Supporting Online Material

Methods Summary

We analyzed 390 ice samples from 175 depths, including data from 36 depths from a previous study (*S1*). For most depths we measured replicate samples within a depth range of 10 cm and we report the mean depths of the replicates (Table S1). Replicate measurements were usually done on different days and averages were used for the data plots. Single measurements were done for two depths due to limited sample size. The standard deviation of the mean for 2~5 replicate ice samples from the same depth averaged 1.5 ppm except for 4 depths (See Table S1). Data for these depths were rejected because the standard deviations of the means were greater than 12 ppm, we believe because of poor quality of the samples. The data are archived at National Snow and Ice Date Center (http://nsidc.org/) and also in Table S1. Each ice sample weighed about 13 g after trimming >1 cm from all surfaces. The detailed methods used will be reported elsewhere (*S2*). Briefly, samples were placed in a double-walled stainless steel vacuum chamber at -35˚C, cooled using cold ethanol circulation between the walls, and then crushed with steel pins, affixed to a pneumatically actuated linear motion feedthrough. Air liberated from the ice was dried in a cold stainless steel coil at -85˚C and then trapped in ~6 cm^3 stainless steel sample tubes at -262°C. After warming the trapped air to room temperature, and expanding to a 5 cm^3 stainless steel sample loop, the CO_2 mixing ratio was measured with an Agilent 6890N Gas Chromatograph (GC) with flame ionization detector, with nickel catalyst conversion of CO_2 to CH_4 prior to measurement. The pressure in the loop was measured with an MKS Baratron capacitance manometer (accuracy better than 0.15%). CO_2 peak area was divided by the sample pressure and the results quantified with similar measurements of standard air. Daily calibration curves used several measurements of standard air with 197.54 ppm CO_2 (WMO scale). Each air sample was measured two times. Daily corrections for the dry extraction and GC analysis were done using several standard airs (197.54 ppm) that were introduced over the ice samples and transported to sample tubes mimicking the procedure of the air samples from ice. To test the linearity between CO_2 peak area and CO_2 mixing ratio, we analyzed a different standard air with 291.15 ppm CO_2. The difference between assigned concentration and measurements was 0.2-1 ppm on average over the course of two years.

CH_4 concentration was measured for 36 ice samples to better constrain the time age of the abrupt warming in Greenland and CO_2. We used high precision wet-extraction methods (*S3*). One of the CH_4 results from the depth of 2099.31-2099.42 m was rejected due to poor quality of the ice, based on CO_2 results from two ice pieces from the same depth that differed by 53.7 ppm.

We used the Byrd ice core ages of ref. *S4* after slight adjustment, which was needed for consistency with the synchronous rapid rise of CH_4 relative to abrupt warming at Dangaard-Oeschger (DO) events 4, 8, 12, 14, 17, 19, 20 and 21 (*S3, S5, S6*), consistent with our previous approach (*S1*). This permits precise timing of Byrd CO_2 relative to abrupt warming in Greenland via Byrd CH_4 as shown in Fig. 2. We determined Byrd gas-age tie points on a Greenland (GISP2) ice core time scale (*S4*) by matching of rapid rise of Byrd CH_4 to the abrupt Greenland warming events. The Byrd gas age difference

between the new and previous (*S4*) ages was linearly interpolated for the ages between the DO events. Byrd CO_2 ages older than 88 ka are determined by extrapolation of the depth-age scale for 82~88 ka. The Byrd $\delta^{18}O_{ice}$ ages are also adjusted to keep the same gas-ice age difference used in ref. *S4*.

We found slight age discrepancy between the Greenland $\delta^{18}O_{ice}$ ages and GISP2 CH_4 in ref. *S4* at the abrupt warming in the DO events. This is due to inaccuracy in gas-ice age difference model used for GISP2 ice core (*S4*). To correct for this we synchronized the GISP2 CH_4 ages to the abrupt warming at DO events 4, 8, 12, 14, 17, 19, 20 and 21.

