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Where do we stand on global warming?*

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Resum. Les temperatures globals han augmentat aproximadament 0,8°C des del final del segle XIX. Aquest creixement no ha estat lineal, atès que hi ha hagut èpoques en què les temperatures es mantenien estables durant un breu període de temps, abans de tornar a augmentar. Les raons d'aquests canvis en l'índex d'augment de la temperatura estan relacionades amb factors antropogènics (contaminació d'aerosols de sulfat enfront de l'entrada de gasos de l'efecte hivernacle en la atmosfera) i amb factors naturals (erupcions volcàniques, variacions de la irradiació solar, les fluctuacions d'El Niño-Oscil·lació del Sud —ENSO—, etcètera). Al llarg de l'ultima dècada, les temperatures no han augmentat en la mateixa proporció que ho van fer en les dècades anteriors; i això ha conduït a especular que el canvi climàtic ha finalitzat. Aquesta visió s'ha reforçat per l'hivern inusualment fred que s'ha viscut fa mesos en molts llocs dels Estats Units i l'oest d'Europa. Tanmateix, aquesta conclusió es prematura. L'hivern 2009-2010 va ser un dels mes càlids registrats a escala global, i l'última dècada va ser la més calorosa des de fa segles. Malgrat aquests fets, molts polítics que no són favorables als controls de les emissions de carboni han aprofitat les condicions actuals per presentar al públic una visió unilateral de la situació. Aquest esforç ha rebut el suport d'una campanya incessant per a trobar i donar publicitat a uns quants errors en el quart informe d'avaluació del Grup Intergovernamental d'Experts sobre el Canvi Climàtic (GIECC), amb l'objectiu d'afeblir la confiança pública en les conclusions principals d'aquest informe. No obstant això, mentre es manté la discussió política, els nivells de diòxid de carboni i d'altres gasos de l'efecte hivernacle en l'atmosfera continuen creixent, s'acumula més escalfor als oceans, el nivell del mar augmenta al mateix temps que les glaceres i els casquets polars es fonen, i els indicadors fenològics de moltes regions mostren pertorbacions en l'estacionalitat de l'activitat biològica. I mentre es produeixen aquests canvis, la població mundial continua augmentant en una proporció d'unes 240.000 persones per dia, moltes de les quals es convertiran

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Abstract. Global temperatures have risen by ~0.8°C since the end of the 19th century. This increase has not been linear, as there have been periods when temperatures were stable for short periods before rising once again. The reasons for these changes in the rate of temperature rise are related to anthropogenic factors (sulphate aerosol pollution versus greenhouse gas inputs to the atmosphere) as well as to natural factors (volcanic eruptions, solar irradiance variations, El Niño/Southern Oscillation [ENSO] fluctuations, etc). Over the last decade or so, temperatures have not risen at the same rate as in previous decades, and this has led to speculation that global warming is over. This view has been reinforced by the unusually cold winter that many parts of the United States and western Europe experienced in recent months. However, such a conclusion is premature. The winter of 2009–2010 was one of the warmest on record when the entire globe is considered, and the last decade was the warmest, globally, for many centuries. In spite of these facts, many politicians who do not favor controls on carbon emissions have seized upon the recent conditions to present a one-sided view of the situation to the public. This effort has been reinforced by a relentless campaign to find and publicize a few errors in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report, to shake the public's confidence in that Report's main conclusions. Nevertheless, while the political bickering goes on, the levels of carbon dioxide and other greenhouse gases in the atmosphere continue to increase, more heat accumulates in the oceans, sea-level keeps rising as glaciers and ice caps melt, and phenological indicators from many regions demonstrate disruptions to the seasonality of biological activity. And as these changes occur, world population keeps increasing, at a rate of ~240,000 people per day, most of whom will grow up to be subsistence or small-scale agriculturalists, who will be just as vulnerable to climatic anomalies as late prehistoric/early historic societies were. Climatologists, and other environmental scientists have a responsibility to ensure that the public, and the

en agricultors de subsistència o a petita escala, i seran tan vulnerables a les anomalies climàtiques com ho van ser les primeres societats històriques o les del final de la prehistòria. Per tant, climatòlegs i altres científics del medi ambient tenen la responsabilitat d'assegurar que la ciutadania i els polítics que ells elegeixen entenen plenament aquests temes, i així podran valorar millor les conseqüències de la passivitat en el control de les emissions de gasos d'efecte hivernacle.

