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A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy

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ABSTRACT

Due to their outstanding resolution and well-constrained chronologies, Greenland ice-core records provide a master record of past climatic changes throughout the Last Interglacial–Glacial cycle in the North Atlantic region. As part of the INTIMATE (INTegration of Ice-core, MArine and TErrestrial records) project, protocols have been proposed to ensure consistent and robust correlation between different records of past climate. A key element of these protocols has been the formal definition and ordinal numbering of the sequence of Greenland Stadials (GS) and Greenland Interstadials (GI) within the most recent glacial period. The GS and GI periods are the Greenland expressions of the characteristic Dansgaard–Oeschger events that represent cold and warm phases of the North Atlantic region, respectively. We present here a more detailed and extended GS/GI template for the whole of the Last Glacial period. It is based on a synchronization of the NGRIP, GRIP, and GISP2 ice-core records that allows the parallel analysis of all three records on a common time scale. The boundaries of the GS and GI periods are defined based on a combination of stable-oxygen isotope ratios of the ice ($\delta^{18}O$, reflecting mainly local temperature) and calcium ion concentrations (reflecting mainly atmospheric dust loading) measured in the ice. The data not only resolve the well-known sequence of Dansgaard–Oeschger events that were first defined and numbered in the ice-core records more than two decades ago, but also better resolve a number of short-lived climatic oscillations, some defined here for the first time. Using this revised scheme, we propose a consistent approach for discriminating and naming all the significant abrupt climatic events of the Last Glacial period that are represented in the Greenland ice records. The final product constitutes an extended and better resolved Greenland stratotype sequence, against which other proxy records can be compared and correlated. It also provides a more secure basis for investigating the dynamics and fundamental causes of these climatic perturbations.

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1. Introduction

During the most recent glacial period, the North Atlantic area experienced a series of dramatic climatic fluctuations known as Dansgaard–Oeschger (D–O) events, during which oceanic and atmospheric conditions alternated between full glacial (so-called *stadial*) and relatively mild (*interstadial*) conditions (Dansgaard et al., 1982; Johnsen et al., 1992). Ice-core records resolve the most recent of the D–O events in sub-annual detail, and analysis of these high-resolution records suggests that fundamental atmospheric circulation changes took place in just a few years (Alley et al., 1993; Steffensen et al., 2008; Thomas et al., 2009). About 25 abrupt transitions from stadial to interstadial conditions took place during the Last Glacial period and these vary in amplitude from 5 °C to 16 °C, each completed within a few decades (Landais et al., 2004, 2006; Huber et al., 2006; Capron et al., 2010a; Guillevic et al., 2013; Kindler et al., 2014). The interstadials vary in duration from around a century to many millennia, with surface air temperature (as reflected in $\delta^{18}O$ values) decreasing gradually before each interstadial ended in a less-pronounced but nevertheless abrupt transition to stadial conditions. Stadials are generally characterized by more stable climates than interstadials but a similarly large range of durations. The alternating pattern of stadials and interstadials is reflected in many different palaeoclimatic records from diverse archives (Voelker and workshop participants, 2002), but is particularly clear in the Greenland ice-core records. We argue that the Greenland ice records, due to their very high stratigraphic and temporal resolution and precise dating, constitute the most comprehensive and best resolved archive of D–O scale climate variability over the Last Glacial, and hence that it is in these records that the D–O sequence of events should be defined and named.

Over the last two decades, the INTIMATE project (INTegrating Ice-core, MArine, and TErrestrial records) has proposed a series of event-stratigraphic templates based on the Greenland ice cores. These reflect the sequence of interstadials and stadials recorded in Greenland profiles, and are designed to promote the consistent naming of events, and to provide a basis for robust correlation between different proxy climate records (Björck et al., 1998; Walker et al., 1999; Lowe and Hoek, 2001; Lowe et al., 2008; Blockley et al., 2012). The event stratigraphies divide the characteristic sequence of Greenland climate changes in the Early Holocene and Lateglacial periods into numbered Greenland Interstadials (GI) and Greenland Stadials (GS). Initially based on the stable isotope record in the GRIP core, these have subsequently incorporated data from other ice cores, and have involved the use of different time scales (Table 1). It is worth noting that the word 'event' is used with different meanings in palaeoclimatology: in a mathematical sense, an 'event' may be defined as an instantaneous shift from one state to another while, in reality, any such shift has a finite duration. Moreover, the term 'D–O event' is used in the literature to refer both to interstadial periods and to the onset of interstadials. Here, we use 'event' to refer to the entire stadial or interstadial periods (or their subperiods). However, the defining characteristic of each 'event' is the abrupt climatic change that occurs at its onset, and it is these major climatic signals that constitute the pinning points for the event stratigraphy.

In this paper, we present a further development of the event stratigraphy stratotype using the annual-layer counted Greenland Ice Core Chronology 2005 (hereafter GICC05) (Andersen et al., 2006b; Rasmussen et al., 2006; Svensson et al., 2008; Seierstad et al., 2014) and its flow model-based extension, GICC05modelext. The mainly NGRIP-based GICC05modelext time scale has recently been applied to the entire undisturbed sections of the GRIP and GISP2 ice cores (Seierstad et al., 2014), and the scheme is therefore now based on 3 parallel records continuously spanning the past 104 ka. Beyond 104 ka b2k (before A.D. 2000) we use only the NGRIP record, which is the only one of the three cores that reaches back to c. 120 ka b2k (the late part of the Last Interglacial, the Eemian) with undisturbed stratigraphy all the way to the bedrock (North Greenland Ice Core Project members, 2004). In addition to the $\delta^{18}O$ profiles, we use calcium ion concentration data (hereafter $[Ca^{2+}]$) which exhibit particularly clear stadial/interstadial contrasts, aiding the identification of individual events. Direct comparisons between these 6 proxy profiles obtained from 3 synchronized ice cores provide a robust template for distinguishing between changes that reflect local influences and those that represent changes of regional or hemispherical significance. Concordance of signals between the data-sets is of particular importance for studies of the internal structure of the interstadials and the discrimination of short-lived climatic events not previously included in the numbered sequence of D–O events.

Following the initial definition of interstadials in the ice-core record proposed by Johnsen et al. (1992), the first INTIMATE protocol introduced the subdivision of GI-1 into substages a–e (Björck

Table 1
The evolution of the INTIMATE event stratigraphy since the original proposal in 1998. b2k refers to years before A.D. 2000.

Event stratigraphy reference	Ice-core records used for defining events	Time period covered	Chronology
Björck et al. (1998), Walker et al. (1999), Lowe et al. (2001)	GRIP $\delta^{18}O$ data probably on equidistant depth scale (leading to variable time resolution)	23–11 ka b1950	ss08c (not clearly stated until Lowe et al., 2001)
Lowe et al. (2008)	Onsets of events back to GI-1e unchanged. GS-2 – GI-4 onsets defined by visual inspection as midpoint of $\delta^{18}O$ transition in 20-year resolution data from NGRIP, GRIP, and GISP2.	30–8 ka b2k	GICC05
Blockley et al. (2012)	As Lowe et al. (2008) until GI-4. Extended back to GI-12, defining event onsets as the steepest part of the $\delta^{18}O$ transitions in 20-year resolution data from NGRIP, GRIP, and GISP2 data.	48–8 ka b2k	GICC05
This work	As Blockley et al. (2012) until GI-12, but with sub-event definitions added for GI-2, GI-7, GI-8, and GI-12. Onsets of sub-events and all onsets beyond GI-12 defined by multiple investigators using combined $\delta^{18}O$ and $[Ca^{2+}]$ data from NGRIP, GRIP, and GISP2.	3 cores: 104–8 ka b2k; NGRIP supported by preliminary NEEM data: 120–104 ka b2k	GICC05 (younger than 60.2 ka b2k) and GICC05modelext (older than 60.2 ka b2k)

et al., 1998), but a similar subdivision was not attempted for older interstadials. It is now clear that several interstadials show internal structure that resembles that of GI-1. For example, a period of high $\delta^{18}O$ values at 44.4 ka b2k at the end of GI-12 (Fig. 1), referred to by Capron et al. (2010a) as a "rebound event", stands out clearly, while several similar but less pronounced events are found elsewhere in the record. The new synchronized scheme we present here allows the practice of subdividing interstadials to be extended beyond GI-1. In addition, beyond 48 ka b2k, the D–O variability reflected in the Greenland records includes a number of short-lived events of similar amplitude to those recognized in the initial schemes of Johnsen et al. (1992) and Dansgaard et al. (1993). Some of these events have already been noted in ice-core records ("precursor events" by Capron et al. (2010a) and Vallelonga et al. (2012)) and equivalent events have also been recognised in speleothems (Boch et al., 2011) and in marine records (Deplazes et al., 2013).

