red) have been standardized for easy comparison with the atmospheric CO_2 concentration (yellow dots). The Holocene, Younger Dryas (YD), Bølling–Allerød (B–A), Oldest Dryas (OD) and Last Glacial Maximum (LGM) intervals are indicated. Notice that changes in CO_2 concentration are either synchronous with or lead global warming. An important exception is the onset of deglaciation, which features about 0.3ºC of global warming before the initial increase in CO_2, circa 17.5 ka ago. This suggests that CO_2 did not trigger the *initial* warming, but was a decisive driver of global warming *during* the deglaciation. The centennial scale lag of global temperature behind CO_2 is consistent with the thermal inertia of the climate system, owing mainly to ocean heat uptake and ice melting. In contrast, the lag of CO_2 and global temperature behind Antarctic temperature is caused by an anti-phased temperature response to ocean circulation changes in the northern and southern hemispheres (so-called "bipolar see-saw"), which highlights the importance of distinguishing global climate changes from their varied regional manifestations.

This conclusion is inspiringly illustrated by Alley's *overspending analogy:* debt leads to interest, which increases the original debt with time (if unpaid). Thus, interest lags debt, but one cannot explain the total amount of debt without taking into account the interests. Likewise, a rise in global temperature may sometimes precede the increase in the atmospheric CO_2 concentration. In this case, the increase in CO_2 lags warming, but one cannot explain the total amount of global warming without taking into account the effect of increased CO_2 concentrations in the atmosphere (Fig. 3).

The advantage of ice core climate records is that they provide *direct access* to past carbon dioxide concentrations through samples of ancient atmosphere preserved in air bubbles within the ice (Fig. 4). Compared to other paleoclimate archives, ice core CO_2 records are the most precise and reliable, especially those extracted from remote sites in Greenland and Antarctica, where regional influences (vegetation, etc.) are negligible and one can drill to depths of several kilometres into ice, corresponding to many hundreds of thousands of years before present. From ice cores we have so far been able to reconstruct Earth's CO_2 concentration history dating back to ca. 800,000 years (Fig. 1), and the quest is on for Antarctic sites that may potentially yield ice core records older than one million years. Carbon dioxide records older than those provided by ice cores do exist as well, although they are less precise and much more difficult to produce, because they require complicated combinations of several indirect geological and paleontological evidences (e.g. carbon isotopes in alkenone compounds, boron–calcium ratio of foraminifera shells, number of stomata in fossilized leaves, and others). In spite of all these difficulties, reliable CO_2 proxy records suggest that in pre-industrial times (viz. prior to 1750) the atmospheric concentration of carbon dioxide fluctuated roughly between 180 ppm and 290 ppm for at least 2.1 million years (WG1-AR5).

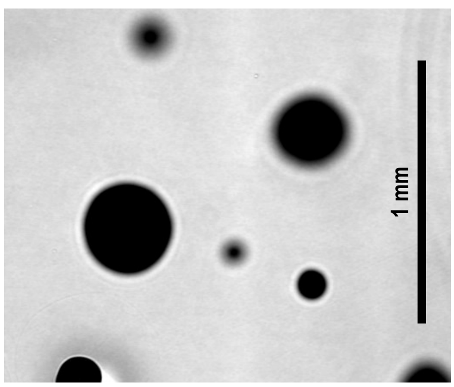

Figure 4: Micrograph of air bubbles (dark) in a 6 mm thick Antarctic ice core sample from 556 m depth (EPICA DML core). The age of the air inside these bubbles is ca. 8,900 years.

§§ Provisional statement of the World Meteorological Organization (WMO) released on 13 November 2013 during the United Nations (UN) Climate Change Conference in Warsaw, 11–23 November 2013.

†† After Shakun et al. (2012) "Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation." *Nature* **484**, 49–54.

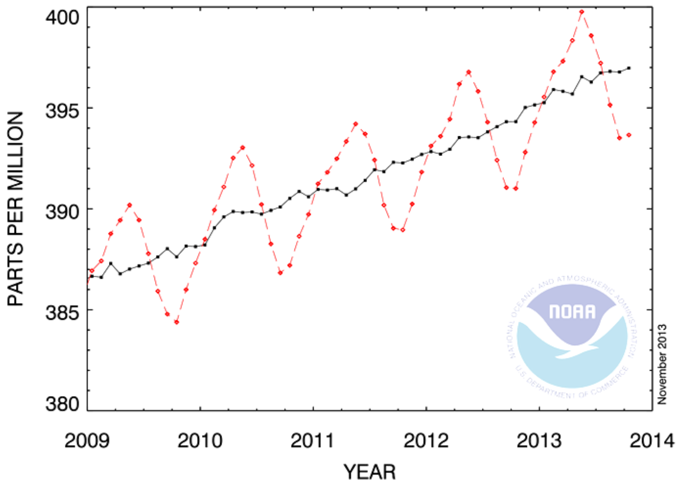

Figure 5: Recent monthly mean CO_2 record at Mauna Loa Observatory, Hawaii. Dashed red line with diamond symbols represents the monthly mean values, centred on the middle of each month. The black line with square symbols represents the same, after correction for the average seasonal cycle. The last year of data are still preliminary, pending recalibrations of reference gases and other quality control checks. This and other records are freely available and regularly updated at the NOAA website: http://www.esrl.noaa.gov/gmd/ccgg/trends/

Topping the 400 ppm CO_2 mark

Over the past century mankind has managed to increase the atmospheric concentration of CO_2 at a rate unprecedented in the last 22,000 years (circa 1.5 ppm/year), and during the last decade this rate has increased even more, reaching an average of 2 ppm/year. In May 2013 the Mauna Loa Observatory in Hawaii registered for the first time in recorded history a daily CO_2 concentration in the atmosphere beyond 400 ppm — the highest value in the last 800,000 years, and probably also in the last 2.1 million years.

