Three amphi-Atlantic century-scale cold events during the Bølling-Allerød warm period

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ABSTRACT Oxygen isotope composition of carbonates in the sediments of Crawford Lake, southern Canada, reveals multiple climatic events during the last deglaciation, including the Bolling warming, Intra-Allerød cold period, Younger Dryas, Preboreal Oscillation, and early-Holocene 8.2-ka cooling. Here we present a high-resolution record (~50-yr sampling interval) of oxygen isotopes from this site during the Bolling-Allerød warm period and discuss its significance by comparing it with other records around the North Atlantic. These new data show three century-scale cold events, including the intra-Bolling cold period. Older Dryas, and Intra-Allerød cold period. These climatic events correlate well in sequence and relative magnitude with those found in Greenland ice cores, European lacustrine sediments, and Atlantic Ocean sediments. Three similar oscillations in glaciochemical records from GISP2 ice core imply shift in atmospheric circulation patterns. The amphibialantic distribution of these climatic events suggests that these events likely originated from the North Atlantic Ocean and that climatic signals were transmitted through the atmosphere.

RESUMEN: Existencia de tres periodos híbridos amphi-Atlanticos a escala centenaria al curso de la etapa cálida del Bolling-Allerød. La composición isotópica de oxígeno de los carbonatos en los sedimentos del Crawford Lake, en el sur de Canadá, revela la presencia de multitud de oscilaciones climáticas durante la última desglaciaciòn, incluyendo el calentamiento de Bolling, el período de enfriamiento intra-Allerød, los Dryas recientes, la oscilación preboreal y el enfriamiento del Holoceno inferior hace unos 8,2 ka. Se presenta a continuación un registro de alta resolución (~50 años de muestreo) basado en los isótopos de oxígeno presentes en este sitio durante el periodo de calentamiento de Bolling-Allerød, se discute además su relevancia en comparación a otros registros realizados en el Atlántico norte. Estos nuevos datos muestran tres eventos fríos que se extienden por unos centenares de años y que incluyen los periodos siguientes: frío de Intra-Bolling, Dryas tardío y frío de intra-Allerød. Estos cambios climáticos se correlacionan adecuadamente en secuencia y magnitud relativa con los registros en muestras de hielo de GISP2 resultando de un cambio en el patrón de circulación atmosférica. La distribución anti-Atlantic de estos eventos climáticos sugiere que tuvieron su origen en el norte del Océano Atlántico y que dichos cambios climáticos fueron transmitidos hasta la atmósfera.
INTRODUCTION

In the North Atlantic region, large and abrupt climatic oscillations during the last glaciation continued into the last deglacial period, including quasi-periodic millennial-scale Dansgaard-Oeschger (D-O) events (~1500-year spacing) from ice and marine records (Dansgaard et al., 1993; Hughen et al., 1996; Bond et al., 1997; Grootes and Stuiver, 1997; Alley, 1998; Alley and Clark, 1999). During the last glacial-interglacial transition, the most recent manifestation of these millennial-scale climatic events was broadly experienced in terrestrial records from both Europe (e.g., Lotter et al., 1992; Björck et al., 1996) and North America (e.g., Lavoie et al., 1993; Yu and Eicher, 1998). These climatic events include the Bølling warming at 14 600 cal. BP (12 700 14C BP) and the gradual cooling trend toward the Younger Dryas climate reversal. Recent paleoclimatic studies in Europe have documented three century-scale oscillations during the general cooling trend of the Bølling-Allerød warm period (BOA) (Von Grafenstein et al., 1999; Brauer et al., 2000; Zolitschka et al., 2000). However, limited data comparable with European records exist in North American terrestrial records. Establishing the geographical extent of these cold events in a warm climate would provide useful insights into understanding the mechanisms of present climate variability.

Here we present a high-resolution (~50-yr sampling interval) oxygen-isotope record during the BOA warm period from a small lake in southern Canada. The coarse-resolution data (~100-yr sampling interval) from this site presented earlier (Yu and Eicher, 1998) documented the intra-Allerød cold period (IACP), Younger Dryas (YD), and Preboreal Oscillation (PB). The new data provide evidence for other cold-climate events (~100-yr sampling interval) from this site presented earlier (Yu and Wright, 2001), justifying the need for a systematic sampling during the BOA warm period. Sediment mixing caused by bioturbation activity was likely minimal at 376-360 cm (the BOA period) because of the banded or laminated nature of the sediments (Yu and Wright, 2001), justifying the fine-interval sampling.

