CONTRIBUTIONS to SCIENCE, **7** (1): 21–25 (2011)
Institut d'Estudis Catalans, Barcelona
DOI: 10.2436/20.7010.01.104 ISSN: 1575-6343
www.cat-science.cat

Celebration of Earth Day at the Institute for Catalan Studies, 2009

Natural archives, changing climates*

Raymond S. Bradley
Climate System Research Center, Department of Geosciences, University of Massachusetts, Amherst

Resum. De canvis climàtics n'hi ha hagut al llarg de tota la història de la humanitat, però els mesuraments instrumentals no ofereixen una perspectiva gaire àmplia sobre les variacions del clima. En moltes regions, els registres instrumentals només es remunten a un segle o dos. Per a entendre la variabilitat del sistema climàtic a més llarg termini, comptem amb els arxius naturals —sediments, casquets glacials, torberes, dipòsits en coves, bandes de corall i anells dels arbres—, en els quals s'ha conservat un registre dels canvis climàtics passats. Aquests arxius són una valuosa mina d'informació per a la història climàtica i ambiental del planeta i proporcionen informació sobre els factors que poden haver fet canviar el clima, com ara grans erupcions volcàniques explosives, canvis en la irradiància solar i efectes en l'atmosfera produïts pels humans. Els arxius paleoclimàtics mostren que la Terra ha experimentat situacions molt diferents de les d'avui, fins i tot en el passat recent, i ens proporcionen un marc de referència per a avaluar la magnitud dels canvis futurs que és probable que s'esdevinguin a mesura que els gasos d'efecte d'hivernacle es vagin acumulant a l'atmosfera. En el passat hi ha hagut societats que s'han ensorrat a causa de canvis climàtics bruscos i inesperats, i les proves paleoclimàtiques demostren que som vulnerables als canvis ràpids en els patrons climàtics. Malauradament, molts dels arxius naturals que ofereixen aquesta perspectiva exclusiva sobre el clima del passat estan avui amenaçats per les activitats humanes, i els mateixos canvis climàtics que intentem entendre.

Paraules clau: paleoclimatologia · arxius naturals · nuclis de gel · anells dels arbres · estalagmites · sediments lacustres · restes arqueològiques · efectes socials

Abstract. Climatic changes have occurred throughout human history, but instrumental measurements do not provide us with a very long perspective on climate variations. In many regions, instrumental records only extend back a century or two. To understand the longer-term variability of the climate system, we rely on *natural archives*— sediments, ice caps, peat bogs, cave deposits, banded corals and tree rings—in which a record of past changes in climate has been preserved. They are a treasure trove of the climatic and environmental history of the planet and provide information about factors that may have caused the climate to change, such as major explosive volcanic eruptions, changes in solar irradiance and human effects on the atmosphere. Paleoclimate archives show that the world has experienced very different conditions from today, even in the recent past, and they provide a framework for us to assess the magnitude of future changes that we are likely to experience as greenhouse gases continue to accumulate in the atmosphere. Societies in the past have been disrupted by abrupt and unexpected climate changes, and the paleoclimatic evidence demonstrates our vulnerability to rapid shifts in climatic patterns. Unfortunately, many of the natural archives that provide this unique perspective on past climate are now under threat by human activities, and the very climatic changes that we seek to understand.

Keywords: paleoclimatology · natural archives · ice cores · tree rings · stalagmites · lake sediments · archeological remains · societal effects

* Based on the lecture given by the author at the Institute for Catalan Studies, Barcelona, on 29 April 2009 for the celebration of Earth Day at the IEC (*1a Jornada de Sostenibilitat i Canvi Climàtic*).

Correspondence: R.S. Bradley, Climate System Research Center, Dept. of Geosciences, University of Massachusetts, Amherst, MA 01003, USA. Tel. +1-4135452120. Fax +1-4135451200. E-mail: rbradley@geo.umass.edu

Almost everything we know about climate has come from scientific instruments that were developed in the late 17th and 18th centuries. The very first information about the environment came from the use of barometers, rain gauges and thermometers. Figure 1 shows an example of these instruments, a thermometer made for Linnaeus which he used in his gardens to understand and to measure temperature with the Celsius scale. Celsius' original scale went from 100°, which was the freezing point, to 0°, which was the boiling point, and Linnaeus changed it around. This particular instrument would have cost the equivalent to 600 or 700 Euros today; they were very expensive, very specialized instruments and so there were not many available. The first temperature records for Europe date from the 18th century whereas in most of North America we do not have records until the 19th century. If we go to the Arctic or Antarctic, we have only maybe 50 years of records. So our perspective on climate change is very, very limited. Similarly, in desert areas and most of Africa we do not have much more than 100 or 150 years of instrumental records. The data are even worse for oceans, which of course make up 70% of the planet. Most of the measurements between 1750 and 1850 were made over the trading routes, so that almost nothing is known about the Pacific, which includes almost half of the world's oceans.