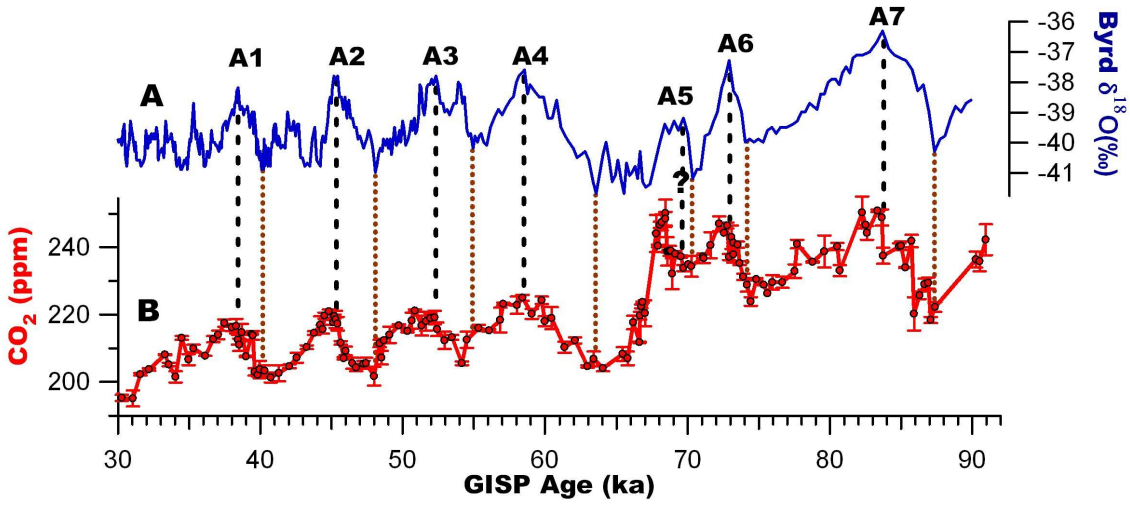

Figure S1. Timing of atmospheric CO_2 and Antarctic temperature. (**A**) Byrd Station, Antarctica temperature proxy, $\delta^{18}O_{ice}$ (*S4*); A1~A6 are Antarctic warming events (*S4*). (**B**) Atmospheric CO_2 from Byrd ice core (*this study, S1*). Black and brown dotted lines indicate the timing of Byrd temperature maxima and minima, respectively. The uncertainty in gas age – ice age difference is conservatively ~125 years (*S4*). The Byrd temperature maximum at A5 seems to occur exceptionally earlier than the abrupt warming in Greenland at Dansgaard-Oeschger (D-O) event 19 (or CO_2 local maximum; see Fig. 1).

