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Current global warming appears anomalous in relation to the climate of the last 20 000 years

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ABSTRACT: To distinguish between natural and anthropogenic forcing, the supposedly ongoing global warming needs to be put in a longer, geological perspective. When the last ca. 20 000 yr of climate development is reviewed, including the climatically dramatic period when the Last Ice Age ended, the Last Termination, it appears that the last centuries of globally rising temperatures should be regarded as an anomaly. Other, often synchronous climate events are not expressed in a globally consistent way, but rather are the expression of the complexities of the climate system. Due to the often poor precision in the dating of older proxy records, such a statement will obviously be met with some opposition. However, as long as no globally consistent climate event prior to today's global warming has been clearly documented, and considering that climate trends during the last millennia in different parts of the world have, in the last century or so, changed direction into a globally warming trend, we ought to regard the ongoing changes as anomalies, triggered by anthropogenically forced alterations of the carbon cycle in the general global environment.

KEY WORDS: Global warming · Long-term perspective · Climate anomaly

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1. BACKGROUND

'The past is the key to the present and the future' is a phrase often used by geologists to explain how their knowledge can be used by society. It is, however, also a well-known fact that each moment in Earth's history is unique, which implies that there are no perfect analogues for today's world or any modeled future scenarios. This is certainly true for the ongoing trend of global warming. The best analogue to a global warming scenario similar to what is expected in the coming centuries, and with some detailed and robust data, may be the Last Interglacial (LIG) with its warmer climate, globally coherent or not, but without increased greenhouse gases (GHGs). Instead, Earth's orbital eccentricity was more than twice today's value during large parts of the LIG (Berger & Loutre 1991), resulting in an overall increase in continental summer temperatures (Antarctica excluded) with at least 0.5°C (Crowley & Kim, 1994) between 132 and 124 kiloyears (kyr) BP. Furthermore, Arctic summers were possibly 2 to

4°C warmer (Otto-Bliesner et al. 2006) and, as expected, this resulted in higher sea levels and smaller ice sheets on Greenland and West Antarctica (e.g. Overpeck et al. 2006). The estimations of the maximum sea level stand during the LIG vary greatly, but according to Kopp et al.'s (2009) integrated analysis of globally distributed LIG data sets, it was 6.6 to >8 m higher than present. Although such scenarios are not directly valid for the present and nearest future, it shows how vulnerable interglacial glaciers and ice sheets may be to global warming and rising sea levels. In the light of these LIG reconstructions and the well-known Arctic amplification effect (IPCC 2007), the concentration of glacial ice around higher latitudes will most likely not prevent it from melting in a warmer world.

Since the Last Glacial Maximum (LGM) 26 500 to 20 000 yr ago (Clark et al. 2009), Earth has undergone profound changes: the large continental ice sheets in the Northern Hemisphere (NH) have vanished (with the exception of the Greenland ice sheet), the Antarctic ice

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sheet has diminished considerably, local mountain ice caps have disappeared (and partly resurfaced in the late Holocene) and global paleogeography has changed considerably due to the coastal evolution caused by the 120 to 140 m rise of sea level generated by the melting ice sheets (e.g. Lambeck & Chappell 2001, Peltier 2007). As a consequence, and with a complex development of a continuously variable world throughout these 20 000 yr, our planet looks very different today compared with the LGM situation. By combining proxies from marine, terrestrial and ice core records from different parts of the globe, it is possible to examine the general climate development since the LGM, and relate and compare these changes to the Intergovernmental Panel on Climate Change (IPCC) reports of the last few centuries of what a majority of researchers regard as a global warming. However, it is not possible to perform a totally flawless analysis on this issue, especially not in a context with very restricted space: the topic is huge. This is partly due to the wealth of data available; in addition, it is problematic to compare, in a statistically sound way, extremely detailed meteorological data of the last century with different types of geologic proxy data of varying time resolution. Instead, I will try to present a short overview of the global climate development since the LGM and put the last 150 yr of the so-called global warming into a more long-term geological context.