Consequently, when we want to look at global change and global warming and then combine this information, we cannot go back very much further than 1850, simply because we do not have the information. Figure 2A shows individual years of temperature, as a departure or anomaly from the average, from 1850 to 2008. You can see the rise in temperature over the last 100 years, not a constant but a generally steady rise, and then an acceleration in temperature over the last 50 years or so. Figure 2B shows the record of CO_2 over the same interval of time, and it is also steadily rising: measurements now are almost 385–390 ppm by volume and this is paralleled by other greenhouse gas increases. There is now a lot of evidence that links this rise in temperature with the rise in greenhouse gases. There are many accumulated lines of evidence, not just for global temperature, but in the overall signature of temperature: seasonal changes, latitudinal changes, changes with elevation in the atmosphere. These provide a fingerprint, a set of clues, rather like when a crime has been committed. You can see the evidence all around the globe and it fits with the culprit, and the culprit is greenhouse gases.

Now the question is, how unusual is this? Is this simply something that happens every 100 years, or every 1000 years? Because of our limited perspective, how can we know how common is this kind of change? And is there a way to figure out how temperatures changed before this 150 year period? How do we know what we know about the change in the Earth's climate over time? The answer is: we have to rely on the natural archives of past climate. And the study of these archives is paleoclimatology. Tree rings, sediments—sometimes laminated—from lakes and oceans, ice from high latitudes and high altitudes, stalagmites—which provide records of the rainfall that fell on the site—as well as early historic records of archeological information are some examples of natural archives; natural phenomena which in some way have captured in their structure a measure of past climate. We call them climate proxies, as they are a measure of climate, and the job of the paleoclimatologist is to decipher the information in these archives.

Figure 3 is an ice core that has just been drilled. The ice is extruded from a core barrel—either thermal or electromechanical—then logged, slid into tubes, and packed into insulated boxes for frozen transport. This particular ice core extends back about 2500 years; it is quite a short ice core, only about 100 m in length. But in Antarctica, the ice cores extend back almost a million years and they go down approximately 4 km, almost to the base of the ice sheet. As snow accumulates on the surface and becomes buried by more snow on top, it is compressed and transformed into solid ice. Inside the ice we find bubbles of gas, which are samples of the atmosphere at the time the snow was formed. And so, if we drill through the ice sheet or the ice cap we can extract the bubbles of gas and

Fig. 1. Thermometer made for Linnaeus in the workshop of the Royal Swedish Academy of Sciences by Johan Gustav Hasselström at the end of the 1770s. Source: Linnaeus Museum, Uppsala.

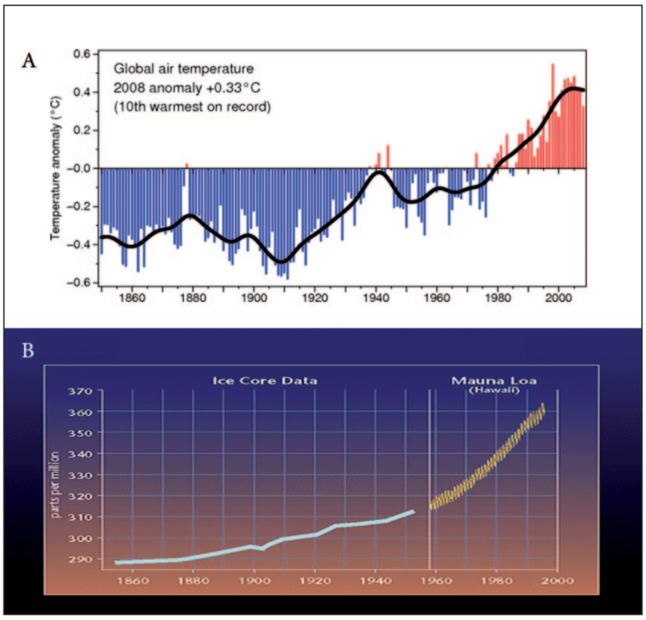

Fig. 2. (**A**) Temperature as a departure or anomaly from the average, from 1850 to 2008. (**B**) Ice core record of CO_2 over the same interval of time.