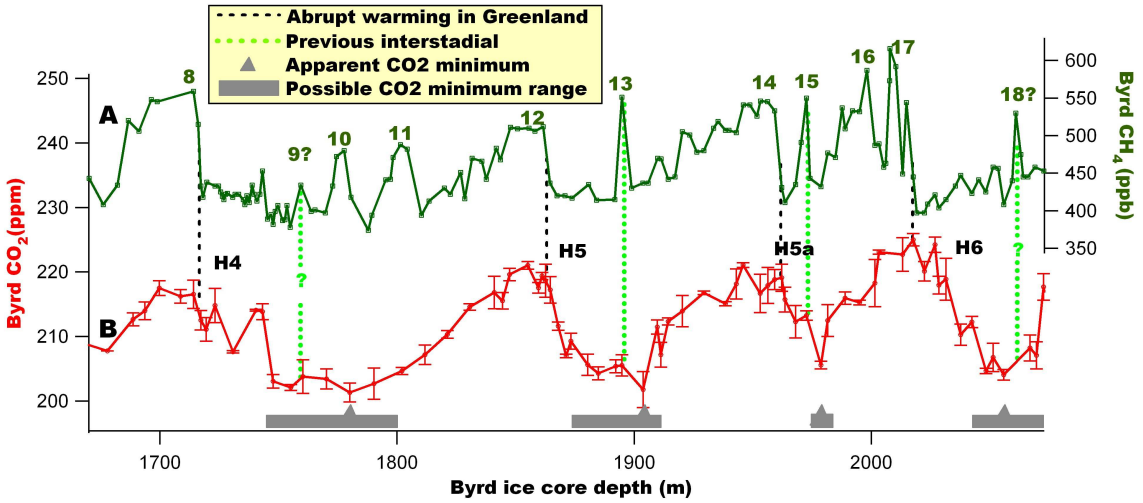

Figure S2. Timing of the CO_2 rise and abrupt warming in Greenland. (**A**) and (**B**) are CH_4 and CO_2 from Byrd ice core, respectively on the Byrd ice core depth domain. The green numbers are Dansgaard-Oeschger (DO) events. Black and green dotted lines indicate abrupt warming in Greenland associated with CO_2 maxima and the next previous intestadials, respectively. The timing of the abrupt warming in Greenland is defined by rapid increase of CH_4 because the CH_4 rise and abrupt warming are essentially synchronous (*S3, S5, S6*). Gray triangles are CO_2 minima with age uncertainties given by horizontal gray bars. Relative ages of Heinrich events (H4~H6) are constrained between two D-O warming events (black and green dotted lines).

Table S1.The last glacial atmospheric CO_2 from the Byrd, Antarctic ice core.

mean depth (m)	Blunier-01 age† (ka BP)	Ahn-08age‡ (ka BP)	mean CO_2* (ppm)	#of replicates	uncertainty** (ppm)
1315.91	19.460	19.286	194.36	2	0.97
1332.34	20.061	19.887	191.14	2	0.19
1334.20	20.152	19.978	192.54	2	0.09
1346.28	20.578	20.404	204.27	2	0.48
1353.02	20.759	20.585	195.37	2	0.02
1363.17	21.065	20.891	197.12	2	1.04
1381.14	21.731	21.557	195.81	2	1.66
1401.95	22.399	22.225	199.75	3	4.49
1410.30	22.729	22.555	194.62	2	0.31
1420.27	23.530	23.356	195.97	2	1.88
1430.78	24.824	24.650	194.74	2	1.94
1441.45	26.002	25.828	189.76	2	1.30
1460.20	26.711	26.537	192.21	2	1.28
1470.77	27.148	26.974	184.40	2	1.42
1480.48	27.619	27.445	188.07	2	1.48
1490.87	27.989	27.815	201.96	2	0.46
1496.52	28.135	27.961	204.98	2	1.71
1503.54	28.395	28.221	205.91	3	2.43
1512.46	28.660	28.486	207.48	2	1.73
1523.46	29.147	28.973	205.54	2	0.40
1533.76	29.568	29.396	201.49	2	1.84
1543.63	30.013	29.843	197.51	2	3.18
1552.76	30.412	30.245	195.36	2	0.89
1573.34	31.216	31.053	195.09	3	2.37
1581.93	31.738	31.577	202.29	2	0.38
1594.06	32.328	32.170	203.67	2	0.40
1615.15	33.450	33.297	208.11	2	0.11
1620.38	33.692	33.541	205.25	2	0.53
1631.11	34.183	34.033	201.53	2	1.67
1640.90	34.630	34.484	213.08	2	0.47
1650.56	35.097	34.953	206.62	2	1.72
1658.96	35.428	35.286	209.93	2	1.10
1677.79	36.249	36.111	207.76	2	0.00
1688.63	36.840	36.704	212.63	2	0.99
1693.68	37.167	37.033	213.98	2	1.37
1699.73	37.621	37.488	217.48	2	1.16
1708.70	38.122	37.992	216.21	2	1.03
1714.20	38.428	38.298	216.52	2	2.21
1717.20	38.545	38.415	212.50	2	1.51
1719.47	38.655	38.520	211.09	2	1.83
1723.22	38.850	38.708	214.78	2	2.64
1730.78	39.163	39.006	207.63	2	0.18
1740.51	39.539	39.364	214.06	2	0.14
1743.27	39.651	39.470	213.84	2	1.23
1747.69	39.811	39.621	203.03	2	1.03