MATERIALS AND METHODS

Crawford Lake (43° 28' N, 79° 57' W; 278 m asl altitude) is located about 60 km southwest of Toronto atop Ontario’s Niagara Escarpment (Fig. 1). The study region was deglaciated about 13 000 14C BP, and the surface around the lake is dominated by bedrock outcrops and coarse materials (gravel, stony or sandy tills) (Karrow, 1987). The lake is small (2.4 ha surface area) and deep (24 m maximum depth) within a bedrock basin in a small watershed (about 80 ha). The data presented in this paper were obtained from a shallow core (core SC), taken with a Wright-Livingstone piston sampler on 7 March 1993 at water depth of 7.6 m (Yu et al., 1997; Yu and Eicher, 1998).

The subsamples for stable-isotope analysis were taken mostly at 1-cm intervals, with higher resolution (at 0.25 cm) during the BOA warm period. Sediment mixing caused by bioturbation activity was likely minimal at 376-360 cm (the BOA period) because of the banded or laminated nature of the sediments (Yu and Wright, 2001), justifying the fine-interval sampling.

Bulk carbonate samples were dried at 50 °C overnight, and macroscopic plant remains and mollusc shell fragments were picked out under a microscope and discarded. Each sample of 40-50 mg of bulk carbonate was reacted with 95 % phosphoric acid (H3PO4) at a constant temperature of 50 °C for 1 hour to produce CO2. The CO2 was then analyzed for its δ18O and δ13C values with a mass spectrometer (Finnigan MAT 250) at the University of Bern, Switzerland (Siegenthaler et al., 2007). The analytical precision is ±0.02 ‰ for both δ18O and δ13C.

RESULTS

The sediments show an upward sequence from clay through transitional clayey marl to marl (Fig. 2; Yu and Eicher, 1998). The basal 5-cm silty clay has a very low content of organic matter and carbonates. The transition from clay to marl at 380-373 cm is laminated, with gradually rising carbonate contents. From 373 to 362 cm, the sediments are banded marl with up to 82 % carbonate.

The δ18O values above 378.5 cm upcore register the isotopic composition of authigenic calcite. Initially, the δ18O values show a positive shift of ~1 ‰ from -10 to -8.7 ‰ from 378.5 to 375 cm. From 375 to 362 cm, the δ18O values are relatively high.
and show a downward trend, with several minor negative excursions at 369.5, 367 and 364 cm. A major negative excursion at 361-351 cm reaches a minimum of -11.1‰ at 358 cm. The abrupt positive shift of 1.4‰ in δ18O from -10.8 to -9.4‰ occurs within 2-cm sediment around 351 cm. After another minor negative excursion of 0.4‰ from 346 to 342 cm, the δ18O values reach a high of -8.6‰.

δ13C values show a stepwise decrease from -0.6‰ to -5.8‰ from 378.5 to 350 cm, with several oscillations. After a positive shift in the early Holocene, δ13C stabilize around -5‰. In general no significant correlation between δ18O and δ13C values is apparent (Fig. 3).

**DISCUSSION**

**RADIOCARBON DATES, CHRONOLOGY AND TERMINOLOGY**

The chronology is based on AMS 14C dates on terrestrial plant macrofossils from core DC at Crawford Lake (9670 ± 70 and 9620 ± 6014C BP) and from nearby Twiss Marl Pond (10 920 ± 80 14C BP; Fig 2; Yu and Eicher, 1998). The ages were transferred to core SC on the basis of pollen correlation and major isotopic shifts. The other ages used for chronology were based on the local deglaciation history and from nearby dated pollen sequences by pollen correlation (Fig 2; see Yu and Eicher, 1998; Yu, 2000 for detail). The multiple proxy data from three cores at this site unequivocally place this interval in the late glacial and early Holocene. However, the equivalent calendar time scale cannot be established closer than 400 years, because of the lack of straightforward conversion between radiocarbon and calendar ages for this time period (Stuiver et al., 1998). For example, the calibration of two AMS ages generates wide ranges (440 and 320 years, respectively for 9650 and 10 92014C BP) of calendar ages (Fig. 4). As a result, the time scale for Crawford Lake as presented in Figure 4 is tuned to GISP2 ice-core time scale based on major isotopic shifts; thus the correlation does not imply synchrony within ± 400 years. On the other hand, there is still an age discrepancy between two Greenland Summit ice cores (GISP2, and GRIP), ~30 km apart (Figs. 4B and 4C). In any case, the remarkable similarity of records as shown in Figure 4 justifies the assumption of

