**Table 5.A.3:** Assessment of leads and lags between Antarctic, hemispheric temperatures and atmospheric CO2 concentration during terminations. Chronological synthesis of publications, main findings, incorporation in IPCC assessments and key uncertainties.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Reference** | **Investigated Period** | **Source CO2 Data** | **Source Temperature Data** | **Lag Quantification Method** | **Lag Between Temperature and CO2 (positive, temperature lead)** | **Key Limitations** |
| *TAR : From a detailed study of the last three glacial terminations in the Vostok ice core, Fischer et al., (1999) conclude that CO2 increases started 600 ± 400 years after the Antarctic warming. However, considering the large uncertainty in the ages of the CO2 and ice (1000 years or more if we consider the ice accumulation rate uncertainty), Petit et al., (1999) felt it premature to ascertain the sign of the phase relationship between CO2 and Antarctic temperature at the initiation of the terminations. In any event, CO2 changes parallel Antarctic temperature changes during deglaciations (*[*Blunier et al., 1997*](#_ENREF_83)*;* [*Petit et al., 1999*](#_ENREF_634)*;* [*Sowers and Bender, 1995*](#_ENREF_754)*).* |
| ([Fischer et al., 1999](#_ENREF_244)) | Termination ITerminations I, II, III | Taylor Dome, Byrd\* (CH4 synchonized age scales)Vostok\*(gas age scales based on firn modeling) | Byrd d18O, Vostok dD (CH4 synchonized age)Vostok\* dD (GT4 ice age scale) | Maximum at onset of interglacial periods | Antarctica:600 ± 400 years | Ice core synchronization for Termination I (~300 years)Gas age-ice age difference simulated by firn models for interglacial conditions could be overestimated by ~400 yearsSignal to noise ratio Resolution of CO2 measurements and firnification smoothing (~300 years) |
| ([Petit et al., 1999](#_ENREF_634)) ([Pépin et al., 2001](#_ENREF_631)) | Terminations I, II, III, IV | Vostok\*(GT4 gas age scale based on firn modeling)Vostok\*(GT4 gas age scale) | Vostok dD(GT4 ice age age)Vostok D(GT4 ice age age) | Onset of transitions | Antarctica:in phase within uncertaintiesPositive  | Gas age-ice age difference simulated by firn models for glacial conditions could be overestimated by up to 1500 yrResolution of CO2 measurements and firnification smoothing (~300 yr)Signal to noise ratio (1 ice core) |
| ([Mudelsee, 2001](#_ENREF_570)) | 0–420 ka | Lagged generalised least square regression with parametric bootstrap resampling, entire record | Antarctica : 1300 ± 1000 years |
| *AR4: High-resolution ice core records of temperature proxies and CO2 during deglaciation indicates that Antarctic temperature starts to rise several hundred years before CO2 (*[*Caillon et al., 2003*](#_ENREF_122)*;* [*Monnin et al., 2001*](#_ENREF_561)*). During the last deglaciation, and likely also the three previous ones, the onset of warming at both high southern and northern latitudes preceded by several thousand years the first signals of significant sea level increase resulting from the melting of the northern ice sheets linked with the rapid warming at high northern latitudes (*[*Pépin et al., 2001*](#_ENREF_631)*;* [*Petit et al., 1999*](#_ENREF_634)*;* [*Shackleton, 2000*](#_ENREF_722)*). Current data are not accurate enough to identify whether warming started earlier in the Southern Hemisphere (SH) or Northern Hemisphere (NH), but a major deglacial feature is the difference between North and South in terms of the magnitude and timing of strong reversals in the warming trend, which are not in phase between the hemispheres and are more pronounced in the NH (*[*Blunier and Brook, 2001*](#_ENREF_80)*).* |
| ([Monnin et al., 2001](#_ENREF_561)) | Termination I | High resolution data from EDC on EDC1 gas age scale (based on firn modeling) | EDC on EDC1 ice age scale  | Crossing points of linear fit | Antarctica:800 ± 600 years | Gas age-ice age difference (±1000 years)Signal to noise ratio (1 ice core) |
| ([Caillon et al., 2003](#_ENREF_122)) | Termination III | Vostok on GT4 gas age scale | Vostok d40Ar on GT4 gas age scale | Maximum lagged correlation | Antarctica:800 ± 200 years | Relationship between d40Ar and temperature assumed to be instantaneous. The 800 yr is a minimum CO2-temperature lag which does not account for a possible delayed response of firn gravitational fractionation to surface temperature change |
| *AR5 : Continental temperatures in Antarctica are governed by a number of processes, including the dominant CO2 radiative effect, orbital forcing and changes in ice-sheet height. Previous reconstructions indicated a lead of Antarctic temperature over CO2 concentration during previous glacial terminations by 800 ± 600 years (Caillon et al., 2003; Monnin et al., 2001; Appendix 5.3). Recently an improved estimate of gas ice-ice age differences in different ensembles of Antarctic ice cores suggested that earlier studies likely overestimated this lead. For the last glacial termination the most recent estimate is indistinguishable from zero (Parrenin et al., submitted; Pedro et al., 2012).**Large-scale reconstuctions of Southern Hemisphere climate change (Shakun et al., 2012) for the last glacial termination document a lead of Southern Hemisphere averaged temperature over Northern Hemisphere temperature. This lead can be explained by the bipolar thermal seesaw concept (Stocker and Johnsen, 2003) (see also Section 5.7) related to changes in the interhemispheric ocean heat transport caused by weakening of the AMOC during glacial termination (Ganopolski and Roche, 2009). Southern Hemisphere warming prior to Northern Hemisphere warming can also be explained by the fast sea ice response to changes in austral spring insolation (Stott et al., 2007; Timmermann et al., 2009). According to these mechanisms, southern temperature lead over Northern Hemisphere neither contradicts the northern hemisphere forcing of deglacial ice volume changes (high confidence), nor the important role of CO2 in generating glacial-interglacial temperature variations due to the greenhouse effect.* |  |
| ([Shakun et al., 2012](#_ENREF_724)) | Termination I  | EDC age scale synchronized to GICC05+([Lemieux-Dudon et al., 2010](#_ENREF_458)) | NH : stack of 50 records including 2 Greenland ice coresSH : stack of 30 records incl. 4 ice cores (Vostok, EDML, EDC, Dome F)\* on their original age scale | Lag correlation (20 to 10 ka) using Monte-Carlo statistics | SH : 620 ± 660 years NH :–720 ± 660 yearsGlobal : –460 ± 340 years | Uncertainties in the original age scales of each record: e.g., reservoir ages of marine sediments, radiocarbon calibration (intCal04), Antarctic gas / ice chronologyAssumption that timescale errors (e.g. from reservoir ages or ice core chronologies) are independent from each other. This could lead to higher-than-reported lag estimation uncertainties.Similar limitations as in earlier studies for Antarctic temperature lead on CO2Non stability of the phase lags : global temperature leads CO2 at the onset of deglacial warming |
| ([Pedro et al., 2012](#_ENREF_630)) |  | Siple Dome and Byrd, synchronized to GICC05+ age scale | d18O composite (Law Dome, Siple Dome, Byrd, EDML and TALDICE\* ice cores) synchronized to GICC05+ using firn modelling ([Pedro et al., 2011](#_ENREF_629)) | Lag correlation (9–21 ka) and derivative lag correlation | Antarctica:-60 to 380 years | Uncertainty on gas – ice age difference in high accumulation sites (<300 years) and on synchronization methods to GICC05Data resolution (145 year for Byrd CO2, 266 year for Siple CO2). The CO2 data were resampled at 20 yr resolution prior to the lag analysis, which may lead to an underestimation of the statistical error in the lag determinationTemperature versus other (e.g., elevation, moisture origin) signals in coastal ice core d18OCorrelation method sensitive to minima, maxima and inflexion points |
| ([Parrenin et al., submitted](#_ENREF_622)) |  | EDC, new gas age scale produced from the modified EDC3 ice age scale using lock-in depth derived from d15N of N2 and adjusted to be consistent with GICC05+ gas age scale. Processes affecting the gas lock-in depth such as impurities are implicitly taken into account when using d15N (no use of firn models). | Stack temperature profile derived from water isotopes from EDC\*, Vostok\*, Dome Fuji\*, TALDICE\* and EDML\* synchronized to a modified EDC3 ice age scale | Monte-Carlo algorithm at linear break points | Antarctica:Warming onset: –10 ± 160 yearsBølling onset:260 ± 130 yearsYounger Dryas onset:–60 ± 120 yearsHolocene onset:500 ± 90 years | Accuracy, resolution and interpolation of d15N of N2; assumption of no firn convective zone at EDC under glacial conditions. Data resolution and noise (e.g., precipitation intermittency biases in stable isotope records) |