Here we propose a revised numbering scheme that incorporates all phases of D–O variability judged to be significant in the Greenland ice-core archive for the Last Glacial period. This revised scheme provides a more comprehensive and unambiguous reference template for the pattern of climate variability during the Last Glacial cycle. The scheme strengthens the case for continued use of the Greenland ice-core record as the stratotype sequence for the last cold stage in the North Atlantic region (Walker et al., 1999), and will serve to underpin investigations into the dynamics and causes of these abrupt climatic changes.

2. The INTIMATE approach

D–O variability is expressed in numerous and diverse climate proxy records, but while millennial-scale events registered in an ice core most probably were related in some way to events of approximately similar structure and age reflected in, for example, North Atlantic sediment cores (e.g., Voelker and workshop participants, 2002) or alpine speleothem records (e.g., Boch et al., 2011), it need not follow that all of the records were registering the same climatic signal at precisely the same time. On the other hand, the fact that the structure and timing of millennial-scale variability in some regions appear to have been different from those in the North Atlantic also does not necessarily imply that the changes are unrelated, for recent studies (see below) have shown that the expression of D–O-scale changes can differ from region to region. The pattern of climate change throughout the North Atlantic region over decadal to centennial time scales was thus more complicated than the synchronous behaviour that has generally been assumed. A key factor is the time required for the propagation of atmospheric and oceanic D–O-scale changes at the regional and hemispherical scales. Modelling studies indicate that high-latitude temperature perturbations can propagate into the tropics within a matter of years, prompting tropical sea-surface temperature and precipitation changes (Chiang and Bitz, 2005). This "fast track" communication between the high latitudes and tropics is a result of atmosphere-surface ocean interactions, with tropical sea-surface temperature changes playing a key role in tropical precipitation shifts (Cvijanovic and Chiang, 2013). Importantly, as the extent and magnitude of the oceanic changes evolve, they will trigger further atmospheric changes. As described by Cvijanovic et al. (2013), the tropical response to high-latitude forcing can comprise multiple precipitation shifts, involving a tropical atmospheric reorganization due to the initial oceanic change (prompted by, for example, changes in ocean overturning in the North Atlantic sector) and subsequent tropical atmospheric reorganization triggered by more slowly-evolving remote ocean responses (e.g., Southern Ocean changes). Thus, even in the simplest scenario, a D–O event observed in a tropical record could have resulted from (1) fast atmospheric teleconnection from a remote high-latitude region where the change was initiated (probable lag a couple of years only); (2) secondary fast atmospheric teleconnections from a remote region experiencing more slowly-evolving oceanic processes (potentially with a decadal-to-centennial lag); and (3) a superposition of both mechanisms, where, depending on the region of the tropics affected, either northern or southern high latitudes can exert the greater influence. Furthermore, the propagation of atmospheric teleconnections can vary between marine and terrestrial environments.

These complexities in coupled ocean-atmosphere response to climatic forcing lead us to recommend that D–O-type events observed in different archives should, whenever possible, be named using a local terminology and independently dated without assuming synchroneity of the observed changes between individual records. This approach, which is in accordance with fundamental stratigraphical principles, is essential for detecting and quantifying spatial and temporal differences between the different records, thereby providing vital clues about the nature of the processes governing D–O variability.

A further difficulty relates to chronological resolution. At present, firm conclusions often cannot be drawn about the relative timing of climatic changes and their impacts simply because of large dating uncertainties that frequently hamper the interpretation of proxy records. Radiocarbon dating of ocean sediment sequences, for example, is compromised by spatial and temporal variability in the marine reservoir age of marine microfossils (Austin and Hibbert, 2012; Stern and Lisiecki, 2013), and many radiocarbon age determinations lack the analytical precision required to date events at less than centennial scale. Developments in radiometric dating techniques may gradually reduce these problems, while the use of other chronological tools, such as varve chronology, and time-synchronous marker horizons, are providing an increasingly robust basis for the precise synchronisation of records from the Last Glacial cycle (Lane et al., 2013). Within the INTIMATE programme, particular attention has been focused on volcanic ash (tephra layers), because of their potential for correlating ice-core, marine, and terrestrial records. Tephrochronology has been a key element in the protocols proposed by Lowe et al. (2008) and Blockley et al. (2012), notably for linking widely-dispersed records to the Greenland event stratigraphy, an approach recently extended to cover the past 60 ka by Blockley et al. (2014). On-going investigations devoted to the detection and geochemical characterization of tephra deposits preserved in the Greenland ice cores has greatly increased the number of marker horizons available for correlating ice-core, marine, and terrestrial archives (Davies et al., 2014; Rasmussen et al., 2013). Indeed, recent high-resolution analysis of Greenland ice cores has revealed traces of many more Icelandic tephras than was previously recognised. However, unambiguous tephra correlation between marine and ice-core records requires careful scrutiny of glass geochemical signatures (Bourne et al., 2013) and consideration of the depositional context (Griggs et al., 2014).

While we acknowledge that the use of time-stratigraphic markers to test assumed synchroneity of climate signals between archives or regions is neither new nor unique, it has formed a core element of the INTIMATE programme since its inception and plays a key role in the INTIMATE protocols that are now widely endorsed. Hence, for brevity, we refer to it as the *INTIMATE approach*.

An excellent example of the successful application of this approach is the ice-core-based analysis of the climatic links between the North Atlantic D–O events and more gradual events observed in Antarctic temperature proxy records (Antarctic Isotope Maxima, AIM (EPICA community members, 2006)) during

Fig. 1. 20-year average values of $\delta^{18}O$ and $[Ca^{2+}]$ (note the reversed logarithmic $[Ca^{2+}]$ scale; see text for data sources) from GRIP (red), GISP2 (green), and NGRIP (blue) on the GICC05modelext time scale. The dots just below the upper NGRIP depth axis show the position of the match points used to transfer the GICC05modelext time scale from NGRIP to the GRIP (red dots) and GISP2 (green dots) records. The proposed extension of the INTIMATE event stratigraphy scheme is shown with interstadials illustrated by grey shading (light grey indicates cold sub-events). In the Eemian interglacial, NGRIP data are extended by NEEM $\delta^{18}O$ data offset by 2‰ (NEEM community members, 2013). See main text for details on the numbering of stadial and interstadial events. Note the small time overlap between the three panels introduced to ease interpretation.

the Last Glacial period. Based on the fact that the atmosphere is relatively well-mixed on a decadal time scale, Blunier et al. (1998) and Blunier and Brook (2001) aligned polar ice-core records from the two hemispheres using abrupt changes in the CH_4 content of air bubbles, since these reflect globally synchronous changes in atmospheric CH_4 content. They showed that Antarctic temperatures increase gradually during Greenland stadials, and that the peaks of AIMs are synchronous (within uncertainties) with the onsets of Greenland interstadials. They argued that this phasing is consistent with the so-called *bipolar seesaw* mechanism proposed by Broecker (1998) and Stocker and Johnsen (2003), which involves variations in the strength of the AMOC, the effects of which are buffered by the large thermal inertia of the Southern Ocean. Subsequent additional ice-core analyses and numerical model experiments have corroborated this phase relationship between Greenland and Antarctic records over the Last Glacial period (EPICA community members, 2006; Capron et al., 2010b; Pedro et al., 2012).

There appears to be little doubt that D–O events are closely associated with changes in the strength of the AMOC (as envisaged in the oceanic bipolar seesaw hypothesis) and with corresponding changes in atmospheric circulation and sea-ice cover (Kaspi et al., 2004; Rasmussen and Thomsen, 2004; Jonkers et al., 2010; Dokken et al., 2013). However, interactions between oceanic changes on the one hand, and atmospheric and sea-ice responses on the other, propagate in complex ways, which must have promoted a variety of regional manifestations of D–O behaviour. Precise dating and correlation of these spatial and temporal climatic perturbations and of their mode and rate of transmission around the globe is critical for gaining a deeper understanding of the processes that drove D–O events and we argue that this objective will best be realised by the application of the INTIMATE approach, as described in the following sections.

3. Data

This work is based on records from the NGRIP, GRIP, and GISP2 ice cores, all now available on a common time scale. For the Holocene, the GICC05 time scale has been constructed by combining data from different depth intervals in the GRIP, NGRIP and DYE-3 ice cores (Vinther et al., 2006), while the GICC05 glacial section is based on annual layer counting in NGRIP down to 60 ka b2k (Rasmussen et al., 2006; Andersen et al., 2006b; Svensson et al., 2008) extended by an ice-flow model below this (Wolff et al., 2010). The combined GICC05modelext time scale has been transferred to the GRIP and GISP2 ice-core records using reference horizons principally of volcanic origin (Rasmussen et al., 2008; Seierstad et al., 2014). The match-point locations are shown in Fig. 1 as red (GRIP-NGRIP) and green (GISP2-NGRIP) dots just below the upper depth axis.