Paraules clau: escalfament global · Grup Intergovernamental d'Experts sobre el Canvi Climàtic (IPCC) · oscil·lació àrtica · nivells dels gasos d'efecte hivernacle · canvis fenològics

politicians they elect, fully understand these issues so that they can better appreciate the consequences of inaction over controlling greenhouse gas emissions.

Keywords: global warming · Intergovernmental Panel on Climate Change · Arctic Oscillation · levels of greenhouse gasses · phenological changes

Changes in the public perception of global warming

Western Europe and the eastern United States experienced an unusually cold winter in 2009–2010, with record snowfall in some areas. Snowstorms paralyzed Washington D.C. and New York in January 2010, and exceptionally cold and windy conditions in parts of Europe brought transportation systems to a halt on several occasions in January and February 2010. To many people in these regions, suffering through a long hard winter, the idea that global warming is a problem seemed far-fetched and absurd. This loss of confidence in scientific proclamations was exacerbated by the theft and publication of private emails between scientists at the University of East Anglia and elsewhere, which—taken out of context—were easily misinterpreted to make it seem like scientific data had been manipulated to exaggerate the issue of global warming. Furthermore, a few minor errors in reports from the Intergovernmental Panel on Climate Change (IPCC) only added to the public uncertainty over climate science. Sensing a controversy, the media amplified these concerns and exaggerated the significance of the e-mails and the IPCC errors, so the public was understandably confused. It was cold and snowy outside, and scientists appeared to have been less than honest with the facts. Not surprisingly, public opinion polls in North America and Europe showed a steady decline in the number of people who considered that global warming was an important issue for their governments to deal with.

The exceptionally cold and snowy winter in Europe and parts of the eastern United States was related to a weather pattern known as the Arctic Oscillation (AO). When the AO is in its negative mode, cold air is advected into both regions, and in December 2009–February 2010 the AO was persistently in one of the most extreme negative modes observed over the last 60 years, leading to severe winter weather conditions. But for almost all other parts of the world, the winter of 2009–2010 was warm and so average winter temperature for the globe as a whole was actually the second highest recorded in the last 150 years of instrumental records (Fig. 1) [3] and this trend has continued (through May 2010). For the last 10–15 years, there have been a succession of record-breaking temperatures; paleoclimatic reconstructions indicate that the most recent decade has been the warmest for well over a millennium [8,13]. So, the public perception in Europe and the US, that "global warming is over," is clearly misplaced as there has been no change in the overall global warming trend. Furthermore, several inquiries into the leaked e-mails have shown that there was no falsification of data, and although there were a few errors in the ~3000-page IPCC reports, none of them had any significant effect on the overall conclusion that, "most of the observed increase in globally averaged temperatures since the mid-20th century is very likely [defined as >90% probability] due to the observed increase in anthropogenic greenhouse gases" [19]. Thus, global warming is still a real and pressing problem, notwithstanding the decline in public confidence.

How can we be confident that the observed warming is due to human activity (i.e. anthropogenic) rather than merely a natural climate variation? The concentration of carbon dioxide in the atmosphere is now ~390 ppmv (parts per million by volume) compared to ~280 ppmv at the beginning of the industrial revolution. This increase is directly the result of the combustion of fossil fuels (mainly coal, oil and natural gas) and a large reduction in carbon 'sinks' (principally tropical forests). There are several factors that have led most climate scientists to agree with the statement of the IPCC, that the rise in global temperatures can be directly linked to the rise in greenhouse gases. First, the role of carbon dioxide (and other so-called green-