measure the history of the atmosphere and the composition of the atmosphere. As shown in Fig. 4, from 1000 years ago to the present, CO_2 levels varied very little and methane, nitrous oxide and sulfate were almost constant. And then, towards the 18th century, we see a change in the slope. Why? Because James Watt, a Scottish engineer developed the steam engine, which required coal, and his success in doing so marked the beginning of the industrial revolution. Coal is an organic material, made of plants that extracted CO_2 from the atmosphere millions of years ago, were subjected to intense compression, and gradually transformed into geological material. When we burn coal, we are returning that CO_2 to the atmosphere. In the 19th century, Daimler and Benz patented the internal combustion engine and the emphasis switched from coal to petroleum—to oil—and the same thing happened. The demand for fossil fuels expanded, such that the CO_2 levels increased almost linearly. Similarly, the levels of methane, which is related to irrigation and animal husbandry, and nitrous oxide, which is related to fertilizers and agriculture, also increased. The last line is world population and it is what really is driving these changes. We can be fairly certain that as the world population increases, from 6.5 billion today to 9 billion in the future, the demand for energy will escalate in parallel and CO_2 levels will continue rising unless we control the use of carbon fuels. Without the natural archive, the ice core in this case, we would not have any real idea whether the CO_2 levels we are currently experiencing are unusual at all. From the records in Antarctica, which extend back over 800,000 years—well before *Homo sapiens* were on the planet—we know that CO_2 levels have never risen above 300 ppm. And now, in a very short period of time, we have driven CO_2 levels to ~390 ppm.

Now let us look at some other natural archives. Among the other tools we can use are tree rings from trees that are stressed and barely able to survive, such as those found in high mountains and high altitudes. Being at their extreme limit of growth, they are very sensitive to climate changes, in this case to variations in temperature at high latitudes, and this sensitivity in recorded as variations in the width of their rings, which can sometimes be almost microscopic in size. A narrow sample of wood is extracted with an auger and the width of the rings is compared to the temperature measures of thermometers from the past 150 years to produce an equation that converts the width of the tree rings to temperature. By taking samples from all the way around the northern limit, from trees in Alaska, Canada, northern Scandinavia and the Ural Mountains in Russia and Siberia, we can go back some 600 years in time and see intervals when it was much warmer, such as in Medieval time, but also colder intervals, such as the Little Ice Age which was particularly cold between 1550 and 1850. But natural archives tell us not just how climate changed in the past, but also why it did.

By looking at the tree rings of individual years when it was extremely cold, we see that they correlate with large explosive volcanic eruptions during the past 600 years: 1601 in Peru, 1783 in Iceland, 1816 in Indonesia and 1912 in Alaska. Trees at high latitudes were affected by explosive eruptions all over the world because the incoming solar radiation was reduced by the cloud of material and by the expelled sulfur, which was oxidized to sulfur dioxide and then to sulfuric acid, with an overall surface-cooling effect. The ice core records of volcanic sulfate also show peaks of sulfur representing the volcanic eruptions, and we know that the Little Ice Age was driven to a large extent by the high frequency of these explosive volcanic eruptions.

But if we want to step back many thousands of years, to the period since the last ice age, the Holocene, we have to look at other natural archives. Diatoms are sensitive to and characteristic of water temperatures; therefore, by looking at the types of diatoms, such as those found in sediments off the coast of Norway, you can identify what the water was like over the last 13,000 years. The isotopes of oxygen in the calcium carbonate of stalagmites found in caves in China reflect the monsoon

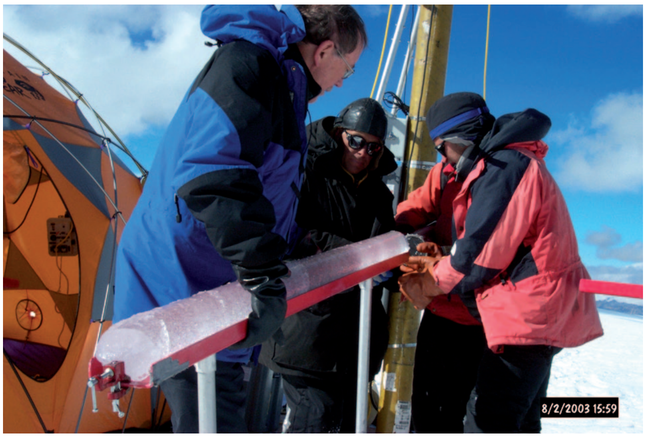

Fig. 3. Ice core that was drilled (in 2003) through the Quelccaya Ice Cap in Peru (5680 m) all the way to the base (Photo by Lonnie G. Thompson).

