ELSEVIER

Quaternary Science Reviews 25 (2006) 2025–2030

QSR
VIEWPOINT

Viewpoint

What is what in the ice and the ocean?

D.-D. Rousseau[a,b,c,*], G. Kukla[c], J. McManus[d]

[a]*Université Montpellier II, Institut des Sciences de l'Evolution, UMR CNRS-UM2 5554, case 61, place E. Bataillon, 34095 Montpellier Cedex 05, France*
[b]*Universität Bayreuth, Lehrstuhl für Geomorphologie, 95447 Bayreuth, Germany*
[c]*Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA*
[d]*Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA*

Received 15 February 2005; accepted 30 March 2006

Abstract

Recently released data from the North Greenland Ice core Project (NGRIP) document several rapid, abrupt climate changes affecting the Northern Hemisphere in the last 110,000 years. In particular, the new core shows high-resolution succession of expressed warm and cold episodes, which occurred during substages of Marine Isotope Stage MIS 5. Some of these variations were reported earlier from the GISP2 and GRIP ice cores. In the NGRIP core, following the INTIMATE group recommendations, the oscillations were given labels, which are in part the same as in the isotope system of deep-sea sediments, although to some extent they are not coeval. Here we recommend honoring the originally published marine designations wherever possible, but distinguishing them by a prefix referring to their recognition in the ice.

The worldwide chronology of palaeoclimates requires Quaternary geoscientists to differentiate and label successions of past climate episodes. Stratigraphic rules call for first defining and naming the unit locally at a specific site or sites (type localities) and only later integrating them into more general climatostratigraphic units of worldwide value (International Subcommission on Stratigraphic Classification, 1976; Murphy and Salvador, 1999). The practice has resulted in Quaternary literature that abounds in local names of oscillations recognized from different biological, lithological, geochemical and geophysical proxies. The marine isotope stratigraphy (Emiliani, 1955; Shackleton, 1969) has been shown to be the most regionally uniform system, with a close to worldwide validity. It is now generally recognized as the basic climatostratigraphic subdivision.

Comparisons between the marine and terrestrial stratigraphic systems are not always based on reliable information. For example, this holds for the correlation of the terrestrial Eemian with Marine Isotope Stage 5 (MIS 5). As shown earlier (Emiliani, 1955; Shackleton, 1969), only substage MIS 5e, not the whole of MIS 5, is coeval with the Eemian in its type area in The Netherlands (Amersfoort) (Kukla et al., 1997; Sanchez-Goni et al., 2000; Shackleton et al., 2002). Further south the Eemian forests appear to correlate not only with MIS 5e, but also with a substantial portion of the subsequent substage MIS 5d, which in the marine stratigraphic system belongs to the early glacial. The comparison and correlation of land and marine records are even more complex when considering older, odd numbered marine isotope stages (Tzedakis et al., 2004).

The ice core records show similar climate oscillations as those described in the marine cores. The marine isotope chronology has therefore also been applied to the ice core stratigraphy. Conversely, some minor oscillations recognized first in the ice and only later in the ocean data such as the Dansgaard–Oeschger events (Dansgaard et al., 1985), or the Antarctic reversal events (Jouzel et al., 1994; Blunier et al., 1998), were later applied worldwide to marine and terrestrial records. However, the different nomenclatures followed the same logic and principles, so that only minor or no confusion resulted.

In the early GRIP ice record from Greenland (Johnsen et al., 1992; Dansgaard et al., 1993), several oscillations

*Corresponding author. Tel.: +33 467 144 652; fax: +33 467 042 032.
E-mail address: denis@dstu.univ-montp2.fr (D.-D. Rousseau).

0277-3791/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2006.03.009

spaced approximately 1500 years apart were identified and named the Dansgaard–Oeschger events (Dansgaard et al., 1993; Grootes et al., 1993; Broecker, 1994a, b; Ganopolski and Rahmstorf, 2001). They were described as interstadials (IS), and labeled in several instances by the name of supposed continental equivalents of European pollen biostratigraphy (Johnsen et al., 1992; Dansgaard et al., 1993).