1755.15	**40.038**	**39.834**	**202.11**	**2**	**0.45**
1760.29	**40.172**	**39.958**	**203.78**	**2**	**2.59**
1770.24	**40.544**	**40.311**	**203.40**	**2**	**1.56**
1779.99	**40.966**	**40.714**	**201.30**	**2**	**1.46**
1790.29	**41.585**	**41.313**	**202.69**	**2**	**2.43**
1802.03	**42.320**	**42.025**	**204.64**	**2**	**0.56**
1811.74	**42.851**	**42.537**	**207.18**	**2**	**1.53**
1821.19	**43.591**	**43.259**	**210.31**	**2**	**0.60**
1830.63	**44.137**	**43.786**	**214.57**	**2**	**0.51**
1840.93	**44.598**	**44.228**	**216.83**	**3**	**2.50**
1844.41	**44.760**	**44.383**	**215.54**	**2**	**1.26**
1847.46	**44.899**	**44.516**	**219.62**	**2**	**0.94**
1855.09	**45.229**	**44.831**	**221.00**	**2**	**0.60**
1859.57	**45.526**	**45.120**	**217.56**	**2**	**0.82**
1861.17	**45.633**	**45.223**	**219.39**	**2**	**0.53**
1862.59	**45.725**	**45.313**	**218.62**	**2**	**2.56**
1864.56	**45.852**	**45.436**	**217.23**	**2**	**2.04**
1867.90	**46.075**	**45.654**	**211.58**	**2**	**0.64**
1871.26	**46.298**	**45.872**	**206.99**	**2**	**0.29**
1873.26	**46.431**	**46.002**	**209.25**	**2**	**1.24**
1880.36	**46.889**	**46.448**	**205.61**	**2**	**1.63**
1884.88	**47.187**	**46.740**	**204.28**	**2**	**1.02**
1892.21	**47.687**	**47.228**	**205.36**	**2**	**1.00**
1894.80	**47.865**	**47.402**	**205.51**	**2**	**1.63**
1903.72	**48.450**	**47.973**	**201.79**	**2**	**2.79**
1909.75	**48.874**	**48.388**	**211.47**	**4**	**1.09**
1911.29	**48.984**	**48.495**	**207.15**	**4**	**1.93**
1914.31	**49.191**	**48.697**	**212.35**	**2**	**0.57**
1920.25	**49.596**	**49.092**	**213.91**	**4**	**2.43**
1929.40	**50.230**	**49.712**	**216.76**	**2**	**0.28**
1938.50	**50.857**	**50.325**	**215.07**	**2**	**0.30**
1943.09	**51.175**	**50.636**	**218.12**	**5**	**2.35**
1945.98	**51.394**	**50.850**	**221.08**	**3**	**0.35**
1953.17	**51.894**	**51.339**	**216.69**	**4**	**2.96**
1956.34	**52.193**	**51.633**	**217.93**	**2**	**2.81**
1959.23	**52.505**	**51.941**	**218.83**	**2**	**1.55**
1962.18	**52.812**	**52.259**	**219.08**	**4**	**2.10**
1963.62	**52.963**	**52.423**	**215.70**	**2**	**1.94**
1968.07	**53.422**	**52.923**	**212.28**	**2**	**2.52**
1972.66	**53.926**	**53.470**	**213.25**	**2**	**0.74**
1978.74	**54.577**	**54.177**	**205.57**	**2**	**0.58**
1981.61	**54.859**	**54.486**	**212.48**	**4**	**2.46**
1988.98	**55.644**	**55.339**	**215.94**	**2**	**0.96**
1995.01	**56.317**	**56.068**	**215.25**	**2**	**0.38**
2001.46	**57.022**	**56.833**	**218.27**	**2**	**3.65**
2003.23	**57.222**	**57.049**	**223.09**	**2**	**0.30**
2013.21	**58.096**	**58.016**	**222.69**	**3**	**2.59**
2017.71	**58.467**	**58.421**	**224.99**	**2**	**0.97**
2022.42	**59.125**	**59.072**	**220.11**	**2**	**1.49**