2. THE LAST TERMINATION

An intriguing feature of the end of the last ice age, the Last Termination, is the step-wise and oscillating warming-cooling scenarios displayed in most of the NH records (e.g. Hafliðason et al. 1995, Björck et al. 1996, Wang et al. 2001, Andersen et al. 2004), compared to the gradual and more or less continuous warming in most of the Southern Hemisphere (SH) and large parts of the equatorial regions (e.g. Lea et al. 2000, Stott et al. 2007). While the complex climate trend of the north is well-mirrored by the development of, for example, atmospheric CH_4 content (Blunier et al. 1998), which is directly coupled to the temperature changes of the land mass-dominated NH, where most of the methane is produced, atmospheric CO_2 content and many SH temperature curves almost 'go hand-in-hand' (Monnin et al. 2001), often explained by changes in sea ice extent and thereby ventilation of the Southern Ocean (Marchitto et al. 2007, Fischer et al. 2010). In the NH, the first, although weak, trend of rising post-LGM temperatures begins slightly before 20 000 calendar yr BP (cal yr BP) (Andersen et al. 2004), preceding the southern rise by more than 2000 yr. On the other hand, this first large deglacial warming in

mid-high southern latitudes began several millennia before a correspondingly significant warming abruptly started in the mid-high latitudes of the north at ca. 14 600 cal yr BP, defining the onset of the Greenland Interstadial 1 (GI-1) (Björck et al. 1998), preceded by the so-called mystery interval (Broecker & Barker 2007).

When the interhemispheric climate relationships of the Last Termination are compared more in detail, often with the aid of the well-dated ice cores from Greenland and Antarctica and in combination with sea temperature proxies (e.g. Barker et al. 2009), a bipolar seesaw pattern emerges. The details of the mechanism behind this pattern have been discussed and are not clear, but changes in the Atlantic meridional overturning circulation (AMOC) certainly play a key role behind the underlying processes. When the AMOC in the north is disturbed by, for example, outbursts and/or large volumes of glacial melt-water, the meridional heat transport (from south to north) is seriously hampered. This results in a cooling in the north, while warmer waters reside in the Southern Ocean with a southerly displacement of sea ice and warming of the atmosphere. Furthermore, there seems to be a direct relation between the duration of the Greenland stadials and the degree of the Antarctic warmings (EPICA Community Members 2006). In general, the glacial climatic anti-phase relationship (with some phase lags) between the 2 hemispheres, the so-called bipolar seesaw mechanism, continued at least until ca. 12 000 cal yr BP and perhaps also throughout the Holocene (Ljung & Björck 2007, Maslin & Smart 2010), and the data available strongly indicate that there is no common global warming (or cooling) event during the Last Termination.

3. EARLY HOLOCENE

At the distinct onset of the Holocene Series/Epoch, as defined by Walker et al. (2009), and warming in the NH, large parts of the SH had already been continuously warming for at least 1000 yr. During the subsequent deglaciations of the NH and Antarctic continental ice sheets, as well as the large mountainous ice sheets of the Rocky Mountains, Andes and Himalaya, huge amounts of freshwater were discharged into the ocean during a fairly short time; the sea level rose ca. 60 m in less than 6000 yr (Siddall et al. 2003). These often periodic freshwater pulses seem to have caused recurrent perturbations of both the atmospheric and marine circulation patterns. This is probably the main reason why the climate of the higher (especially northern) latitudes in the early Holocene displays a seemingly chaotic behavior. However, when marine, ice core and terrestrial records are compared from these