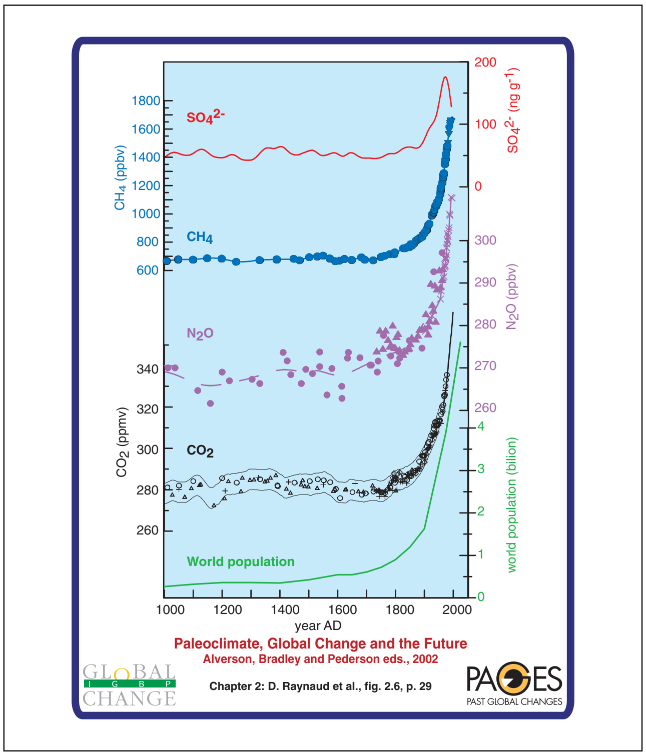

Fig. 4. Anthropogenic increase: records of carbon dioxide, methane, nitrous oxide, and sulfate over the last millennium [1].

strength over the last 9000 years, with a stronger monsoon between 6000 and 8000 years ago. Lake sediments from Africa also show that it was a much wetter time in Africa between 6000 and 9000 years ago because monsoon rains extended further into the Sahara desert. Archeological remains from people who lived there, together with the bones of crocodiles and hippos can be found at the Gobero site in Niger, indicating that freshwater must have been present, yet today this is one of the most arid places on Earth.

From these three sets of records we know that in the early Holocene it was warmer at the higher latitudes in the summer; monsoon rains were stronger and they penetrated further inland. However, it turns out that these conditions had nothing to do with human activity; they were due to a natural change in which the Earth was oriented towards the sun. Periodic changes in the Earth's rotation, tilt and orientation, called the Milankovitch cycles, influence how sunlight is distributed across the Earth's surface. Today, we are closest to the sun in the northern hemisphere winter, but if you go back 7000 to 10,000 years we were closest to the sun in the northern hemispheric summer. The result was that continents were warmer in the early Holocene, more warm moist air was drawn to the continental interior, leading to a stronger monsoon in China, wetter conditions in Africa, and warmer air reaching far into the north Atlantic. This is an example in which we know that climate was very different not so long ago, and it had direct effects on people—they were able to live in places they cannot live today—but it was due to natural factors, not to human activity. However, we can perhaps learn something about the overall environmental changes that occurred during that period, because we know that at the time the North Atlantic was warmer, and today it is also becoming warmer for totally different reasons, because of greenhouse gases.

Paleoclimate records also provide evidence for regional climatic (mainly hydrological) anomalies. These were sometimes abrupt and unexpected, unprecedented and persistent, and had severe societal consequences that led to societal upheaval, abandonment, migration and the rise of new 'management' (whether it was change in religion statuses, dynasties, etc.). An example is the disappearance of the native Indians who lived in what is now the Mesa Verde National Park area, in southern Colorado and Utah. In the Arabian Peninsula, we see that the biggest period of drought in the last 2600 years was in 540 A.D., which was of course the time of Mohammed but also the time of the plague of Justinian and many social disruptions in that part of the world. Might this persistent, unusual, and unprecedented drought have led to social disruption, driving people to look for a new direction or leadership? Perhaps.