In the previous INTIMATE event stratigraphies, events were defined by visual inspection of $\delta^{18}O$ data initially re-sampled to c. 50-year resolution (Björck et al., 1998; Walker et al., 1999), and subsequently to 20-year resolution (Lowe et al., 2008; Blockley et al., 2012). The temporal resolution is determined by the choice of *averaging period* which reflects different considerations, as follows:

- The lowest meaningful averaging period is determined by the resolution of the $\delta^{18}O$ data. The sampling resolution is typically 5 cm for the GRIP and NGRIP cores (Johnsen et al., 1997; North Greenland Ice Core Project members, 2004) and up to 20 cm in glacial sections of the GISP2 ice core (Grootes and Stuiver, 1997; Stuiver and Grootes, 2000). In temporal terms, this corresponds to a range from approximately annual resolution in GRIP and NGRIP at the onset of the Holocene, to about 20 years for GISP2 sections from the early glacial.
- Individual $\delta^{18}O$ records represent regional and hemisphere-scale changes as well as local climatic variability (e.g. depositional noise), and measurement uncertainty. Andersen et al. (2006a) showed that an optimal trade-off between removing depositional noise and maintaining good resolution in Greenland records is achieved when averaging over at least 5 years. This compares with an averaging period of 30 years adopted by the World Meteorological Organization for removal of short-term and local variability when constructing climate observation reference baselines (WMO, 2011).
- The NGRIP, GRIP, and GISP2 records used in this work are synchronized to the GICC05modelext time scale, and the relative dating precision between the records depends on the spacing of time-synchronous horizons used in the time-scale transfer. The spacing varies markedly through the record as illustrated by green and red dots above the $[Ca^{2+}]$ curve in Fig. 1, but the relative dating precision is better than 20 years over most of the length of the combined records (Seierstad et al., 2014).

We therefore contend that a 20-year averaging period is justified, and thus maintain the practice, adopted for the most recent INTIMATE protocols, of basing the definitions of the onsets of events on $\delta^{18}O$ records re-sampled to 20-year resolution.

As a supplement to the $\delta^{18}O$ data, we found that event detection could be significantly improved by considering also $[Ca^{2+}]$ data, reflecting primarily changes in dust concentration due to regional-to-hemispherical-scale circulation changes (Fischer et al., 2007a, 2007b). We chose $[Ca^{2+}]$ rather than dust measurements, as $[Ca^{2+}]$ is the only dust proxy available in comparable quality for NGRIP, GRIP, and GISP2. The motivation for including the $[Ca^{2+}]$ record is that it has an excellent signal-to-noise ratio: it changes by an order of magnitude across interstadial onsets, and the changes start with or up to a few decades before the changes observed in $\delta^{18}O$ (Alley et al., 1993; Ruth et al., 2003; Steffensen et al., 2008; Thomas et al., 2009). The $[Ca^{2+}]$ signal is primarily a record of dust concentration which is, in turn, reflective of changes in dust source conditions and transport paths. As such, the $[Ca^{2+}]$ record is indicative of regional-to-hemispherical-scale circulation changes (Fischer et al., 2007a). The close relative timing of $\delta^{18}O$ and $[Ca^{2+}]$ changes supports the idea that the main shift in Greenland atmospheric dust loading, and thus in $[Ca^{2+}]$, is likely to be linked to the same large-scale circulation changes that also lead to changes in $\delta^{18}O$. Our assumption therefore, is that both $\delta^{18}O$ and $[Ca^{2+}]$ in Greenland begin to change simultaneously, at least within the 20-year resolution of the applied data-set.

The resampling of $\delta^{18}O$ and $[Ca^{2+}]$ data onto the GICC05modelext time scale has been performed in the same manner as described by Seierstad et al. (2014), and is only briefly described here. For GRIP, $\delta^{18}O$ data from Johnsen et al. (1997) and $[Ca^{2+}]$ data from Fuhrer et al. (1993) are used; for GISP2, $\delta^{18}O$ data are from Grootes and Stuiver (1997) and Stuiver and Grootes (2000), and the $[Ca^{2+}]$ data are from Mayewski et al. (1997). For NGRIP, the $\delta^{18}O$ data are described in North Greenland Ice Core Project members (2004), while the $[Ca^{2+}]$ data are from Bigler (2004). Resampling of NGRIP data was conducted in depth space but is otherwise trivial as the GICC05modelext time scale is based on NGRIP for the entire glacial period. To resample GRIP and GISP2 data, NGRIP depths corresponding to 20-year intervals were converted to GRIP and GISP2 depths by linear interpolation using stratigraphic matching (Seierstad et al., 2014). The original GRIP or GISP2 data were then re-sampled in depth space. The alternative of re-sampling in age space between the GICC05modelext ages of the match points of Seierstad et al. (2014) gives a different result because this approach implicitly

assumes constant annual layer thicknesses between the match points. This is clearly an invalid assumption given the large variations in accumulation rates across stadial-interstadial boundaries and the fact that most match points are located in interstadials (due to stadial ice being more alkaline than interstadial ice, which tends to mute the volcanic signals used for synchronization). Linear interpolation in depth space implicitly assumes constant accumulation ratios between the different sites and between each set of match points, which is a better assumption. For all records, a re-sampled value is assigned to each 20-year period with at least 50% data coverage in the corresponding depth intervals.

The combined $\delta^{18}O$ and $[Ca^{2+}]$ records from NGRIP, GRIP, and GISP2 re-sampled to 20-year resolution are shown in Fig. 1. Calcium concentrations are higher in stadials than in interstadials, and, in general, impurity levels are approximately log-normally distributed within each climatic state. To emphasize its close similarity with the $\delta^{18}O$ record, the $[Ca^{2+}]$ record is presented on a reverse logarithmic scale.

4. Strategy and criteria for defining and naming events

The establishment of an event stratigraphy, including the numbering or naming of stadials and interstadials, is an inherently pragmatic process in which the record of the past is divided into sequential episodes to allow convenient and unambiguous referral to specific intervals (stratigraphic units, in this work denoted 'events') and transitions (stratigraphic boundaries, in this work denoted 'onsets'). However, the divisions should primarily reflect changes in the underlying dynamics in a way that supports or enhances our understanding of the physical system. At the same time, definitions should be compatible with existing nomenclature where practical, but remain flexible to allow further refinement to the scheme as more is learned about the climate dynamics reflected in the proxy records.

4.1. Defining stadials and interstadials

Any modification of the original interstadial numbering of Johnsen et al. (1992) and Dansgaard et al. (1993) must respect the underlying concept of numbering the main $\delta^{18}O$ excursions that typically involve $\delta^{18}O$ shifts of at least a few per mille. However, the relatively coarse stratigraphic resolution of the original isotopic dataset, based on a single record only, meant that a number of events of either short duration or smaller amplitude were not initially recognised although they may represent variability of the same nature. Starting from the top of the record presented in Fig. 1, the first example appears around 30.7 ka b2k. Concealed within the short-term variability of the individual $\delta^{18}O$ records, $\delta^{18}O$ values elevated about 2‰ above the stadial base-line persist in all three $\delta^{18}O$ records for more than two centuries. This event is more pronounced in the $[Ca^{2+}]$ record with a $\log([Ca^{2+}])$ amplitude of about 2/3 of those of the two adjacent events. The isotope signal, considered in isolation, may not warrant the designation of this period as an interstadial, but the expression of the event in the $[Ca^{2+}]$ data is highly significant, particularly when compared to the intra-stadial variability observed over the entire length of the $[Ca^{2+}]$ record. The collective data thus clearly indicate an interstadial mode of atmospheric circulation bringing relatively little dust to Greenland. This example serves to illustrate how the designation of an 'event' in the event stratigraphy scheme is governed by our current understanding of how climatic change manifests itself in the $\delta^{18}O$ and $[Ca^{2+}]$ records, which is the basis used for defining stratigraphic events.

Analysis of older sections of the record reveals numerous additional events of full interstadial amplitude, but of such short duration that they were overlooked in the original numbering scheme. Some of these have previously been referred to as 'precursor events' (Capron et al., 2010a), and indeed, the short periods of interstadial-level $\delta^{18}O$ and $[Ca^{2+}]$ values that precede interstadials 21 (c. 85 ka b2k) and 23 (c. 104.4 ka b2k) last for only about a century and are succeeded by only a few centuries of stadial conditions, before the climate shifts again to an interstadial mode for several millennia. However, other equally brief episodes of interstadial climate that do not precede longer interstadials are also apparent, for example at c. 55 and 69.5 ka b2k, and in the 58–59.5 ka b2k interval which comprises a complex series of brief episodes of both interstadial and stadial nature. Based on these observations, we recommend a scheme where interstadial periods are defined and named without reference to any adjacent interstadials, but based on amplitude alone. The amplitude of interstadial onsets is remarkably constant throughout the glacial, with $\delta^{18}O$ typically changing by about 4‰ over one or two 20-year data points and $[Ca^{2+}]$ changing by up to an order of magnitude.