FIGURE 2. Photograph of late-glacial and early-Holocene sediment section and oxygen and carbon isotopes of carbonates from core SC at Crawford Lake, Canada. PB, Preboreal Oscillation; IACP, intra-Allerød cold period; OD, Older Dryas; IBCP, intra-Bølling cold period. The 14C dates and ages on the right side were transferred from other cores at same and nearby sites on the basis of major isotopic shifts and regional pollen correlation (see Yu and Eicher, 1998 and Yu, 2000 for detail). The dashed horizontal lines show the correlation of δ18O and δ13C during the century-scale climate oscillations.

synchrony for the major climate shifts, unless future inde-
pendent chronology from lake sediments indicates otherwise.

In this paper, we chose to use the terms of the Balling, Old
Dryas, Allerød, and Younger Dryas in a climatostatigraphic
sense ("climatic events"; Wohlfarth, 1996), but not necessari-
ly the chronostratigraphy of Mangerud et al. (1974). As many
authors have pointed out (e.g., Broecker, 1992; Lowe, 1994;
Wohlfarth, 1996; Björck et al., 1998; Walker et al., 1999), there
are several problems with the Mangerud et al. (1974) chrono-
stratigraphy, which was originally proposed for northwest
Europe and was based on bulk radiocarbon dates. For exam-
ple, the Balling was originally defined as starting from
13 000 14C BP (calibrated to ~15 650 cal BP; Stuiver et al.,
1998). However, most recent records based on AMS dates or
independent annual chronology indicate a much later onset
of the Balling (e.g., 14 600 cal BP as in most records in Fig. 4).
Broecker (1992) suggested the use of a single warm interval
(the Belling-Allerød: BOA) because there were limited num-
er of records at that time showing evidence for the Older Dryas. As summarized in this paper, more recent high-reso-
lution records show not only the Older Dryas but also other
minor oscillations during the BOA warm period. As a result, the
placement of these minor cold events may not be consistent
among records and may not correspond with the chrono-
stratigraphy of Mangerud et al. (1974). We take the advice of
Wohlfarth (1996) to use these historical terms in a climatic
sense, because these terms have already been widely used
in the literature and the sequence of these events is not in
dispute. Perhaps it is more appropriate now to properly define
these "climatic events" as represented in these existing terms,
especially when more well-dated records are available from
terrestrial, oceanic and ice-core sources. A new set of termi-
nology for this event stratigraphy as proposed by Björck et al.
(1998) is probably premature and may be even further con-
fusing the matter (Broecker, 1992; Brauer et al., 2000), for the
ages used in the scheme are still preliminary (see Table 2 in
Björck et al., 1998) and the GRIP ice core and its oxygen iso-
topic proxy may not be representative of the amphi-Atlantic
region (Hughen et al., 1996; Bond et al., 1997; Von Grafenstein
et al., 1999; Figs. 4D, E).

OXYGEN AND CARBON ISOTOPES IN LACUSTRIENE CARBONATES

The isotopic fractionation between carbonate and water
has a negative temperature coefficient of -0.24 ‰ per °C
(Friedman and O'Neill, 1977), whereas δ18O in precipitation is
positively correlated with air temperature at 0.6 ‰ per °C for
the global average (Rozanski et al., 1992). The combination
of these two temperature-dependent factors suggests a coeffi-
cient of 0.36 ‰ per °C, assuming that water temperature
closely tracks air temperature (Yu and Eicher, 1998). In high-
and mid-latitude regions, the isotopic signal of the water in
general prevails over the temperature effect (Dansgaard, 1964;
Siegenthaler and Eicher, 1986; Rozanski et al., 1992). The
Δ13C/13C ratio of authigenic marl depends mainly on local fac-
tors, particularly through the change in δ13C of dissolved inor-
ganic carbon (DIC) of lake water. These factors include exchange rates between water and atmospheric CO2 resi-
dence time of the lake water and the associated evaporation
effect, decomposition of organic matter, and biological pro-
ductivity (Siegenthaler and Eicher, 1986; Yu et al., 1997). The
general lack of correlation between δ18O and δ13C suggests
that the effect of local hydrology is unimportant in determining
overall isotopic pattern of lacustrine carbonate and lake water
(Fig. 3; Talbot, 1995).