During the same interval, in 540 A.D., something unusual happened on the other side of the world. The tissues of tree rings in Mongolia were destroyed by the cold conditions in the middle of the growing season. There is little evidence for major volcanic eruptions (no sulfate is found on the ice caps); instead, it has been suggested that the near passage of a comet created a cloud that reduced solar radiation, monsoon heating, and lowered the rainfall at the time. We are faced with an example in which something happened that had direct societal effects but we do not yet understand why; and if we do not understand why it happened in the past, we cannot know if it might happen again in the future.

We often look at our cultural treasures and we preserve them, value them, we put them in museums and visit them, and we recognize their value for our society and our culture. But there are also treasures of our natural history. If we compare the ice cap in Kilimanjaro in 1930 and 2005 (Fig. 5), we can see it is almost gone. There were over 12 km^2 of ice at the beginning of the century in Kilimanjaro; today there are less than 2 km^2 [2]. The unique environmental history that was in that icecap has now disappeared, and so we do not have that record of how climate changed in Africa because it melted away, by our very effects on the planet's climate.

Many important natural archives that provide this unique perspective on past climate are now under threat by human activities, disappearing before we have the opportunity to sample them and study the history of past environmental conditions that they contain. There is an urgent need to recover these archives before they are lost forever. Natural archives enable us to understand how climates have changed and, more importantly in many cases, why; they allow us to distinguish anthropogenic changes from those due to natural factors; they inform us of the societal effects of abrupt climate changes in the past and may provide insight into the environmental consequences of the future. Understanding why the changes in climate have occurred provides rich opportunities for future research, and for making contributions to the on-going debate about climate change and the implications for national and international policies.

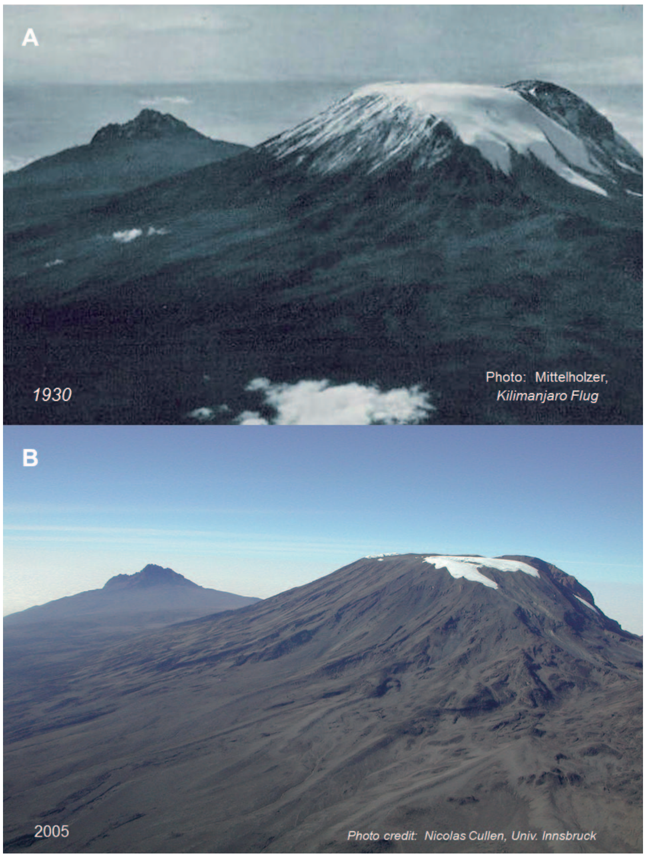

Fig. 5. Kilimanjaro ice cap in (A) 1930 and (B) the year 2005.

References

1. Raynaud D, Blunier T, Ono Y, Delmas RJ (2003) The late Quaternary history of atmospheric trace gases and aerosols: Interactions between climate and biogeochemical cycles. In: Alverson KD, Bradley RS, Pedersen TF (eds) Paleoclimate, global change and the future. Springer Verlag, Berlin, New York, 235 pp.
2. Thompson LG, Mosley-Thompson E, Davis ME, et al. (2002) Kilimanjaro Ice Core Records: Evidence of Holocene Climate in Tropical Africa. Science 298:589-593