The presumed time-equivalents of these interstadials have also been described in North Atlantic deep-sea cores (Bond et al., 1992, 1993; McManus et al., 1994; Elliot et al., 2002). The corresponding intervals of relatively warm sea surface water were prefixed with a W and numbered the same way as those in Greenland ice (McManus et al., 1994). Thus for example, IS 24 in Greenland's NGRIP record is considered coeval with the W24 warm surface water interval in the North Atlantic. C labels were used to mark marine cold-water events, mostly but not always associated with intense ice rafting (IRD) intervals. A cold water episode precedes a warm one of the same number (i.e. C24 precedes W24) (McManus et al., 1994). This nomenclature has been used in every marine record in the North Atlantic region since (van Kreveld et al., 2000) allowing good correlation with continental records (Woillard, 1978; Kukla et al., 1997; Shackleton et al., 2002).

As seen in the interval dated by the NGRIP community between 130 and 70 ka (North Greenland Ice Core Project, 2004), the variation of different proxies indicating cold climate including $\delta^{18}O$ percentages of planktonic foraminifera *Neogloboquadrina pachyderma sinestral* and percentages of non-arboreal pollen in both the marine and continental records, are remarkably similar (Fig. 1).

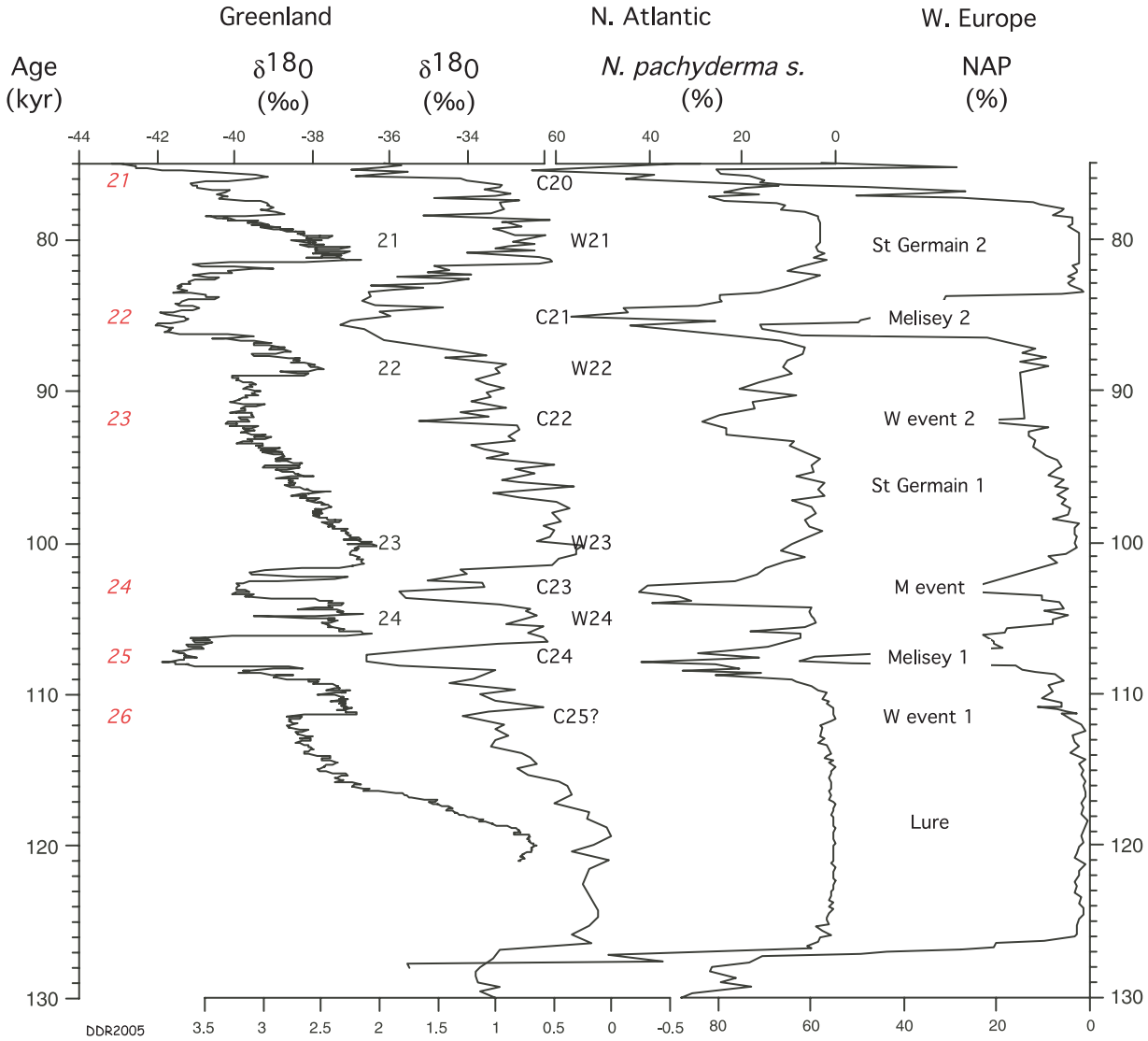

Fig. 1. Comparison of different climate proxies from ice, marine cores, and continental records for the 75–130 ka interval. All time scales have been tuned to the MD95-2042 chronology (Shackleton et al., 2002) in order to show the irrelevance of the Greenland stadials labeling. From left to right Greenland NGRIP $\delta^{18}O$ (North Greenland Ice Core Project, 2004), MD95-2042 planktonic $\delta^{18}O$ (Shackleton et al., 2002), V29-191 percentages of *N. pachyderma* left (McManus et al., 1994) and Grande Pile percentage of non-arboreal plants (NAP) (Woillard, 1978). The different labels are those originally published in the papers (see references) describing these events.

It is highly probable that the two major cold spells appearing about 4000 years apart during the glacial inception are coeval. Even though some uncertainty remains on their absolute age, their synchronicity is highly likely. They are respectively designated C24 and C23 in the deep sea, Melisey stadial and Montaigu event on the continent, but as stadials 25 and 24 in the Greenland ice core (Fig. 1). It is unfortunate that the designation of the cold events in the ice and in the marine records is so similar despite different timing.