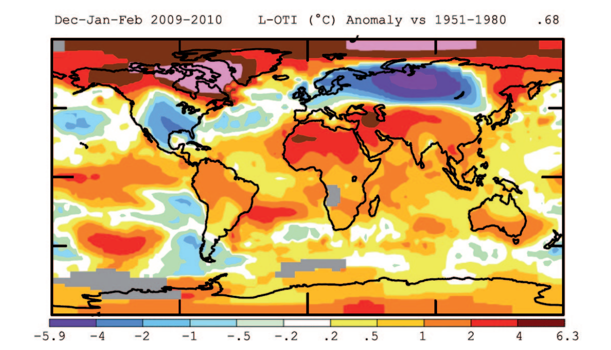

Fig. 1. Winter 2009–2010 (December–February) mean temperature anomalies, relative to 1951–1980 averages. Overall global mean anomaly was +0.68°C Source: NASA Goddard Institute for Space Studies.

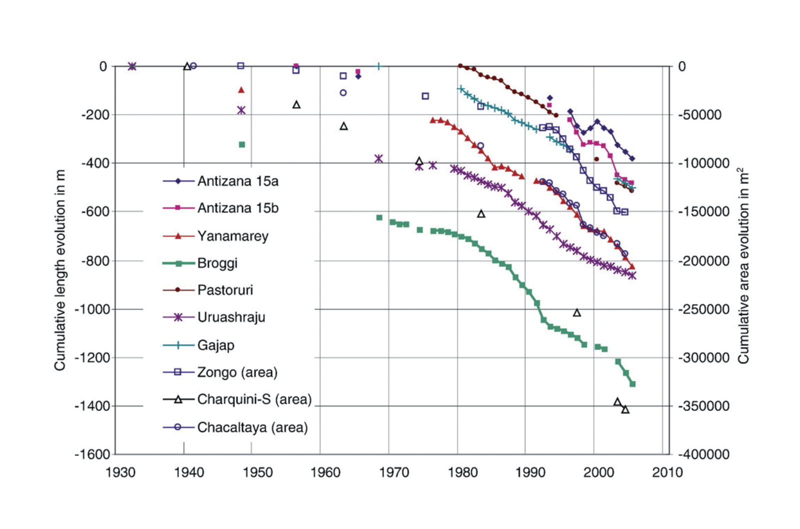

Fig. 2. Change in length and surface area of 10 tropical Andean glaciers from Ecuador (Antizana 15a and 15b), Peru (Yanamarey, Broggi, Pastoruri, Uruashraju, Cajap) and Bolivia (Zongo, Charquini-S, Chacaltaya) between 1930 and 2005 [23].

house gases, such as methane, CH_4, and nitrous oxide, N_2O) in the Earth's energy balance is well understood. These gases are transparent to incoming solar radiation, but play a crucial role in absorbing radiation emitted by the Earth, thereby raising the temperature of the lower atmosphere. More than a century ago, Arrhenius calculated that the temperature of the Earth would rise if carbon dioxide levels were higher [25]; thus, there is a clear physical basis for global warming due to a rise in greenhouse gases. The important issue is how much will the Earth warm for a given increase in CO_2? This is complicated because it depends on many feedbacks, both positive and negative, within the climate system. For example, warming will increase evaporation from the oceans and, since water vapor is a greenhouse gas too, this might be expected to enhance warming. But as water vapor increases, so too do clouds, and these might then reduce the amount of solar radiation reaching the Earth's surface, thereby compensating for the effect of higher CO_2 levels. In polar regions, higher temperatures may lead to a reduction in sea-ice and snow cover, causing a decline in surface reflectivity (albedo) which would lead to more energy being absorbed at the Earth's surface, thus amplifying the warming trend. These are just a few examples of the complex interactions that occur as greenhouse gas concentrations rise, and warming occurs. However, this complexity does have some benefits because the pattern of warming—temporal, geographical, seasonal—as well as its distribution with elevation in the atmosphere, provides a unique fingerprint. This has been determined by comparing the simulations of global climate models that have different levels of CO_2 in the atmosphere. These models (which incorporate all the complex interactions between components of the climate system) indicate that greenhouse gases result in more warming at higher latitudes (related to the decline in snow and ice), more warming in spring, and enhanced warming at higher elevations in the Tropics (compared to the surface) due to the release of latent heat from higher amounts of water vapor in the atmosphere. These patterns can be examined in observational data to determine if the 'CO_2 signal' has been detected, and indeed there is compelling evidence to show that this is true [4,17]. Furthermore, model simulations with only natural factors driving changes in the Earth's energy balance (principally aerosols from explosive volcanic eruptions and small changes in solar radiation) are unable to reproduce the observed changes in global temperature over the last 50 years. It is only when simulations with the same models are repeated, but adding the measured rate of CO_2 increase in the atmosphere, that the observed record of temperature change is obtained. Thus, there are multiple lines of evidence to support the argument that greenhouse gases (principally CO_2) are affecting global temperatures to a much greater extent than can be explained by any natural factor, and the overall patterns of change are just as one would expect from both theoretical considerations, and from model simulations.