Following the characteristic slow decline of $\delta^{18}O$ and slow rise of $[Ca^{2+}]$ during each interstadial, the magnitudes of the $\delta^{18}O$ and $[Ca^{2+}]$ shifts at interstadial terminations are much more variable, and often also more gradual, with the century-long transition into stadial values at around 70.4 ka b2k being an extreme example. This accords with the results obtained from analysis of multi-proxy records derived from several cores, reported in Steffensen et al. (2008) which showed that most proxies reflected significantly longer transitions out of GI-1 than into GI-1.

4.2. Interstadial substructure

From the very first INTIMATE event stratigraphy scheme, GI-1 has been divided into sub-events, denoted a–e, reflecting the fact that the overall fall in $\delta^{18}O$ values during GI-1 is interrupted by several short-lived declines which, while not reaching stadial values, are still significantly greater than typical intra-interstadial variability. That there is no clearly-defined criterion for what constitutes a sub-event is illustrated by the historical fact that two $\delta^{18}O$ declines around 13.2 ka b2k (GI-1b) and 14.0 ka b2k (GI-1d) were formally recognized and named as distinct sub-events while a slightly smaller inflection at c. 13.6 ka b2k was not.

Until now, no interstadials older than GI-1 have been subdivided in the INTIMATE event stratigraphy scheme, but it is now clear that in the earlier part of the record there are numerous examples of intra-interstadial variability similar to that in GI-1. Capron et al. (2010a) discussed the abrupt $\delta^{18}O$ shifts to higher values observed near the ends of interstadials 11, 12, 14, 16, 21, and 23 and referred to these as 'rebound events'. Most often, but not always, these episodes are preceded by a brief period of low $\delta^{18}O$ and high $[Ca^{2+}]$ values comparable to GI-1b and GI-1d. Similar brief intervals of low $\delta^{18}O$ and high $[Ca^{2+}]$ values, that deviate from typical interstadial values without reaching stadial levels, are found elsewhere in the record (e.g. during interstadials 13, 14, and 16) and are seemingly unrelated to the rebound events suggested by Capron et al. (2010a). Although a number of physical mechanisms may be responsible for different types of sub-events, we suggest that they cannot be differentiated on the basis of their expression in the $\delta^{18}O$ and $[Ca^{2+}]$ records alone, and therefore propose that they should be defined and named in the event stratigraphy scheme using the same set of criteria as employed hitherto.

As the amplitude of apparent sub-events in the $\delta^{18}O$ and $[Ca^{2+}]$ signals is variable, and as the lower threshold for what should constitute a sub-event is somewhat arbitrary, we use the magnitude of the sub-events already defined in the existing INTIMATE

GI-1 subdivision and those defined by Capron et al. (2010a) as guidelines, and employ the criteria that a sub-event should: (a) register in all three cores for at least two consecutive data points (i.e., have a duration of at least 40 years), and (b) involve a shift in $\delta^{18}O$ of 1‰ and a factor 2 change in $[Ca^{2+}]$. While the division of older events into sub-events may not appear as pressing and important as for the younger events, we anticipate that, in due course, the assignment of sub-event status will allow easy reference to these characteristic types of behaviour (cf. the rebound events of Capron et al. (2010a)). An additional objective is to stimulate the discussion on the extent to which the interstadial substructure observed in Greenland ice-core records matches those increasingly being recognised in high-resolution records from other archives (e.g. Liu et al., 2010; Boch et al., 2011; Capron et al., 2012).

4.3. Stadial substructure

GS-2 was initially subdivided into three sub-events by Björck et al. (1998), but the distinction between GS-2a and GS-2b was subsequently questioned when it was found that there were significant differences between the GRIP and NGRIP $\delta^{18}O$ records in this interval (Lowe et al., 2008; Rasmussen et al., 2008). Here, based on comparison of this interval in three ice-core records, we suggest that the subdivision of GS-2 is only marginally supported by GRIP and GISP2 $\delta^{18}O$ data and is not clearly discernible in the NGRIP $\delta^{18}O$ record, although GS-2b (designated GS-2.1b in Fig. 1) is characterized by slightly lower $[Ca^{2+}]$ values than GS-2a and GS-2c. The differences between the sub-events in GS-2 are therefore less strongly defined than appeared to be the case at the time of the original sub-division, and it is unclear as to whether the differences are more a reflection of climatic contrast between the Summit region (GRIP and GISP2) and the more northerly NGRIP drill site, as opposed to a regional climatic signal. As this matter cannot be resolved at present, we retain the previously-published subdivision, while accepting that this matter may require revisiting at some time in the future.

In GS-3, $[Ca^{2+}]$ levels more than double during two periods in the middle and late part of the stadial. These so-called 'GS-3 dust peaks' were first reported by Hammer et al. (1985) and were dated by Rasmussen et al. (2008) to 23,380 ± 20–24,150 ± 10 a b2k and 25,140 ± 20–25,980 ± 60 a b2k, respectively. Although the GRIP and GISP2 $\delta^{18}O$ records have small excursions during these intervals, the onset and end points of the phases of low $\delta^{18}O$ do not align with the $[Ca^{2+}]$ peaks. This apparent decoupling of $\delta^{18}O$ and $[Ca^{2+}]$ is not observed elsewhere in the record. As such, we consider that the dust peaks form no basis for a subdivision of GS-3 in the event stratigraphy.

Using the criterion that a sub-event should register in all three cores and involve a shift in $\delta^{18}O$ of at least 1‰ and a factor 2 change in $[Ca^{2+}]$ sustained for no less than 40 years, we find that no other stadials exhibit structures that would warrant formal sub-divisions.

4.4. Numbering and naming of events

Several naming and numbering systems for interstadials and stadials have been proposed, leading to some degree of confusion in terminology. While there seems to be a broad measure of agreement on the numbering of interstadials (following the original definitions of Johnsen et al. (1992) and Dansgaard et al. (1993)), there are different conventions for the labelling and numbering of stadials.

For example, when comparing the GRIP isotope record with North Atlantic sediment records, McManus et al. (1994) adopted the interstadial numbering introduced by Johnsen et al. (1992) and Dansgaard et al. (1993) for periods of high North Atlantic SSTs, using the label W for *warm*, while low-SST periods were denoted by C for *cold* and accompanied by the number of the succeeding warm event (McManus et al., 1994, Fig. 3). In this scheme, therefore, cold events precede (i.e. are older than) warm events with the same number. The distinction between events in the marine realm and in the ice-core records is in full agreement with the thinking of INTIMATE, which was being established during the same period. However, the stadial numbering differs: in the INTIMATE event stratigraphy of Björck et al. (1998), the numbering scheme begins with the most recent cold event (broadly equivalent to the Younger Dryas stadial) which was designated GS-1 while the preceding interstadial (corresponding roughly to Bølling–Allerød) was numbered GI-1. GI-1 was designated as such because it was the first significant climatic event detected downcore in the GRIP isotope record, and the INTIMATE event stratigraphy was modelled on the 'count from the top approach' applied to the marine isotope record.

In a later development, Rousseau et al. (2006) advocated the naming of marine events NAW and NAC (North Atlantic Warm/Cold instead of just W and C) and applied the numbering of McManus et al. (1994) to both marine and ice-core records, using the GS label which had also been used by INTIMATE to denote ice-core stadials. In this way, only the presence of a hyphen (recommended by INTIMATE but not by Rousseau et al. (2006)) was left to distinguish between the two ice-core event naming systems. The same event would thus be named GS-12 in the INTIMATE event stratigraphy but GS11 according to Rousseau et al. (2006), meaning that minor inconsistencies in typesetting and use of the event names in spoken language would potentially lead to confusion. While we support the concept of Rousseau et al. (2006) of using different labels for events registered in marine and ice-core sequences, there is clearly a problem in that two almost identical, but conflicting, numbering systems are in the public domain. The INTIMATE event stratigraphy has been widely adopted by the international Quaternary community, and it is therefore our contention that the INTIMATE designations should continue to be used, and that changing the numbering schemes in line with McManus et al. (1994) without introducing entirely new labels for stadials and interstadials will simply create further difficulties and confusion for the user community.

While interstadial numbering seems less contentious, the choice of designations (or labels) does vary. Johnsen et al. (1992) introduced the numbering of interstadials without using a label, while Dansgaard et al. (1993) used the designation 'IS'. Recognizing that the label should refer to the region as well as the defining character of the event, the terms Greenland (Isotope) Interstadials/Stadials were coined (Björck et al., 1998), but the "(Isotope)" was subsequently removed (Walker et al., 1999). The label 'GIS' is also used by some authors, but we argue that GI is preferable because it prevents possible confusion between Greenland InterStadial and Greenland Isotope Stadial.