The ocean system designation, recognized and named first (McManus et al., 1994), has priority and according to the stratigraphic rules is the valid label. In the interval younger than MIS 5 the synchronicity of the equally numbered zones in the ice and on the land is unquestioned. It is highly probable that even in the older part of the records, the major climate oscillations are coeval, and the designation of the units should be labeled accordingly.

So how can we minimize potential confusion? The INTIMATE group recommended a procedure to investigate the Last Termination and named it the event stratigraphy (Bjorck et al., 1998). Using the GRIP ice-core record, the aim was to identify a series of isotope events of global significance and to apply a top–down count to label the events. Furthermore, recognizing and accepting the previously defined climatostratigraphy in the GRIP record (Johnsen et al., 1992; Dansgaard, et al., 1993) of using the numbering of the interstadials back to IS2, the INTIMATE group proposed labeling the stadial episodes beginning with Greenland Stadial 1 (GS1). The concept is certainly valuable and deserves our attention as it seems to be the most appropriate approach to define the well known and reliable stratigraphic subdivisions of Quaternary deposits. Indeed, it properly takes into consideration that both upper and lower boundaries of a climatic event may be diachronous from place to place. Fig. 1 shows such a case although some tuning was performed. The INTIMATE group expanded the approach to the whole Upper Pleistocene (Walker et al., 1999) and invited: "Quaternary scientists to adopt an inductive approach to stratigraphic subdivision, the initial stage of which is to identify local events or sequences of events at key sites on the basis of independent evidence. The second stage is to correlate these site-specific records with the type sequence, i.e. the GRIP oxygen isotope profile, on the basis of what are considered to be comparable major events. The third step (which is perhaps the most difficult, but perhaps also the most important) is to use independent dating evidence to establish the degree of synchroneity between local and GRIP events".