The measurements performed at the Mauna Loa Observatory started by Charles David Keeling in 1958, who chose this remote location atop a Hawaiian volcano at almost 3,400 m above sea level because the air up there is neither industrial (as in densely populated areas) nor pristine (as e.g. in Antarctica). That is, the air is well-mixed and regarded by climatologists as the reference for the mean CO_2 concentration in Earth's atmosphere. The Mauna Loa CO_2 records show a typical vegetation-driven seasonal cycle, with a peak-to-peak amplitude of ca. 6 ppm, an annual minimum in early October, and a maximum in May. Accordingly, a minimum close to 393 ppm has been measured in early October 2013, and now CO_2 concentrations are rising once again to top 400 ppm anew in the summer of 2014. If the increase in mean atmospheric CO_2 concentration continues at this breath-taking pace, we may see the last CO_2 record below 400 ppm in this decade, and we could be tapping on the 450 ppm mark —the decisive stabilization target to limit global mean temperature rise to 2ºC level— by 20 years from now.

From the physical point of view, the value 400 ppm of CO_2 has no particular significance: it does not lead to an imminent climate catastrophe. Global warming, sea-level rise, ocean acidification, loss of Arctic sea ice, enhanced extreme climatic events, and other indicators of human-driven climate change have already been occurring for years and they will continue to occur in the years to come. From the political point of view, however, crossing the 400 ppm, especially in the manner we are doing it — without any significant reduction in the rate of increase of CO_2 concentrations— represents indeed a regrettable event. It highlights the inaction and indifference of governments and society to our self-triggered climate changes, which affect mostly the poor and weak, who have low adaptive capacity and suffer the greatest consequences of a changing climate, including an increase in health burdens.

Concluding remarks

This brief has shown that the atmospheric concentration of carbon dioxide is going up at a rate that makes meeting the 450 ppm stabilisation target increasingly difficult. This target is the one that is likely to keep global surface temperature increases within 2ºC of pre-industrial levels, a figure the global community agreed upon under the Copenhagen Accord in 2009 (15th Conference of Parties).

It is important to realize the crucial difference it makes when the reductions of carbon emissions begin. Over the

Typhoons such as Haiyan and its impacts represent a sobering reminder to the international community that we cannot afford to procrastinate on climate action. […]

What my country is going through as a result of this extreme climate event is madness. The climate crisis is madness.

[…] It seems that despite the significant gains we have had since the UN framework convention on climate change (UNFCCC) was born, 20 years hence we continue to fail in fulfilling the ultimate objective of the convention. Now, we find ourselves in a situation where we have to ask ourselves — can we ever attain the objective set out in Article 2, which is to prevent dangerous anthropogenic interference with the climate system?

By failing to meet the objective, we may have ratified the doom of vulnerable countries and have to confront the issue of loss and damage from climate change — a reality today across the world. Developed country emissions reduction targets are dangerously low and must be raised immediately, but even if they were in line with the demand of cutting by 40–50% below 1990 levels, we would still have locked-in climate change and would still need to address the issue of loss and damage.

Naderev "Yeb" Saño

Commissioner for the Philippines Climate Change Commission and Head of the Philippines Delegation to the UN Climate Talks.

Excerpts from the Philippines' Statement in the opening plenary of the United Nations (UN) Climate Change Conference in Warsaw (COP19), on 11 November 2013.‡‡

‡‡ For more details about the UN Warsaw Conference, see Galarraga, I. and M. Román (2013),"Warsaw conference: "small steps forward while awaiting major decisions at the 2015 paris conference", BC3 Policy Briefing Series 2013/Special Issue-01, Basque Centre for Climate Change (BC3), Bilbao, Spain.

last decade the average growth rate of fossil fuel emissions has been 3% per year, twice the rate observed between 1980 and 2000. Such growth has been spurred by the greater use of relatively cheap coal. In a business as usual scenario, atmospheric CO_2 concentrations by the middle of the 21st century would reach just over 500 ppm, a change of 25% above the present value, which would probably lead to an increase of more than 2ºC in the global mean surface temperature. On the other hand, reducing emissions by 2% per year starting no later than 2020 would limit the global carbon dioxide concentration to below 450 ppm.

Delaying emission cuts will only increase the risks of dangerous, and potentially irreversible, climate change affecting future generations and nature, and increasing future costs of mitigation and adaptation. On a purely economic basis, the costs of mitigating climate change will bring benefits that are up to an order of magnitude greater than the costs to achieve reductions. That the net present value of action is positive is a robust conclusion that is independent of the social discount rate applied in the analysis for a wide range of values of that rate. Therefore, urgent action is needed to make progress toward the 450 ppm stabilisation target. We believe these are both possible and justifiable, on climate, health, and economic grounds. Societies need to take the big steps necessary to make this transition and the time to start is now.

Unrestrained demographic growth and uncompromised exploitation of natural resources, which have in the past been mankind's most effective strategies of adaptation to new or changing environments, now render us victims of our own attempts to improve living conditions in a densely populated world. Our ancestors set the basis for our current lifestyle and triggered the climate changes we are now experiencing. We cannot blame them for that. They did not know better. We, on the other hand, are very aware of it. We can no longer deny it and hide ourselves behind the false excuse of ignorance. It is up to us to decide whether our descendants may praise us for initiating a novel, sustainable way of life, or blame us for selfishly insisting on the frustrated attempt to maintain an old-fashioned lifestyle at the costs of their well-being.

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BASQUE CENTRE FOR CLIMATE CHANGE
Klima Aldaketa Ikergai

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