Individual short events not recognized in the existing INTIMATE numbering framework have been named elsewhere, effectively on an *ad hoc* basis. For example, the somewhat subdued interstadial event at 30.7 ka b2k located between the existing GI-4 and GI-5 events was assigned the number 4.1 by EPICA community members (2006). However, using the GI-4.1 event name, and following the general rule that stadials and interstadials come in pairs with the same number, if this scheme was to be followed the former GS-5 would then comprise the sequence GS-4.1, GI-4.1, GS-5, and the term 'GS-5' would thus refer only to a part of the stadial previously designated GS-5. Hence, any reference to GS-5 would be ambiguous unless it is specified whether or not GI-4.1 is included as

Table 2
Onsets of events in the updated and extended INTIMATE event stratigraphy.

Event	NGRIP depth (m)	Age (a b2k) and definition uncertainty	Maximum counting error (years)	Notes and comments
End of 8.2 ka BP event	1219.47	8140 + 50/−10	45	1, 2
Volcanic peak inside 8.2 ka	1228.67	8236 ± 1	47	2, 3
Start of 8.2 ka BP event	1234.78	8300 + 10/−40	49	1, 2
End of 9.3 ka BP event	1322.88	9240 + 30/−10	68	1, 2
Start of 9.3 ka BP event	1331.65	9350 + 10/−20	70	1, 2
End of 11.4 ka BP event	1476.16	11,400[a]	96	13
Start of 11.4 ka BP event	1482.32	11,520[a]	97	13
Start of Holocene	1492.45	11,703 ± 4	99	3, 4, 5
Start of GS-1	1526.52	12,896 ± 4	138	3, 5
Start of GI-1a	1534.5	13,099[a]	143	6
Start of GI-1b	1542.1	13,311[b]	149	6
Start of GI-1c1	1554.75	13,600[b]	156	13
Start of GI-1c2	1557.08	13,660[b]	158	13
Start of GI-1c3	1570.5	13,954[a]	165	6
Start of GI-1d	1574.8	14,075[a]	169	3
Start of GI-1e	1604.64	14,692 ± 4	186	3, 5
Start of GS-2.1a	1669.09	17,480[c]	330	8, 13
Start of GS-2.1b	1745.31	20,900[c]	482	7, 8
Start of GS-2.1c	1783.62	22,900[a]	573	7, 8
Start of GI-2.1	1786.28	23,020[a]	583	8, 13
Start of GS-2.2	1790.26	23,220[a]	590	8, 13
Start of GI-2.2	1793.19	23,340[a]	596	7, 8, 9
Start of GS-3	1861.69	27,540[b]	822	7, 8
Start of GI-3	1869.12	27,780[a]	832	7, 8, 9
Start of GS-4	1882.62	28,600[a]	887	7, 8
Start of GI-4	1891.57	28,900[a]	898	7, 8, 9
Start of GS-5.1	1916.08	30,600[b]	1008	8, 13
Start of GI-5.1	1920.56	30,840[b]	1024	8, 13
Start of GS-5.2	1939.68	32,040[b]	1107	8, 11
Start of GI-5.2	1951.65	32,500[a]	1132	8, 9
Start of GS-6	1964.3	33,360[b]	1191	8, 11
Start of GI-6	1974.55	33,740[a]	1212	8, 9
Start of GS-7	1990.28	34,740[b]	1286	8, 11
Start of GI-7a	1993.79	34,880[b]	1293	8, 13
Start of GI-7b	1997.04	35,020[b]	1299	8, 13
Start of GI-7c	2009.44	35,480[a]	1321	8, 9
Start of GS-8	2026.66	36,580[b]	1397	8, 11
Start of GI-8a	2032.67	36,860[b]	1408	8, 13
Start of GI-8b	2038.23	37,120[b]	1417	8, 13
Start of GI-8c	2070.02	38,220[a]	1449	8, 9
Start of GS-9	2094.64	39,900[b]	1569	8, 11
Start of GI-9	2099.61	40,160[a]	1580	8, 9
Start of GS-10	2109.71	40,800[b]	1615	8, 11
Start of GI-10	2124.03	41,460[a]	1633	8, 9
Start of GS-11	2134.99	42,240[b]	1682	8, 11
Start of GI-11	2157.49	43,340[a]	1736	8, 10
Start of GS-12	2170	44,280[b]	1780	8, 11
Start of GI-12a	2174.8	44,560[a]	1791	8, 13
Start of GI-12b	2176.61	44,680[a]	1796	8, 13
Start of GI-12c	2222.3	46,860[a]	1912	8, 10
Start of GS-13	2240.96	48,340[d]	1988	8, 11
Start of GI-13a	2252.8	49,060[a]	2021	8, 13
Start of GI-13b	2253.84	49,120[a]	2023	8, 13
Start of GI-13c	2256.89	49,280[a]	2031	8, 10
Start of GS-14[QS]	2261.46	49,600[d]	2051	8, 13
Start of GI-14a	2293.25	51,500[b]	2136	8, 13
Start of GI-14b	2295.9	51,660[b]	2144	8, 13
Start of GI-14c	2340.38	53,960[a]	2289	8, 13
Start of GI-14d	2341.38	54,020[a]	2292	8, 13
Start of GI-14e	2345.52	54,220[a]	2301	8, 10
Start of GS-15.1	2353.65	54,900[a]	2338	8, 13
Start of GI-15.1	2355.34	55,000[a]	2349	8, 13
Start of GS-15.2	2359.64	55,400[a]	2368	8, 13
Start of GI-15.2	2366.32	55,800[a]	2392	8, 10
Start of GS-16.1	2374.41	56,500[b]	2430	8, 13
Start of GI-16.1a	2396.75	57,920[a]	2492	8, 13
Start of GI-16.1b	2397.35	57,960[a]	2494	8, 13
Start of GI-16.1c	2398.78	58,040[a]	2497	8, 13
Start of GS-16.2	2400.34	58,160[a]	2505	8, 13
Start of GI-16.2	2402.55	58,280[a]	2511	8, 10
Start of GS-17.1	2406.01	58,560[b]	2528	8, 13
Start of GI-17.1a	2409.78	58,780[a]	2540	8, 13
Start of GI-17.1b	2410.65	58,840[a]	2542	8, 13
Start of GI-17.1c	2415.01	59,080[a]	2557	8, 13
Start of GS-17.2	2417.66	59,300[a]	2569	8, 13
Start of GI-17.2	2420.44	59,440[a]	2573	8, 10
Start of GS-18	2461.82	63,840[a]	n.a.	8, 13
Start of GI-18	2465.85	64,100[a]	n.a.	8, 13
Start of GS-19.1	2504.86	69,400[b]	n.a.	8, 13
Start of GI-19.1	2507.59	69,620[a]	n.a.	8, 13
Start of GS-19.2	2512.54	70,380[c]	n.a.	8, 13
Start of GI-19.2	2535.96	72,340[a]	n.a.	8, 13
Start of GS-20	2547.52	74,100[b]	n.a.	8, 13
Start of GI-20a	2549.63	74,320[b]	n.a.	8, 13
Start of GI-20b	2550.96	74,440[b]	n.a.	8, 13
Start of GI-20c	2579.13	76,440[a]	n.a.	8, 13
Start of GS-21.1	2590.25	77,760[d]	n.a.	8, 13
Start of GI-21.1a	2594.45	78,080[b]	n.a.	8, 13
Start of GI-21.1b	2602.13	78,740[b]	n.a.	8, 13
Start of GI-21.1c	2609.14	79,240[a]	n.a.	8, 13
Start of GI-21.1d	2614.5	79,700[e]	n.a.	8, 13
Start of GI-21.1e	2687.29	84,760[a]	n.a.	8, 13, 12
Start of GS-21.2	2689.81	84,960[a]	n.a.	8, 13
Start of GI-21.2	2691.13	85,060[a]	n.a.	8, 13, 12
Start of GS-22	2717.11	87,600[b]	n.a.	8, 13
Start of GI-22a	2719.69	87,820[b]	n.a.	8, 13
Start of GI-22b	2721.56	88,000[b]	n.a.	8, 13
Start of GI-22c	2730.94	88,800[b]	n.a.	8, 13
Start of GI-22d	2732.29	88,920[b]	n.a.	8, 13
Start of GI-22e	2743.58	89,800[a]	n.a.	8, 13
Start of GI-22f	2744.08	89,840[a]	n.a.	8, 13
Start of GI-22g	2746.53	90,040[a]	n.a.	8, 13
Start of GS-23.1 [QS]	2747.54	90,140[b]	n.a.	8, 13
Start of GI-23.1	2891.53	104,040[a]	n.a.	8, 13
Start of GS-23.2	2894.99	104380[a]	n.a.	8, 13
Start of GI-23.2	2896.61	104,520[a]	n.a.	8, 13
Start of GS-24.1	2905.05	105,440[f]	n.a.	8, 13
Start of GI-24.1a	2914.17	106220[f]	n.a.	8, 13
Start of GI-24.1b	2915.31	106,320[f]	n.a.	8, 13
Start of GI-24.1c	2920.6	106,750[f]	n.a.	8, 13
Start of GS-24.2	2922.06	106900[f]	n.a.	8, 13
Start of GI-24.2	2938.19	108,280[f]	n.a.	8, 13
Start of GS-25	2954.08	110,640[f]	n.a.	8, 13
Start of GI-25a	2956.85	110,940[f]	n.a.	8, 13
Start of GI-25b	2961.07	111,440[f]	n.a.	8, 13
Start of GI-25c	3003.17	115,370[f]	n.a.	8, 13
Start of GS-26	3040.89	119,140[f]	n.a.	8, 13