Applying this approach to the NGRIP record (NGRIP members, 2004), the stadial events are labeled downward to the so-called GS26, preceding GIS 25 (NGRIP members, 2004), following the top–down counting approach

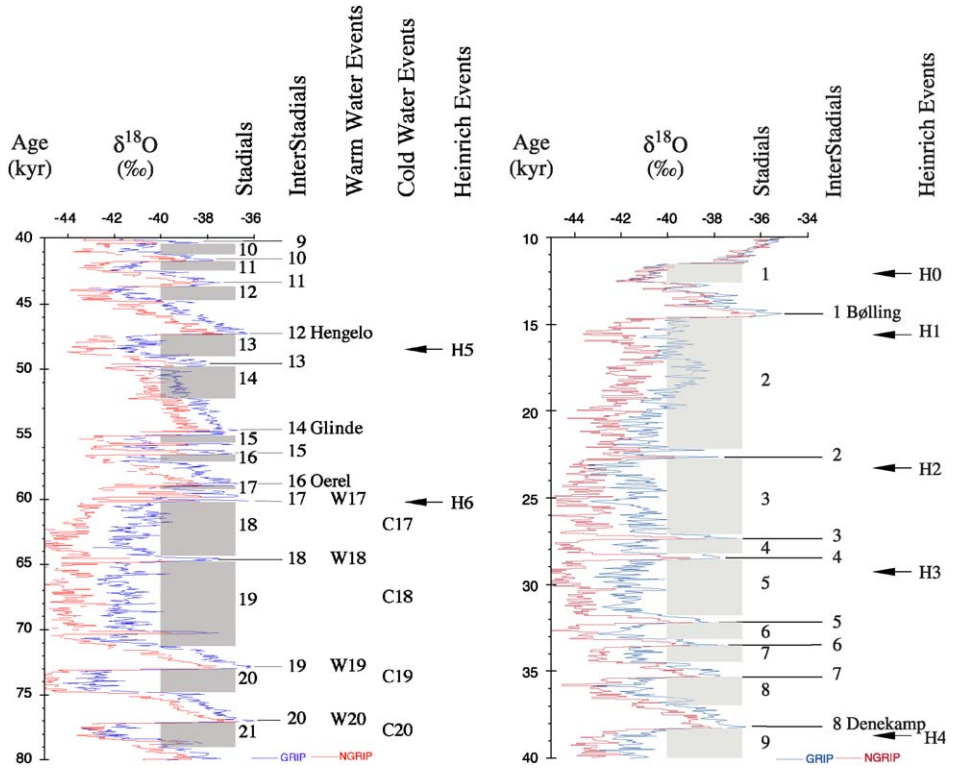

Fig. 2. Comparison of the different label protocols applied to or related to the Greenland ice cores. Because of the similarities of the ice-cores variations, we used the GRIP and North GRIP $\delta^{18}O$ variations with the ss09sea chronology (Johnsen et al., 2001). Interstadials after Johnsen et al. (1992) and Dansgaard et al. (1993), stadials after Walker et al. (1999), and NGRIP (North Greenland Ice Core Project, 2004), warm water and cold water events after McManus et al. (1994), Heinrich events after Bond et al. (1992, 1995, 1999) and Elliot et al. (1998). (a) Variation between 40 and 80 ka; (b) variation between 10 and 40 ka.