What effect has the warming of recent decades had on the environment?

Some of the most visible changes have occurred in the cryosphere (the areas covered by snow and ice). In the Arctic, permafrost has been thawing as ground temperatures rise [15], and there has been a steady decline in the extent and mean thickness of sea ice at the end of each summer [20]. In the late 1970s and early 1980s, August sea-ice extent averaged around 8M km^2 whereas over the last few years it has been ~6M km^2, and much of the ice is now thinner 'first-year' ice, rather than the thicker 'multi-year' ice that was more common in the 1970s. In virtually all mountain regions, glaciers have receded rapidly, but recession has been particularly rapid in the Tropics. In Colombia, for example, the area of glaciers in the high mountains declined from ~10km^2 in the 1940s to < 4km^2 by the first decade of the 21st century. Ice cover on Cotopaxi, Ecuador, declined by 30% from 1976–1997 and these losses have continued [6]. Similar glacier recession has occurred throughout South America (Fig. 2) and this has serious implications for water resources and hydroelectric power production in many areas [22,24]. Other environmental effects include widespread phenological changes, with particular effects on insects, birds and flowering plants [16]. Rising temperatures have also led to thermal expansion of ocean waters, causing global sea-level to rise. This effect has been exacerbated by the melting of glaciers and ice sheets, so that the rate of sea-level rise has been increasing [23].

How will climate change in the future if the concentration of carbon dioxide in the atmosphere (and other greenhouse gases) continues to increase? This question is difficult to answer, mainly because there are huge uncertainties in what the pattern of global energy consumption will be in the future. This is closely linked to global population levels, and to the overall standard of living of societies, particularly those in the developing world. Fossil fuel use is rising most rapidly in China, India and other emerging economies, but the extent to which they adopt renewable energy technologies will have a big impact on their long-term fossil fuel consumption. And, of course, this is also true in the more developed economies, where fossil fuel use is already the highest per capita. The rate of loss of tropical forests, particularly in Indonesia and Southeast Asia, in Equatorial Africa and in Amazonia, also pose difficult questions. As these important sinks of CO_2 decline, more of the fossil fuel being consumed will remain in the atmosphere. Because of these large uncertainties, the Intergovernmental Panel on Climate Change developed a range of possible future energy use scenarios, based on different assumptions about population growth rates, energy technologies adopted, land use patterns, etc. These provided a set of projections about how CO_2 emissions might evolve through the 21st century, which could then be used to drive global climate models [12]. These future states can then be compared with baseline simulations, using current CO_2 levels as a reference to determine how the climate might be expected to change in future decades [10].

In all of the scenarios, even those in which CO_2 emissions eventually decline later in the century, CO_2 levels in the atmosphere at the end of the century are higher than today. This is because the rate of removal of carbon dioxide from the atmosphere (by terrestrial plants and by the oceans) is slower than the rate of emissions, and so without significant reductions in CO_2, beginning very soon, a future of much higher CO_2 levels is almost certain [1]. Given that CO_2 levels today (390 ppmv) are already higher than at any time in (at least) the last 850,000 years (based on gas bubbles trapped in ice cores from Antarctica) [7], the implications of much higher, sustained levels of CO_2 for ecosystems that are not accustomed to such conditions is a matter of serious concern, quite apart from any possible changes in climate.