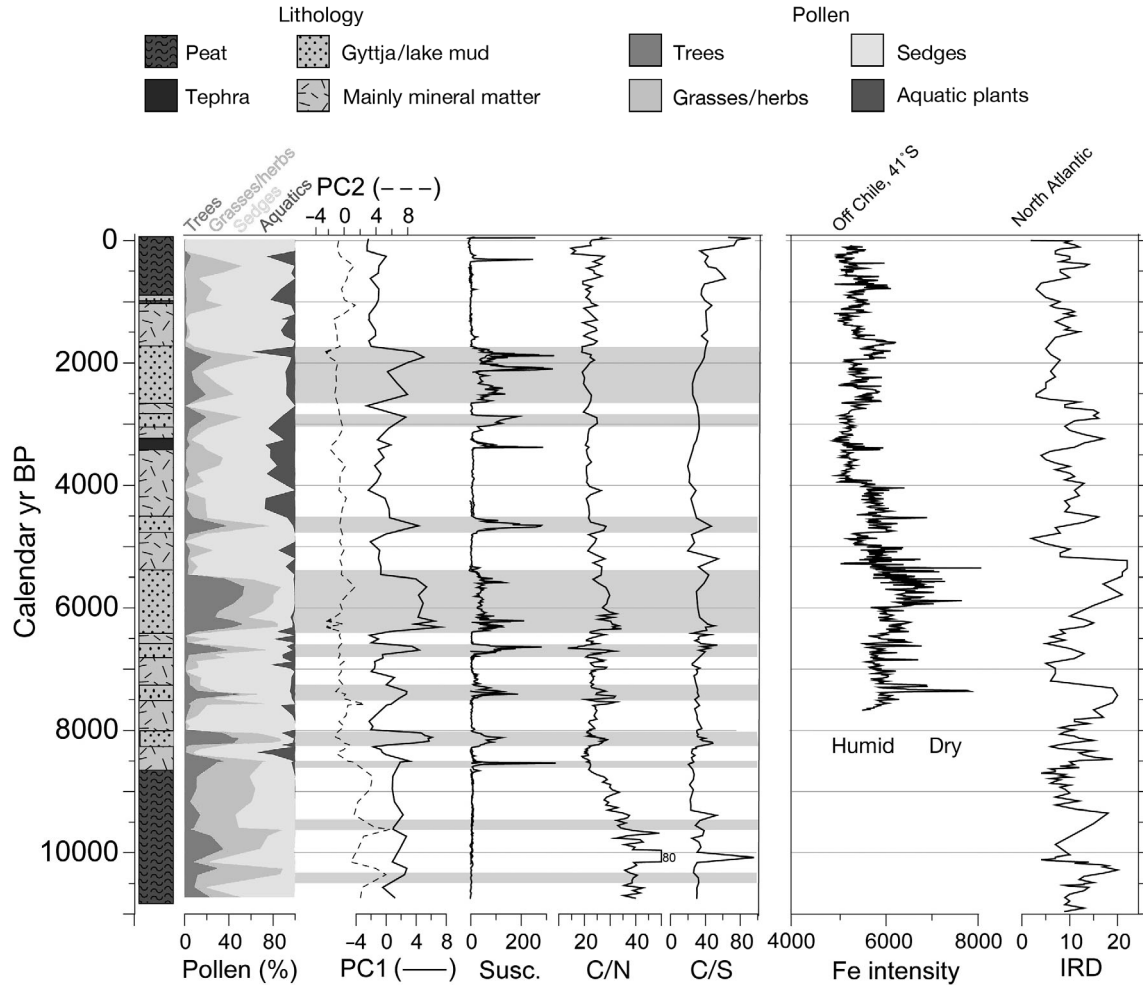


Fig. 1. A unique Holocene record from an overgrown lake, 2nd Pond, on Nightingale Island in the South Atlantic (37° S, 12° W), situated in the Tristan da Cunha island group between Cape Town and Montevideo. Shown are the lithology, pollen and geochemistry records from the 2nd Pond basin, including Principal Components 1 and 2 (PC1, PC2; after Ljung & Björck 2007). Peaks of the C/N ratio and magnetic susceptibility (Susc; 10⁻⁶ SI units) record imply increased input of terrestrial organic and mineral matter, respectively, indicating periods of increased precipitation, while the C/S ratios imply varying input of aerosols and/or sea spray. Also note that high PC1 values are interpreted as increased precipitation, i.e. increased in-wash of pollen from more distant growing trees. Horizontal shaded stripes mark periods with increased precipitation. This record is compared with the Fe intensity (XRF counts s⁻¹) record in a marine core off Chile (Lamy et al. 2001), indicating higher or lower precipitation in central Chile, and a stacked record of hematite-stained grains, interpreted as ice rafted debris (IRD; amount of hematite-stained grains, expressed as percentage of lithic grains in the 63–150 μm size range), in marine cores in the North Atlantic (Bond et al. 2001), implying more or less sea-ice and icebergs

different regions it is not difficult to find consistent climate oscillations within each region, consistent trends within each hemisphere—possibly insolation-forced—and even some roughly synchronous interhemispheric oscillations (Fig. 1). It is, however, virtually impossible to find evidence for globally synchronous climate events with the same climate signature, for example warmings or coolings. In terms of possible forcing mechanisms, apart from freshwater outbursts, some of the events have been assigned to still partly unknown climate-related processes, such as decreased solar activity or irradiance and/or increased cosmogenic radiation (e.g. Björck et al. 2001, Bond et al. 2001).