QS: Quasi-stadial (see text).
1: Rasmussen et al. (2007).
2: NGRIP1 depths used for 8.2 and 9.3 ka events. NGRIP2 depths used elsewhere. To convert these NGRIP1 depths to NGRIP2 depths, subtract 0.43 m.
3: Rasmussen et al. (2006).
4: Walker et al. (2009).
5: Steffensen et al. (2008).
6: Original Björck et al. (1998) definition transferred from GRIP to NGRIP depths using the volcanic markers of (3).
7: Lowe et al. (2008). NGRIP depth of start of GI-2 changed from the previous erroneous value.
8: NGRIP depths derived from the definitions based on 20-year resolution data on GICC05 or GICC05modelext (below 60 ka b2k) ages.
9: Andersen et al. (2006).
10: Svensson et al. (2008).
11: Blockley et al. (2012).
12: Vallelonga et al. (2012).
13: This work.
[a] Definition uncertainty estimated to 1 data points/20 years (1σ).
[b] Definition uncertainty estimated to 2–3 data points/40–60 years (1σ).
[c] Definition uncertainty estimated to 200 years (1σ).
[d] Definition uncertainty estimated to 100 years (1σ).
[e] Definition uncertain as the sub-event starts by a long soft slope.
[f] Definition uncertainty estimated to 1–2 data points/20–40 years (1σ) but is based on one data series only (NGRIP $\delta^{18}O$).

a numbered event. This approach is clearly inappropriate for the purposes of INTIMATE, where stadials are considered to be distinct, clearly defined entities, and are numbered as such.

Given that we do not regard the introduction of a new labelling and/or numbering system to be tenable, we propose that the present GI and GS labels and the accompanying numbering sequence that is already in place should be extended to include the additional events that register in the Greenland records. We thus propose additions to the existing scheme based on the following principles:

- Meaningfulness: The existing meaning of the labels GI (Greenland Interstadial) and GS (Greenland Stadial) is maintained, as is the principle that GS and GI events are paired with each GS being younger than the GI with the same number.
- Completeness: All events and sub-events should have a unique label within the nomenclature scheme.
- Conservatism and uniqueness: Existing numbering should be changed as little as possible, and when periods have to be renumbered, any existing event label/number cannot be reused in a new designation.
- Consistency: The subdivision of interstadials should follow the practice adopted for subdividing GI-1 into sub-events, i.e., from top, a, c, e etc. refer to the warmer sub-events and b, d etc. refer to the colder spells.

Where additional event numbers are deemed to be necessary, these can be adopted by adding a decimal to either the preceding or succeeding event. As the event durations and spacings are highly variable, this should be determined on a case-by-case basis, with adjacent event numbers remaining as close to their original designations as possible. If we take as an example the new interstadial event located at 30.7 ka b2k referred to above, the former GS-5 period could be designated either GI-4.2 or GI-5.1. While we have no preference between these two options, the consequent naming of the former GS-5 makes the choice simpler: by adopting 'GI-4.2', the former GS-5 would be composed of GS-4.2, GI-4.2, and GS-5 (requiring the renumbering of GS-4 and GI-4 to GS-4.1 and GI-4.1, respectively), whereas adopting 'GI-5.1' results in a more logical combination of GS-5.1, GI-5.1 and GS-5.2. By contrast, for short precursor-type interstadial events, adding the decimal to the "parent" interstadial event number would seem the more logical choice.

5. The revised INTIMATE event stratigraphy

Stadial and interstadial events have been defined by combining the results of visual inspection by several investigators of the 20-yr dataset shown in Fig. 1, following the criteria outlined above. The onsets of interstadials are often the easier to define while the gradual transitions into stadials make it difficult to determine the precise point of termination of some interstadials. The aim has been to define the event onsets at the first clear mark of a transition, e.g. at the first data point of the steep part that clearly deviates from the base-line level preceding the transition. The subdivision of interstadials based on the isotopic signal alone is often difficult due to the relatively high short-term variability and inter-core differences and, in these cases, more emphasis was placed on the less noisy [Ca^{2+}] record. Below 104 ka b2k, where GRIP and GISP2 data no longer can be synchronized to GICC05modelext, and in particular below 107.6 ka b2k where only NGRIP $\delta^{18}O$ data are available, the event classification becomes less certain. The definitions have been supported by preliminary data from the new NEEM ice core between GS-24.1 and GS-25, but the NEEM core does not contain ice from the interval 110–116 ka b2k (values from NEEM community members, 2013, converted approximately to the GICC05modelext time scale). Hence, the assignment of sub-events within GI-25 in particular must be regarded as tentative.

The onsets of all events are listed in Table 2 together with estimated uncertainties. The latter have been estimated from the steepness of the transitions and the level of agreement between the $\delta^{18}O$ and [Ca^{2+}] records. Some of the uncertainties assigned to the event definitions in the previously-published 8–48 ka b2k interval have been re-evaluated based on the augmented data set.

In the following passage, we describe the event-stratigraphic sequence, highlighting changes to existing definitions and cases where the definition or numbering of events is problematic or ambiguous. Wherever possible, we have maintained existing event definitions for compatibility with the previous and widely employed schemes. Indeed, rather than making minor adjustment to existing definitions at this stage, we are currently evaluating the potential of applying a robust statistical detection algorithm for the definition of events, as a means of interrogating the entire record. Experimentation with a repeatable Bayesian statistical classification method, working in parallel on $\delta^{18}O$ and [Ca^{2+}] records from all three cores, has been initiated. This provides posterior distributions for the onsets of a given set of events by explicitly modelling their shapes in parallel on all 6 data series. We aim to extend the model to also calculate probability measures for each event and possibly also each sub-event. This task has proved challenging, especially with respect to data beyond GI-14, due to the changeable nature of the signals and the large variability in event durations but, in due course, may lead to a further refinement of the Greenland event stratigraphy.

5.1. Adjusting the existing event stratigraphy (8–48 ka b2k)

The INTIMATE event stratigraphy encompasses the record of climate variability during the Last Glacial, across the deglaciation, and throughout the Early Holocene up to and including the 8.2 ka event (Walker et al., 2012). The period younger than 8 ka b2k is therefore not considered here. The 8.2 ka and 9.2 ka events have been subject to detailed investigations based on data from several ice cores (Rasmussen et al., 2007), and we recommend no changes to the previously published definitions. However, in Rasmussen et al. (2007), a significant cold period around 11.4 ka b2k, tentatively correlated with the Preboreal Oscillation (Björck et al., 1997; Hoek and Bos, 2007, and references therein), was recognised but not precisely defined in time or depth due to the absence of a clear $\delta^{18}O$ baseline so close to the onset of the Holocene. Here, we note that the event is clearly expressed in the [Ca^{2+}] data at 11.40–11.52 ka b2k. On the basis of ice-core $\delta^{15}N$ measurements, Kobashi and Barnola (2008) characterized the event as a gradual cooling over 100–150 years followed by an abrupt warming of 4 ± 1.5 °C at 11,320 b2k. In line with the naming of the 8.2 ka and 9.3 ka events, we refer to this event as the '11.4 ka event'.

The onsets of GS-1 and GI-1 in the INTIMATE event stratigraphy scheme are defined on the basis of high-resolution multi-proxy ice-core data (Steffensen et al., 2008). Of particular significance are deuterium excess values, and this data set was the principal climatic indicator that underpinned the formal designation of the Holocene Global Stratotype Section and Point (GSSP) boundary in the NGRIP ice core (Walker et al., 2009). Deuterium excess is interpreted as a proxy for precipitation vapour source temperature and is shown to change between states in 1–3 years at the onsets of GI-1 and GS-1. The shifts in $\delta^{18}O$ and [Ca^{2+}] are more gradual and begin no more than a couple of decades after the abrupt deuterium excess changes.