Climate models provide guidance as to how future climates will develop under these higher levels of greenhouse gases. All future climate scenarios indicate significant global warming, to levels far beyond those experienced over the last millennium (Fig. 3) [14]. This will result in an increase in extremes, making exceptionally warm conditions (such as those experienced in western Europe in August 2003) more common events [11,18]. The shift towards higher temperatures will be accompanied by changes in atmospheric circulation, which will alter rainfall patterns across the globe. Furthermore, rising ocean temperatures and melting glaciers and ice sheets will cause global sea-level to rise by ~1m, perhaps more, by 2100 [23]. Currently, more than 100M people live in coastal areas that are within 1m of present sea-level. All of these changes will play out in a world where the population is expected to increase by 50%, to ~9M people, by ~2070 [21]. Clearly, this will impose significant stresses on many societies where poverty is endemic and conditions are marginal for life. Such stresses have important moral implications for more affluent societies, as well as more pragmatic security concerns [2].

In summary, global warming is real and is driven by anthropogenic activities, involving fossil fuel combustion and deforestation. Short-term weather anomalies may occur, but these have no significance in terms of the long-term warming trend, which continues. Public perceptions of global warming have been influenced by this misunderstanding, and fueled by media exaggerations of a few inconsequential errors in the IPCC reports, and misinterpreted e-mail communications between scientists. Meanwhile, global warming continues apace, with temperatures in the last 12 months reaching record-breaking levels. Model simulations of future climate, under a range of plausible economic and environmental scenarios, all point to an acceleration of the warming trend, with all of its environmental consequences, unless the relentless rise in greenhouse gas levels can be curtailed. Scientists have a responsibility to clearly communicate this information to the general public and to government officials so that policies may be adopted to address the negative consequences of anthropogenic climate changes.

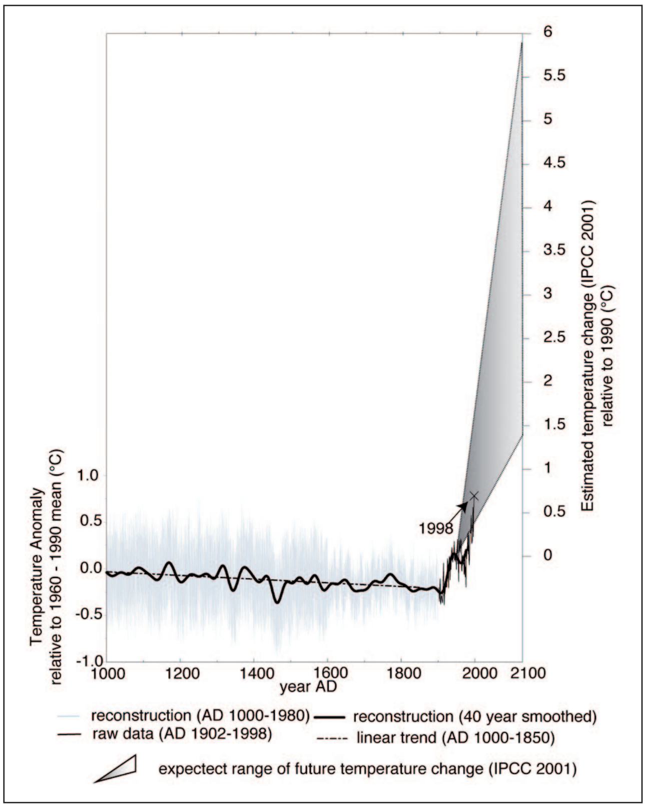

Fig. 3. A multiproxy reconstruction of mean annual northern hemisphere temperature [9] plotted with the range of IPCC estimates of future temperature change through 2100 [5]. The uncertainty in the paleoclimate reconstruction is shown as pale grey shading [14].

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