The oxygen-isotope records from Crawford Lake document
the classic Balling - Allerød - Younger Dryas - Preboreal cli-
matosequence (Yu and Eicher, 1998). During the BOA warm
period, three cold events with negative excursions of 0.5 to
0.8 ‰ in δ18O occurred (Fig. 4A), including the intra-Ball-
cold period (IBC: Koç Karpuz and Jansen, 1992; Hugenh et al.,
1996), the Older Dryas (OD: Dansgaard et al., 1993), and
the intra-Allerød cold period (IACP: Lehman and Keigwin,
1992). If we use a simple carbonate δ18O - air temperature
relation of 0.36 ‰ per °C and attribute the isotopic shifts to

FIGURE 3. Covariance of δ18O and δ13C for the period of 14 600 -
10 000 cal. year BP at core SC of Crawford Lake. The general lack of
correlation (r = 0.056; dashed regression line) suggests minimal role
of local hydrology in causing major isotopic shifts. Three century-scale
cold events during the Belling-Allerød warm period show different pat-
tern of δ18O and δ13C variations (trends indicated by double-arrowed
lines): IBCP, inverse relation; OD, positive relation; and IACP, constant
δ13C.
temperature changes, then these climatic events as a first approximation represent 1-2°C cooling. The δ13C results show a step-wise decrease of 5% from the Oldest Dryas before the B3A warming to the beginning of the Holocene (Fig. 2). Yu et al. (1997) attributed this gener-
al depletion trend to an increased input of organic matter from the watershed into the lake, when upland vegetation changed from treeless tundra through spruce woodland to closed pine forest. Subsequently the 13C-depleted particulate organic car-on was oxidized and recycled back into the water to affect the δ13C of DIC. The lack of covariance between δ18O and δ13C during the late glacial and early Holocene suggests that the local hydrology did not play a significant role in driving the δ18O shifts in carbonates (Talbot, 1990), rather that the δ18O shifts most likely reflected climatic changes, specifically tem-
perature changes. Close examination of δ18O and δ13C covari-
ance during these century-scale cold events may help to
determine the nature of these oscillations (Fig. 3). During the
IBCP and perhaps also IACP, δ18O values inversely correlate
with δ13C, but during the OD δ18O shows positive correlation
with δ13C, suggesting dry conditions with high evaporation, as
well as cold.

FIGURE 4. Correlation of paleorecords during the last deglaciation (15 000 -10 000 cal. BP) around the North Atlantic. A) δ18O of lacus-
tine carbonates at Crawford Lake; B) δ18O of ice-core GRIP (Dansgaard et al., 1993); C) Snow accumulation rates of ice-core
GISP2 (Cuffey and Clow, 1997); D) δ18O of lacustrine carbonates at Ammersee, south Germany (Von Grafenstein et al., 1999); E) Grey
scale of core PLO7-56PC at Carapao basin off Venezuela (Hughen et al., 1996, revised age scale). Solid correlation lines indicate major cli-
matic shifts, whereas dashed lines indicate minor cold climatic events. Ages for Crawford Lake based on AMS 14C dates from nearby cores
are tuned to GISP2 ice-core time scales on the basis of similar climatic
oscillations, so the similarity in timing does not mean synchrony of
events at centennial scales. The hatched bars along the time scale on
the left side show the ranges of calibrated ages of two AMS 14C ages
in Figure 2 on the basis of calibration program Calib 4.2 (Stuiver et
al., 1998); (a) 10 750 –11 190 cal. BP for 9650 14C BP; and (b) 13 140 –
12 820 cal. BP for 10 920 14C BP at 2σ significance level (95 % pro-
bability). Three century-scale cold events during the Bolling-Aller-
ded warm period are the IBCP (intra-Bolling cold period), OD (Oldest
Dryas), and IACP (intra-Allerod cold period). PB: Preboreal Oscillation.
Most of these data sets are available from the World Data Center – A
Paleoclimatology at the National Geophysical Data Center, Boulder,
CO, USA (www.ngdc.noaa.gov/paleo).