The definitions of the boundaries dividing GI-1 into sub-events 'a' through 'e' are from Björck et al. (1998) and are based on GRIP data alone. While the precise onset of GI-1b may be contested, we

retain the current definitions for consistency. However, the cold episode at 13.60–13.64 ka b2k within GI-1c fulfils the criteria for classification as a sub-event although it was not designated as such in the previous event stratigraphy. The term 'Intra-Allerød Cold Period' has been proposed for this event, but this term has also been used with reference to GI-1b (e.g., Hughen et al., 1996; Pedro et al., 2011) and to avoid confusion we do not use the term here. Relabelling the sub-events of GI-1a through GI-1g to accommodate this new sub-event would violate the principle of uniqueness (see Section 4.4). Instead, we propose the subdivision of GI-1c into three new sub-events GI-1c1, GI-1c2, and GI-1c3 (see Fig. 1). These we regard as sub-events of the same hierarchical order as the other sub-events of GI-1, the different level of numbering being merely a consequence of omission of the GI-1c2 cold phase from the original event stratigraphic scheme.

As described in Section 4.3, we retain the existing subdivision of GS-2 and note that small differences in the [Ca^{2+}] record lend support to the proposed sub-event definitions. In the succeeding interstadial, formerly GI-2, two distinct peaks in both the $\delta^{18}O$ and [Ca^{2+}] records are evident, and as both proxies reach full stadial values in the short period separating them, we propose that they should be recognised as two separate interstadials, labelled GI-2.1 and GI-2.2 bracketing the short stadial GS-2.2. As a consequence, the former GS-2 interval (and its sub-events) is re-designated GS-2.1.

No changes are needed in the interval from GS-3 to GI-4. As discussed in Section 4.4, we suggest that the newly named interstadial event within the former GS-5 should be designated GI-5.1, splitting the stadial parts of the former GS-5 interval into GS-5.1 and GS-5.2, the name of the former GI-5 event changing to GI-5.2. This allows the new and old event names to be used side-by-side without risk of confusion, as the existing names GS-5 and GI-5 have not been re-assigned to represent a different period.

From GS-6 to GS-13, no changes are proposed to the existing numbering, but GI-7, GI-8 and GI-12 have been subdivided, as they show clearly-defined substructure in both the $\delta^{18}O$ and [Ca^{2+}] records. GI-11, classified as having a rebound event by Capron et al. (2010a), has not been subdivided since an inflection in $\delta^{18}O$ is recorded in the NGRIP record only, and no clear sub-event signature is observed in the [Ca^{2+}] profiles.

We note that GS-10 and the onset of GI-9 are atypical; during GS-10, [Ca^{2+}] levels are lower than in the adjacent stadials 9 and 11, and the onset of GI-9 is more gradual than in the neighbouring transitions. This accords with the Cariaco Basin and Arabian Sea records, which also do not register strong cooling at this time, possibly indicating that interstadials 9 and 10 could be considered parts of the same interstadial period (Deplazes et al., 2013), as also appears to be the case with respect to GI-14/GI-13 and GI-23/GI-22, discussed below. However, based on the data presented here, we note that GS-10 differs only slightly from the preceding and succeeding stadials, suggesting a different climatic gradient between the mid-latitudes and Greenland over this period.

In the most recent extension of the INTIMATE event stratigraphy scheme, all events down to and including GI-12 were defined using NGRIP and GRIP $\delta^{18}O$ data (Blockley et al., 2012). While most of the existing definitions are well supported by the [Ca^{2+}] record, with $\delta^{18}O$ shifts typically aligning with the early or middle parts of the corresponding [Ca^{2+}] shifts, the [Ca^{2+}] records support the choice of older onset points of stadials GS-9 and GS-10. However, yet again we retain current definitions to maintain compatibility with the existing event stratigraphy scheme.

5.2. Extending the event stratigraphy (section older than 48 ka b2k)

As noted by Capron et al. (2010a), GI-13 and GI-14 can be seen as one long interstadial event with GI-13 being a strongly expressed 'rebound event' ending GI-14. Indeed, the decline in $\delta^{18}O$ and rise in [Ca^{2+}] during the period designated as GS-14 does not reach the stadial base-line levels of GS-13 and GS-15, although in both duration and amplitude it is more pronounced than other typical interstadial sub-events. Simply on the basis of the data, therefore, a case could be made for merging GI-13 and GI-14 into one interstadial event. However, this would require the introduction of either a new set of designations or the re-employment of existing names in a new context. We therefore retain the existing nomenclature of GI-13, GS-14, and GI-14, but regard GS-14 as a *quasi-stadial* event. Consequently, it is colour-coded as a sub-event in Fig. 1, with GI-13 subdivided into a–c and GI-14 into a–e. We observe that the combined interstadial is unusual in that it includes sub-events with a wide range of amplitudes and durations, suggesting major instabilities in the climate system during this part of the record and the possibility that several different mechanisms leading to sub-event behaviour were in operation during this period.

In the middle of the former GS-15, there is an interstadial event just 100 years long, which is designated GI-15.1 following the same logic as for GI-5.1 described above. The occurrence of short interstadial events continue for GI-16 (now GI-16.1), which includes a 120-year-long precursor event (GI-16.2) as well as a 40-year-long cold spell just 80 years after its onset. In a similar way, the former GI-17 consists of two short closely-spaced interstadial periods, one of which also has substructure. In contrast to this phase of several short events, the preceding GS-18 and GS-19.1 span 10 kyr of cold conditions interrupted only by the 260-year-long GI-18. We observe unusually high variability of [Ca^{2+}] and, to some degree, of $\delta^{18}O$ within GS-18 and especially in GS-19.1, but find the variations to be too gradual and the $\delta^{18}O$ and [Ca^{2+}] too poorly aligned to provide a basis for subdivision. Note that the slight offset of the GRIP record relative to the two other records, evident over GI-18, is probably a reflection of the fact that in this part of the record there are no clear match points for time-scale transfer to the GRIP record. As a consequence, the time scale has been interpolated across an unusually long interval (Seierstad et al., 2014).

Centered at 69.5 ka b2k, a hitherto unnamed interstadial event is designated GI-19.1, again following the naming strategy applied to GI-5.1 and GI-15.1. This event was tentatively named D–O 18.1 in Boch et al. (2011) and DO 19a in Jouzel et al. (2007), but as the INTIMATE event stratigraphy does not contain events numbered 18.1 or 19a, there is no risk of confusion with these schemes. During the later part of GI-19.2 (formerly GI-19), $\delta^{18}O$ and [Ca^{2+}] return to stadial levels over a 1000-year-long interval. The slopes of the $\delta^{18}O$ decline and log([Ca^{2+}]) increase are about double those observed during other interstadials, but the gradual change continues until stadial levels are reached and there is therefore no sharp onset of GS-19.2. This is in contrast to GI-20, GI-21 and GI-23 that all terminate abruptly after rebound-type events, again underlining the wide range of expressions of glacial climate variability in this part of the record. In addition, GI-21 and GI-23 have precursor events that are most logically named by adding the suffix '.2'. We note that the onsets of GI-21.1 and GI-21.2, as defined by Vallelonga et al. (2012) based on $\delta^{18}O$ data, accord with our definitions, while the onset of GS-22 diverges by 80 years, because [Ca^{2+}] data show an abrupt change occurring late relative to the more gradual change of $\delta^{18}O$ into GS-22.

As was the case with GI-13 and GI-14 discussed above, GI-22 and GI-23.1 are probably not separate interstadials. Instead GI-22 more likely represents a long rebound-type event at the end of the extremely long GI-23.1. Indeed GS-23.1 is very short and the [Ca^{2+}] record in particular does not reach stadial values, although establishing a stadial base-line is made difficult by the long duration of GI-23.1. Again, we maintain the status of GS-23.1 as a stadial event

in the numbering scheme, but consider it as an interstadial sub-event (reflected by its colour-code in Fig. 1 and its 'quasi-stadial' label in Table 2) and view the entire period from 104 to 87.6 ka b2k as one 'super-interstadial' with a duration of 16.5 kyr.

Beyond 104 ka b2k, the GRIP and GISP2 records are too disturbed by flow over the uneven bedrock to allow stratigraphic matching of the profiles to the NGRIP record (Seierstad et al., 2014), and the classification of events therefore relies on NGRIP data alone. Furthermore, beyond 107.6 ka b2k (2930 m depth), the stratigraphic record is based only on NGRIP $\delta^{18}O$ data, as $[Ca^{2+}]$ data are not available. Although the Greenland ice cap is likely to have contracted markedly during the Eemian interglacial, and hence at this stage may still have been relatively small (Kopp et al., 2009), GI-24 and GI-25 are comparable in character to the later interstadials. We note that GI-24 is interrupted by a short period of stadial climate (denoted GS-24.2) similar to GS-16.2 and GS-17.2 and both GI-24.1 and GI-25 have substructures similar to events occurring later in the glacial period, suggesting that the mechanisms driving millennial-scale variability are not critically influenced by the size of the Greenland ice sheet. The analogy with later interstadial events only breaks down for the onset of GI-25, which has an exceptionally small amplitude. We maintain the designation of GS-26 as a stadial event, as proposed by North Greenland Ice Core Project members (2004), although the onset of GS-26 has more the appearance of a gradual cooling into the glacial stage than of an abrupt onset.