The high summer insolation to lower (northern) latitudes and the meridional displacement of the Inter-tropical Convergence Zone (ITCZ), as a boreal summer perihelion effect of the precession cycle, strengthened the monsoon in many subtropical regions. Although this led to a fairly stable climate on these lower latitudes during the first few millennia of the Holocene—often with warm and humid summers as a consequence—there is also ample evidence for a link between North Atlantic climate and the Asian Monsoon (AM). High-resolution analyses of Chinese stalagmites (Wang et al. 2005) show that many of the ice-rafted debris (IRD) events in the North Atlantic

(Bond et al. 2001) correlate very well to weakened AM events. According to Wang et al. (2005), some of these were possibly triggered by changes in AMOC such as, for example, during the so-called 8.2 kyr event (Alley et al. 1997), but some also correlate to changes in solar output as revealed by, e.g. comparisons to the atmospheric $\delta^{14}\text{C}$ record. Thus, examples of how common triggers result in various climate scenarios in different parts of the world are very common and seem to be a normal feature.

4. MID-HOLOCENE

Around 6000 cal yr BP, only 2 major inland ice sheets remained: the huge Greenland and Antarctic ice caps. However, modeling and data from the southern Greenland ice sheet imply that it was considerably smaller in the early-mid Holocene than today (Jönsson Sparrenbom 2006, Vinther et al. 2009), and new data from Iceland indicate that the Vatnajökull ice cap may perhaps have disappeared in the mid-Holocene (Stricker et al. 2009). In addition, it is very likely that many of the alpine glaciers had also melted as a consequence of the high summer insolation of the early Holocene, and did not begin to build up until in the later part of the Holocene. As a direct consequence, the sea level rise had more or less reached today's or even slightly above today's level (Yu & Zhao 2010) due to glacier melt. So in terms of ice sheet extent and sea levels, the mid-Holocene world did not look totally different from today's world.

However, in spite of the absence of the large continental ice sheets that had previously covered large parts of Eurasia and North America and, thereby, the absence of this large potential in impacting the climate system, paleoclimate records show that climate variability continued. The frequency of this variability varies between regions, latitudes and time periods. By analyzing a large set of Holocene records (Wanner et al. 2008), the spectral peaks are found in a band between 100 and 2200 yr, and no global consistency regarding the character of climate events can be found. Some events may be synchronous, e.g. the IRD pulses in the North Atlantic (Bond et al. 2001) and precipitation events in the South Atlantic (Ljung & Björck 2007; see Fig. 1), but their nature in terms of temperature, precipitation, etc., never seems globally consistent. However, some general long-term trends can be seen in several records, and this is most likely connected to gradual changes in the insolation-related parameters: for example, a cooling trend in the north-east Atlantic region (e.g. Andresen et al. 2006), decreasing strength of the AM (e.g. Fleitmann et al. 2003) and decreased intensity of the Southern Hemisphere

westerlies in southern South America (e.g. Unkel et al. in press), all superimposed on a series of oscillations. Although many of these oscillations may be more or less synchronous, they represent the natural variability and complexity of the climate system triggered by a variety of mechanisms, often stochastic in their nature, ultimately produced by insolation and seasonality changes and possibly also by a combination of other external (e.g. solar forcing) as well as internal (e.g. volcanism and carbon cycle changes) factors.

5. LATE HOLOCENE

The last few thousand years have been studied in great detail by several research groups and in many multidisciplinary projects, e.g. the EU Millennium project (<http://ralph.swan.ac.uk/millennium/>), and global consistency regarding climatic changes is difficult to find evidence for. The often-cited climate pattern of the last 2000 to 3000 yr with the Roman Warm Period, the Dark Cold ages, the Medieval Warm Period and the Little Ice Age (LIA) seems to be restricted to the NH or parts of it, and does not show up as a global pattern of warmings and coolings. In fact, these changes, as well as the often more or less synchronous changes in the SH, seem to be the result of a temporally variable atmospheric and marine circulation pattern, with e.g. meridional shifts of the Hadley cells, ITCZ and ocean currents, and in part also changing solar variability and/or forcing and fluxes of cosmogenic radio-nuclides. Although the latter 2 should have more or less global impacts, too little is known about the underlying climate-related mechanisms and how they may trigger different processes in the atmosphere and/or cryosphere.