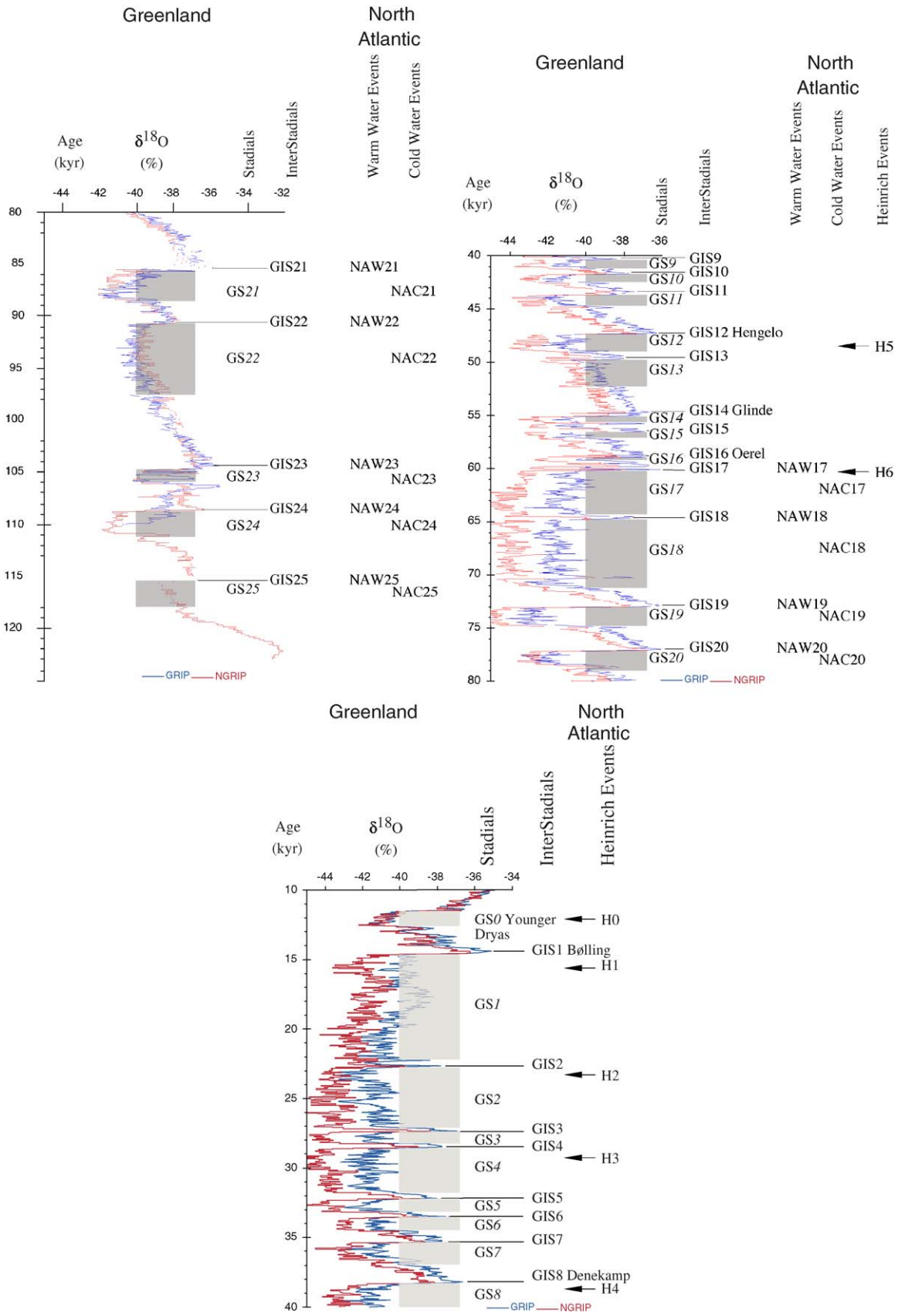

Fig. 3. Proposed renumbering for GRIP–North GRIP stadials and labels in Greenland ice cores and the North Atlantic between: (a) 130 and 80 ka; (b) 80 and 40 ka; (c) −40 and 10 ka. Same time scale as in Fig. 2.

(Figs. 2 and 3). The new climatostratigraphic subdivision has been already used in the literature: the basic stadial number was extended by identifying prefixes, i.e. keeping the C for terrestrial stadials (Sirocko et al., 2004), or AS for Alboran stadials (Matrat et al., 2004). The problem stemming from using single numbers in describing complicated stratigraphic records is that the original succession of recognized subdivisions becomes frozen. This requires inserting more detailed subcategories as may be called for in future investigations.