5.3. Recommended use of the INTIMATE event stratigraphy scheme

The series of events identified above in the Greenland ice-core records represents, in the first instance, a record of local-to-regional-scale change in and around Greenland. We note, however, that the methane concentration measured in entrapped air samples from the NEEM ice core in NW Greenland exhibits variability similar to that observed in the GRIP, NGRIP and GISP2 $\delta^{18}O$ and $[Ca^{2+}]$ records (Chappellaz et al., 2013). As the methane sources are not local to Greenland, or even to the North Atlantic, this suggests that the revised event stratigraphy represents a record of climate change on a regional-to-hemispherical scale. As discussed in Section 2, however, it may well be the case that there were significant lags in terms of climatic response between regions and in how the signals were registered by different proxies. There is a growing need, therefore, for precisely-dated, high-resolution proxy records, to determine how the events represented in the Greenland records are expressed at sites further away from Greenland. When comparing records between proxy archives and/or regions, a lack of dating precision can obscure the precise ordering of events over centennial-to-millennial-scale time scales. In such cases, alignment of records and tuning of time scales may be necessary using the major inflections that reflect interstadial or stadial events in the proxy climate curves. When taking this approach, however, the uncertainties associated with the resulting interdependent time scales must be taken into account (Blaauw, 2012). In these cases, we recommend the use of the term 'Dansgaard–Oeschger event', or 'DO' as the label for interstadials, adding the number of the associated Greenland Interstadial where appropriate (with a hyphen for consistency with the INTIMATE event stratigraphy), e.g. DO-4. Hence, in situations where dating is uncertain, for example as a result of marine reservoir age variability, the D–O events can be used as tie-points between different proxy records, as long as (i) the records contain events of approximately similar structure and (ii) the aforementioned time-scale limitations are acknowledged when drawing conclusions from the analysis of the aligned records.

However, where the objective is to determine the relative timing of events and to identify possible leads and lags in the climate system, both independent dating *and* a framework for naming events that does not assume synchroneity between records are essential. Here, the optimal approach is to use the GI/GS notation for the Greenland events and suitable alternative labels and/or numbering system for other records. We encourage the establishment of such local/regional event stratigraphies, where the labels refer to both the region and to the proxy or physical manifestation of the change as, for example, in the case of the AIM (Antarctic Isotope Maxima) labels used for Antarctic ice-core records (EPICA community members, 2006), the NAW/NAC (North Atlantic Warm/Cold events) labels of McManus et al. (1994) and Rousseau et al. (2006) described above, and the CIS (Chinese InterStadial) labels of Liu et al. (2010). Where no such regional event stratigraphy has been established, our recommendation is to maintain the GI/GS notation for Greenland events only and use non-archive-specific DO labels for interstadials expressed in other records. An alternative non-archive-specific nomenclature is to use "stadial" and "interstadial" together with the numbering proposed here, which has the advantage over the DO notation that direct reference can be made to stadial periods. It is therefore appropriate, for example, to discuss the relationship between GI-4 in Greenland and DO-4 (or interstadial 4) as expressed in a given terrestrial record, but not to refer to GI-4 in the terrestrial record, as GI-4 defines the event as registered in the Greenland ice-core record only.

A widely-employed nomenclature for climatic change during the Last Termination is the sequence Oldest Dryas, Bølling, Older Dryas, Allerød, and Younger Dryas. These episodes were originally defined as periods of biostratigraphic change reflected in terrestrial records in Denmark (Iversen, 1954), but they have subsequently been widely used in other geological contexts, and in areas for which they were never initially intended. Strictly speaking, this terminology should be restricted to Scandinavian terrestrial records (*sensu* Mangerud et al. (1974)), but we acknowledge that the terms are now so firmly embedded in the Quaternary literature that they cannot realistically be replaced. Hence, it is important to make clear how they relate (or equate) to the event stratigraphy and how (and if) the two sets of terminology should be employed. Our recommendations are that:

- Bølling–Allerød (or the Bølling–Allerød chronozone) can be used as a synonym for DO-1, but *not* as a synonym for GI-1, i.e. that the Bølling–Allerød (chronozone) can be used as a non-archive-specific name for the generally mild climate period approx. 14.6–12.9 ka b2k,
- Younger Dryas (or the Younger Dryas chronozone) can be used as a non-archive-specific synonym for the stadial period between Bølling–Allerød and the Holocene (approx. 12.9–11.7 ka b2k), but *not* as a synonym for GS-1,
- Oldest Dryas (the period of stadial climate just prior to the onset of Bølling) is *not* used as it is poorly defined, and
- Older Dryas (the relatively cold period between Bølling and Allerød) and the Intra-Allerød Cold Period are *not* used because of the risk of confusion with other sub-events of the Bølling–Allerød interval as reflected by the now 7-fold subdivision of GI-1.

Finally, we turn to the relationship between stadial periods and Heinrich events. Heinrich events are defined by the existence of layers of ice-rafted debris (IRD) of mainly (but not exclusively) Laurentide origin in North Atlantic sediment cores (e.g., Bond et al., 1992; Heinrich, 1988; Hemming, 2004, and references therein). Heinrich events have been noted during several of the longer stadials, but most likely do not span the entire stadial period (Roche et al., 2004; Marcott et al., 2011). Abrupt changes in

sedimentation rates during Heinrich events make dating of these episodes challenging (Austin and Hibbert, 2012). In addition, Heinrich events may be time-transgressive, further complicating analysis (Stanford et al., 2011). Heinrich events and the stadial periods during which they occur are therefore not necessarily coterminous. We recommend that the term 'Heinrich Event' (or, more accurately, 'Heinrich Layer') is used to designate only the period where IRD is found in a particular record. Stadial events expressed in marine sediments should be named and numbered independently from the occurrence of Heinrich events, e.g. based on SST reconstructions (Austin and Hibbert, 2012). However, the term Heinrich Stadial (HS) is used in the literature to refer to a stadial containing a particular Heinrich Event (with the numbering following that of the Heinrich Event). We recommend that in this case, the meaning of HS is specified clearly at first use, for example to clarify whether it refers to the entire stadial period in question, or to part of a stadial only, defined, for example, by variations observed in proxies of IRD, SST or AMOC activity (Barker et al., 2009).

6. Discussion and final remarks

One of the most striking features of the sequence of events mapped out in the Greenland event stratigraphy is the irregular occurrence of short interstadial events and sub-events throughout the entire record. However, it is apparent that the most marked change in the expression of centennial-to-millennial-scale variability takes place over the interval from 68 to 48 ka b2k. This period is characterized by a change from stable, predominantly cold, climate (GS-19.1 and GS-18), through a period of 'flickering' between states (GI-17 to GI-15), to a c. 6-kyr-long predominantly mild climate (GI-14 to GI-12), suggesting that the climate system slowly passed a dynamical threshold. Capron et al. (2010a) suggested that 65°N summer insolation could not only be the modulator of this behaviour but also a determining factor for the existence of recurring short-lived interstadials. Indeed, summer insolation at 65°N was high at the time of GI-24, GI-23, and GI-21, as well as during interstadials 15–17, and low during GS-19.1 and GS-18, but also high during GI-1 when no short interstadials are observed. Another feature of the 68–48 ka b2k period is that sea level was rising at the highest rate around 60–55 ka b2k, at the time where 'flickering' behaviour is most prevalent in the Greenland records (Siddall et al., 2003). Although relative dating uncertainties make direct correlation between the ice-core and sea-level records difficult, sea level also seems to have been rising at the time of the GS-23.2 and GS-21.2 precursor events.

To what extent sea-level change or, indeed, changes in insolation, influenced the amplitude and pacing of Dansgaard–Oeschger events remains to be established. However, unravelling the relationship between the different modes of variability that characterises the Last Glacial period, not only in ice cores but also in other proxy archives, requires an unambiguous and well-resolved time-stratigraphic framework, such as that provided by the newly-extended Greenland event stratigraphy outlined above. Only with such a system in place will it prove possible to disentangle lead and lags, cause and effect, and the dynamics of different components of the climate system. Further progress in understanding the complex interplay between atmosphere, ocean, and cryosphere, and the mechanisms linking them, will require closer collaboration at the interface between palaeoclimate observation and Earth system modelling with more firm protocols for palaeodata-model comparisons. In this regard we contend that the INTIMATE approach offers a robust and effective way forward.

Data access

With this paper and the companion paper by Seierstad et al. (2014), $\delta^{18}O$ and $[Ca^{2+}]$ data re-sampled to 20-year resolution on the GICC05modelext time scale from NGRIP, GRIP, and GISP2 will be released at www.iceandclimate.dk/data. Table 2 is also supplied in a spreadsheet format.

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