Corrélations entre les paléo-relevés au cours de la dernière glaciation
(15 000 -10 000 ans. cal. BP) autour de l’Atlantique Nord. A) δ18O de
carbonates lacustres au Crawford Lake; B) δ18O de la carotte de
glace GRIP (Dansgaard et al., 1993); C) Taux d’accumulation de la
neige dans la carotte GISP2 (Cuffey et Clow, 1997); D) δ18O de car-
bonates lacustres à Ammersee, dans le sud de l’Allemagne (Von
Grafenstein et al., 1999); E) Mesures des sédiments marins varvés
da la carotte PLO7-56PC, bassin de Carapao, au large du
Venezuela (Hughen et al., 1996, échelle révisée). Les lignes de cor-
rélations continues signalent des changements climatiques majeurs,
tandis que les lignes brisées identifient des phases de rétrograde-
ment mineures. Les âges donnés au Crawford Lake fondent sur des
dates SMA des environ ont été ajustés à l’échelle temporelle de la
carotte GISP2 sur la base de la similitude des oscillations climatiques,
sans que la similitude temporelle signifie synchronisme des événe-
ments à l’échelle séléctaire. Les deux barres sur le long de l’échelle tem-
porelle (à gauche) donnent l’étendue des âges établis sur de deux
dates SMA données à la figure 2 tôt parti du programme Calib 4-2
(Stuiver et al., 1998); (a) 10 700 -11 190 cal. BP pour 9650 14C BP
et (b) 13 140 –12 820 cal. BP pour 10 920 14C BP au niveau de signi-
ficiance 2 σ (probabilité à 95 %). Les trois phases froides à échelle séléctaire au cours de la période chaude du Bolling-Allerod sont les
suivantes : la période froide intra-Bolling (IBCP), la Dryas ancien (OD)
La plupart de ces ensembles de données font partie du World Data
Center – A Paleoclimatology at the National Geophysical Data Center,
TELECONNECTION OF CENTURY-SCALE COLD EVENTS

Three century-scale cold events during the Belling-Allerød warm period were clearly documented at several high-resolution paleoclimatic records around the North Atlantic Ocean (Fig. 1). The δ18O record from GISP ice core shows all three cold events (Fig. 4B; Dansgaard et al., 1993), as do other earlier Greenland ice cores (e.g., G10, Grønland, Johnsen et al., 1992; see their Fig. 2). The GISP2 δ18O record only clearly shows two of them (Grootes et al., 1993; but see 3-yr resolution δ18O in Figure 4 of Stuiver and Grootes, 2000), but snow-accumulation record indicates three events (Fig. 4C; Alley et al., 1993; Cuffey and Clow, 1997). Both δ18O and snow accumulation represent changes in local climate over Greenland (Alley, 2000). Similar oscillations in chemistry of GISP2 ice core (e.g., Ca, Mg, Na) and derived Polar Circulation Index suggest shifts in large-scale atmospheric-circulation pattern (Mayewski et al., 1994, 1997; Alley, 2000), which indicates a broad geographic signature. These multiple cold events have also been documented in terrestrial δ18O records at Ammersee, southern Germany (Fig. 4D; Von Grafenstein et al., 1999), and at other European sites, including Gerzensee, Switzerland (Eicher and Siegenthaler, 1976; Lotter et al., 1992; Birks and Ammann, 2000; Schwander et al., 2000). These continental isotopic records represent changes in mid-European air temperatures. These short-term climatic oscillations have also been documented in marine records. In Cariaco basin (offshore Venezuela) in tropical Atlantic Ocean, grey-scale measurements of varved marine sediments, which are thought to be related to upwelling and trade-wind strength, also show three oscillations during the BOCB warm period (Fig. 4E; Hughen et al., 1996). The BOCB period of these records is expanded in Figure 5, which also shows difference in trend and details after detrending of these records. The Belling-Allerød Interstadial Complex was recorded in diatom-inferred sea-surface temperature record from high-resolution sediment record from the Norwegian Sea (Koç Karpuz and Jansen, 1992). The petrologic tracers from VM23-81 in the North Atlantic show 3-4 oscillations during the BOCB period, though Bond et al. (1999) only labelled two of them in their numbering system of 100,000-year cycles (their numbers 10 and 11; see their Fig. 7).