In conclusion, preference should be given to stratigraphic designations that would indicate the known or suspected time relationships as closely as possible. We propose to renumber the ice core units in NGRIP by keeping the labels consistent with the marine cold events previously described. As suggested by the INTIMATE group, these new numbers could be preceded by prefixes corresponding to the original records such as GS or GI for Greenland stadials or interstadials, respectively. Doing so would remove potential confusion with similarly designed but earlier defined deep-sea units of different ages (Walker et al., 1999; Matrat et al., 2004). North Atlantic cold or warm water events, previously labeled with C or W would then be labeled NAC and NAW (Fig. 3b). This practice would allow later improvements when more information becomes available. Such a system was already successfully applied to the Last Termination (Björck et al., 1998) in the Greenland GRIP ice core, and to the ice rafted events in the North Atlantic (Bond and Lotti, 1995).

Comments on draft versions of the manuscript by Christine Hatté, Uli Hambach, and Ludwig Zöller are greatly appreciated. Nick Shackleton and Mark Maslin provided valuable suggestions in their reviews. The first author benefited from financial support from the von Humboldt Foundation during preparation of the manuscript. This is ISEM contribution 2006-27.

References

Björck, S., Walker, M.J.C., Cwynar, L.C., Johnsen, S., Knudsen, K.L., Lowe, J.J., Wohlfarth, B., and INTIMATE Members, 1998. An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. Journal of Quaternary Science 13, 283–292.

Blunier, T., Chappellaz, J., Schwander, J., Dällenbach, A., Stauffer, B., Stocker, T.F., Raynaud, D., Jouzel, J., Clausen, H.B., Hammer, C.U., Johnsen, S.J., 1998. Asynchrony of Antarctic and Greenland climate change during the last glacial period. Nature 394, 739–743.

Bond, G.C., Lotti, R., 1995. Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. Science 267, 1005–1010.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., Ivy, S., 1992. Evidence for massive discharges of icebergs into the North Atlantic Ocean during the last glacial period. Nature 360, 245–249.

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. Nature 365, 143–147.

Bond, G.C., Showers, W., Elliot, M., Evans, M., Lotti, R., Hajdas, I., Bonani, G., Johnson, S., 1999. The North Atlantic's 1-2 kyr climate rhythm: Relation to Heinrich events, Dansgaard/Oeschger cycles and the Little Ice Age. In: Clark, P.U., Webb, R., Keigwin, L.D. (Eds.), Mechanisms of Global Climate Change at Millennial Time Scales. Geophysical Monograph. American Geophysical Union, Snowbird, UT, pp. 35–58.

Broecker, W.S., 1994a. Massive iceberg discharges as triggers for global climate change. Nature 372, 421–424.

Broecker, W.S., 1994b. An unstable superconveyor. Nature 367, 414–415.

Dansgaard, W., Clausen, H.B., Gundestrup, N., Johnsen, S.J., Rygner, C., 1985. Dating and climatic interpretation of two deep Greenland ice cores. In: Langway, C.C., Oeschger, H., Dansgaard, W. (Eds.), Greenland Ice Core: Geophysics, Geochemistry and the Environment. Geophysical Monograph. AGU, Washington, DC, pp. 71–76.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahi-Jensen, D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjöprnsdottir, A.E., Jouzel, J., Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. Nature 364, 218–220.

Elliot, M., Labeyrie, L., Bond, G., Cortijo, E., Turon, J.L., Tisnerat, N., Duplessy, J.C., 1998. Millennial-scale iceberg discharges in the Irminger Basin during the last glacial period: relationship with the Heinrich events and environmental settings. Paleoceanography 13, 433–446.

Elliot, M., Labeyrie, L., Duplessy, J.C., 2002. Changes in north Atlantic deep-water formation associated with the Dansgaard–Oeschger temperature oscillations (60–10 ka). Quaternary Science Reviews 21, 1153–1165.

Emiliani, C., 1955. Pleistocene temperatures. Journal of Geology 63, 538–578.