Notes:

\* Names of different Antarctic ice cores (Byrd, Taylor Dome, Vostok, Siple Dome, Law Dome, TALDICE, Dome Fuji, EDML, EDC), with different locations, surface climate and firnification conditions. For the most inland sites (Vostok, EDC, Dome Fuji), at a given ice core depth, gas ages are lower than ice ages by 1500–2000 years (interglacial conditions) and 5000–5500 years (glacial conditions) while this gas age-ice age difference is lower (400–800. years) for coastal, higher accumulation sites (Byrd, Law Dome, Siple Dome).

+GICC05: Greenland Ice Core Chronology 2005, based on annual layer counting in Greenland (NGRIP, GRIP and DYE3 ice cores) ([Rasmussen et al., 2006](#_ENREF_655)), back to 60 ka([Svensson et al., 2008](#_ENREF_788)). The synchronism between rapid shifts in Greenland climate and in atmospheric CH4 variations allows to transfer GICC05 to Greenland and then to Antarctic CH4 variations ([Blunier et al., 2007](#_ENREF_82)).

Additional point: CO2-Antarctic temperature phase during AIM events

Studies on CO2 phasing relative to CH4 during Dansgaard Oeschger event onsets ([Ahn and Brook, 2008](#_ENREF_8); Bereiter et al., 2012)(Ahn and Brook, GRL, 2012) suggest a lag of maximum CO2 concentration relative to the Antarctic Isotope Maxima (AIM) 19, 20, 21, 23 and 24 by 260±220 yr during MIS5 and 670–870 yr±360 yr relative to AIM 12, 14, 17 during MIS3 (Bereiter et al., 2012). Accordingly, the lag is dependent on the climate state. A lag is not discernable for shorter AIM. This study avoids the ice age/gas age difference problem, but relies on the bipolar seesaw concept, i.e., it assumes that maximum Antarctic temperatures are coincident to the onset of DO events and the concurrent CH4 increase.