In their mid- to late Holocene overview, Wanner et al. (2008) performed an interesting comparison on climate-related trends between 6000 cal yr BP and 1700 AD. These long-term trends can usually be explained by insolation changes; e.g. decreasing summer insolation to mid-high northern latitudes explains cooling conditions in Arctic Canada, Greenland and north-western Eurasia as well as the southwards displacement of the Arctic tree line. In addition, decreasing summer insolation to subtropical latitudes explains a weaker monsoon and a southwards shift of ITCZ. However, most of these insolation-related trends have clearly broken down during the last century, implying that an additional and important mechanism is now in action. This reversal of long-term trends is probably most significant in the Arctic, where climate reconstructions show that, for example, 4 of the 5 warmest decades of the last 2000 yr occurred during the last 5 decades of the 20th century (Kaufman et al. 2009).

It has long since been argued that the occurrence of the Maunder sunspot minimum during the 'heart of' the LIA shows the climatic importance of changes in solar activity and/or irradiance (Eddy 1976), an argument also often put forward to explain at least the onset of global warming and high solar activity during the early 20th century. In this respect it is important to note that while the LIA was not a period of global cooling, but a rather complex period of climate change, the last 100 to 150 yr have seen an almost globally consistent warming. Moreover, reconstructions of solar activity during the last millennium are not consistent (Bard et al. 2000, Usoskin et al. 2003), but it seems clear that the solar activity of the last 50 to 60 yr was not exceptional and has been at this or higher levels several times during the last millennium (Muscheler et al. 2007). For many reasons it is therefore not too controversial to state that the warming of the last century comes across as an anomalous climate event, not only in the perspective of a few centuries to a few millennia but also on longer time scales.

6. CONCLUSIONS

I find it fair to conclude that in the perspective of 10 to 20 millennia, the ongoing global warming seems to be an anomaly. Owing to often incomplete chronologies of the proxy based paleo-archives, especially in relation to the last 150 yr of daily to annual instrumental records, it may, however, be difficult to find clear-cut evidence for such a statement. One might also ask the question: What is the likelihood of seeing a global warming in our proxy records of comparable magnitude to the present warming, and arising only due to natural variations? A statistically reliable answer is of course difficult to give, but with the gradually increased focus on high-resolution records, I would be surprised if it would not have been found in many of our records.

Then again, as geologists we could try to put the ongoing warming into a thought experiment. Firstly, if we use the 8.2 kyr cooling event in the NH (Alley et al. 1997, Hammarlund et al. 2005), which lasted less than 100 yr, as a Holocene analogue of a partly enigmatic climate event, we cannot say for certain what triggered it. How can we try to better understand the underlying processes behind it? Perhaps by climate modeling? In fact, modeling of available data on early Holocene cooling events (Renssen et al. 2007) shows that this event was most likely triggered by freshwater outbursts that severely disturbed the thermohaline circulation and meridional heat advection to the north. This fits well with the geological observations that a large North American glacial lake was drained out into the

North Atlantic at that time, i.e. a normal procedure: testing models with data and vice versa. Secondly, if we found a short geologic warming event during, for example, the Holocene, and were able to analyze proxies from that period which disclosed that, for example, aerosols and solar activity had been rather high and that GHGs were >30% higher than during the preceding period, what conclusions would we have drawn? With data in a quantifiable form, modeling attempts would certainly have been carried out to find out the most likely hypothetic mechanisms behind the warming. After critical analyses of the data and repeated model runs, I think it is likely that geologists and/or geoscientists would find that the high atmospheric GHGs would be the main candidate for the warming, but perhaps with a reservation concerning the effects from increased solar forcing. The type of procedures described above is what the IPCC modelers have performed, by testing different climate scenarios, such as ones with or without increased GHGs, etc.

To summarize, as long as there is no positive and clear evidence for distinct, globally synchronous climate events (since the LGM) with consistent climate signals, we should consider the ongoing global warming as an anomalous climate event, possibly with a global forcing mechanism—increasing atmospheric content of GHGs—altering the energy budget of the Earth. The basis behind and consequences of such a standpoint can obviously be discussed, but the effects of our giant 'climate experiment' are undoubtedly difficult to estimate and evaluate since we have no past analogues to a situation with abruptly rising GHGs more than 10 000 yr into an interglacial period. We should therefore be cautious about how and to what degree we contaminate our environment and both directly and indirectly influence natural climate processes: the dangers of crossing climate thresholds in a greenhouse world have been pointed out by many scientists (e.g. Stocker 1999, Alley et al. 2003, Keller et al. 2008).

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