Ganopolski, A., Rahmstorf, S., 2001. Rapid changes of glacial climate simulated in a coupled climate model. Nature 409, 153–158.

Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S., Jouzel, J., 1993. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. Nature 366, 552–554.

International Subcommission on Stratigraphic Collaborat Classification, I., 1976. A guide to stratigraphic classification, terminology, and procedure. In: Hedberg, H.D. (Ed.), International Stratigraphic Guide. Wiley, New York, p. 200.

Johnsen, S.J., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrump, N., Hammer, C.U., Iversen, P., Jouzel, J., Stauffer, B., Steffensen, J.P., 1992. Irregular glacial interstadials recorded in a new Greenland ice core. Nature 359, 311–313.

Johnsen, S.J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E., White, J., 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. Journal of Quaternary Sciences 16, 299–307.

Jouzel, J., Lorius, C., Johnsen, S., Grootes, P., 1994. Climate instabilities: Greenland and Antarctic records. Comptes Rendus de l'Académie des Sciences de Paris 319, 65–77.

Kukla, G., McManus, J.F., Rousseau, D.D., Chuine, I., 1997. How long and how stable was the last interglacial? Quaternary Science Reviews 16, 605–612.

Matrat, B., Grimalt, J.O., Lopez-Martinez, C., Cacho, I., Sierro, F.J., Flores, J.A., Zahn, R., Canals, M., Curtis, J.H., Hodell, D.A., 2004. Abrupt temperature changes in the western Mediterranean over the past 250,000 years. Science 306, 1762–1765.

McManus, J.F., Bond, G.C., Broecker, W.S., Johnsen, S., Labeyrie, L., Higgins, S., 1994. High-resolution climate records from the North Atlantic during the last interglacial. Nature 371, 326–329.

Murphy, M.A., Salvador, A., 1999. International Stratigraphic Guide—An Abridged Edition. Episodes 22, 255–271.

North Greenland Ice Core Project, m., 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period. Nature 431, 147–151.

Sanchez-Goni, M.F., Turon, J.L., Eynaud, F., Gendreau, S., 2000. European climatic response to millennial-scale changes in the atmosphere-ocean system during the last glacial period. Quaternary Research 54, 394–403.

Shackleton, N.J., 1969. The last interglacial in the marine and terrestrial records. Proceedings of the Royal Society of London 174, 135–154.

Shackleton, N.J., Chapman, M., Sanchez-Goni, M.F., Pailler, D., Lancelot, Y., 2002. The classic marine isotope substage 5e. Quaternary Research 58, 14–16.

Sirocko, F., Cubasch, U., Kaspar, F., von Storch, H., Widmann, M., Litt, T., Kühk, N., Mangini, A., Pachur, H.J., Claussen, M., Kubatzki, C., Junge, F.W., Böttger, T., Krbetschek, M., Degering, D., 2004. Climate change at the very end of a warm stage: first results from the Last Glacial Inception at 117,000 yr BP. PAGES News 12, 18–20.

Tzedakis, P.C., Roucoux, K.H., de Abreu, L., Shackleton, N.J., 2004. The duration of forest stages in Southern Europe and interglacial climate variability. Science 306, 2231–2235.

van Kreveld, S., Sarnthein, M., Erlenkeuser, H., Grootes, P., Jung, S., Nadeau, M.J., Pflaumann, U., Voelker, A., 2000. Potential links between surging ice sheets, circulation changes, and the Dansgaard-Oeschger cycles in the Irminger Sea, 60–18 kyr. Paleoceanography 15, 425–442.

Walker, M.J.C., Björck, S., Lowe, J.J., Cwynar, L.C., Johnsen, S., Knudsen, K.L., Wohlfarth, B., Intimate, g., 1999. Isotopic "events" in the GRIP ice core: a stratotype for the Late Pleistocene. Quaternary Science Reviews 18, 1143–1150.

Woillard, G., 1978. Grande Pile Peat Bog: a continuous pollen record for the last 140,000 years. Quaternary Research 9, 1–21.