The trans-Atlantic similarity and difference in patterns of these cold events may reveal the nature of these climatic changes. Von Grafenstein et al. (1999) identified a climatic asymmetry between Greenland and Europe on the basis of their derived oxygen isotopes in precipitation from ostracode shells. During the OD, Europe has cooling similar to that in Greenland, whereas during the ICBP and IACP Greenland was much colder than Europe. This suggests shifts in the climate gradient across the Atlantic, probably caused by shifts in atmospheric circulation pattern (Von Grafenstein et al., 1999). This asymmetry may relate to differences in covariance of δ18O (a proxy of air temperatures and evaporative strength) and δ13C (a proxy of lake productivity and evaporation) at Crawford Lake. Clearly this aspect of BOCB century-scale climatic events deserves further investigations with multiple-proxy paleorecords. Another contrasting pattern is the general trend during the BOCB warm period. At Crawford Lake, the δ18O values declined more than 2 ‰ during the BOCB warm period. The ice-cores from Greenland show declining trend in δ18O values (Johnsen et al., 1992; Dansgaard et al., 1993; Grootes et al., 1993); a similar declining trend was documented in European fossil beetle (Atkinson et al., 1987) and isotopic records (Eicher and Siegenthaler, 1976; Lotter et al., 1992). However, the Ammersee and Cariaco records show a plateau-like Belling-Allerød warm period (Figs. 4D and 4E). A similar plateau-like BOCB was documented in marine records from Norwegian Sea (Koç Karpuz and Jansen, 1992; Lehman and Keigwin, 1992; Hallidason et al., 1995). The atmospheric CH4 records from GRIP and GISP2 also show a plateau-like or even increasing trend during the BOCB; however, the coarse temporal resolution from GRIP prevents detection of century-scale oscillations (Chappellaz et al., 1993), while the high-resolution CH4 record from GISP2 shows evidence for the IACP (Brook et al., 2000). This difference may relate either to different regional responses to change in oceanic and atmospheric circulations or to differential responses of individual sites and proxies.

Similarly of climatic variations as summarized above indicates that the three events are real features during the BOCB warm period. The teleconnection of these century-scale minor climatic oscillations from North America to central Europe suggest that they originated in the North Atlantic Ocean, likely caused by switching of different modes in thermohaline circulation (Broecker et al., 1985), which would affect surface temperatures and atmospheric circulation over large geographic regions.

CONCLUSION

During the Belling-Allerød warm period, three century-scale climatic oscillations existed, as inferred from high-resolution (~50-yr sampling interval) oxygen isotopes of carbonates at Crawford Lake, southern Canada. These events correspond to the inter-Bellings cold period, Older Dryas, and intra-Allerød cold period, which have been documented in proxy records from Greenland ice cores, Ammersee, and Cariaco Basin. The broad geographic distribution of these climate events suggests that they were probably caused by changes in thermohaline circulation in the North Atlantic and subsequent change in sea-surface temperatures. Change in atmospheric circulation patterns is implied by similar patterns in glaciochemical records from the GISP2 ice core. The results indicate that climatic signals were transmitted by the atmosphere.

Alternatively, the nature and response of climate change at Crawford Lake in particular and in North America in general may be different from Greenland and Europe, but assessing this possible difference requires high-resolution independent chronology from this site and other sites. New multiple proxy data together with lake water isotopic calibration data collected from this site in the future can also be used to address possible change in the climatic gradient across the North Atlantic during this period of abrupt climatic oscillations (e.g., Von Grafenstein et al., 1999). Similarly, the North Atlantic region might have responded to an even broader forcing, if records with sufficiently
FIGURE 5. Details of climatic fluctuations during the BOA period in paleoclimatic records as shown in Figure 4. The top panels show the trend lines based on linear fits, whereas the bottom panels show the detrended records after subtracting the fits and means.
detailed analyses from other parts of the world show similar patterns. In any case, there is a great need to obtain high-quality paleo-records from different regions in resolving century-scale oscillations during the most recent warm period before the Holocene. Understanding spatial patterns and regional links of past climate changes are critical in testing and improving climate models and projecting future climate.

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REFERENCES