2026.90	**59.806**	**59.746**	**224.21**	**3**	**1.18**
2028.47	**60.039**	**59.976**	**217.96**	**2**	**1.39**
2031.50	**60.526**	**60.459**	**218.85**	**2**	**3.26**
2037.68	**61.451**	**61.374**	**210.28**	**2**	**1.65**
2042.43	**62.186**	**62.102**	**212.26**	**2**	**0.85**
2048.32	**63.079**	**62.986**	**204.65**	**2**	**0.39**
2051.40	**63.526**	**63.429**	**206.76**	**2**	**2.20**
2055.90	**64.152**	**64.048**	**204.06**	**2**	**0.84**
2066.85	**65.565**	**65.444**	**208.22**	**2**	**2.01**
2069.64	**65.938**	**65.813**	**207.08**	**2**	**2.09**
2072.65	**66.333**	**66.204**	**217.67**	**2**	**2.07**
2075.59	**66.779**	**66.644**	**211.79**	**2**	**0.25**
2075.75	**66.818**	**66.683**	**219.64**	**3**	**1.17**
2076.02	**66.890**	**66.755**	**222.40**	**2**	**0.47**
2076.43	**66.997**	**66.861**	**223.63**	**2**	**0.27**
2077.02	**67.151**	**67.014**	**220.43**	**2**	**3.79**
2080.12	**67.959**	**67.818**	**244.03**	**2**	**5.52**
2080.61	**68.086**	**67.944**	**240.28**	**2**	**0.28**
2081.10	**68.213**	**68.071**	**246.47**	**2**	**0.93**
2081.59	**68.340**	**68.197**	**247.22**	**2**	**2.42**
2082.54	**68.582**	**68.435**	**249.96**	**3**	**3.97**
2082.64	**68.608**	**68.460**	**248.32**	**2**	**2.08**
2083.09	**68.721**	**68.571**	**238.70**	**4**	**4.19**
2083.54	**68.837**	**68.685**	**238.61**	**2**	**0.33**
2083.82	**68.908**	**68.755**	**238.78**	**2**	**1.42**
2084.14	**68.989**	**68.834**	**238.84**	**2**	**0.02**
2084.52	**69.086**	**68.929**	**231.99**	**3**	**4.59**
2085.44	**69.314**	**69.149**	**237.98**	**2**	**0.97**
2087.02	**69.706**	**69.527**	**237.26**	**3**	**0.40**
2087.75	**69.886**	**69.700**	**233.74**	**2**	**0.93**
2089.24	**70.246**	**70.048**	**234.85**	**2**	**0.19**
2090.16	**70.469**	**70.262**	**234.35**	**2**	**3.03**
2093.50	**71.337**	**71.101**	**237.17**	**2**	**0.49**
2093.71	**71.395**	**71.158**	**236.62**	**3**	**1.43**
2095.46	**71.875**	**71.622**	**240.58**	**2**	**3.79**
2097.91	**72.515**	**72.240**	**246.81**	**3**	**2.23**
2099.29	**72.885**	**72.598**	**244.19**	**1**	**N/A**
2100.05	**73.073**	**72.783**	**246.30**	**2**	**0.85**
2100.69	**73.230**	**72.937**	**236.93**	**2**	**0.88**
2101.27	**73.369**	**73.079**	**242.80**	**2**	**3.41**
2101.80	**73.492**	**73.209**	**241.26**	**2**	**0.14**
2101.97	**73.531**	**73.251**	**237.79**	**4**	**2.31**
2103.15	**73.805**	**73.542**	**240.63**	**3**	**0.85**
2103.60	**73.909**	**73.653**	**235.11**	**2**	**0.58**
2104.68	**74.184**	**73.944**	**231.11**	**2**	**0.89**
2105.52	**74.410**	**74.182**	**228.82**	**2**	**2.08**
2106.32	**74.656**	**74.440**	**223.79**	**2**	**1.22**
2107.63	**75.055**	**74.858**	**230.49**	**2**	**0.28**
2109.17	**75.518**	**75.343**	**228.85**	**2**	**0.25**

2110.06	**75.783**	**75.621**	**226.25**	**1**	**N/A**
2111.20	**76.120**	**75.975**	**229.45**	**2**	**2.14**
2113.37	**76.765**	**76.651**	**229.56**	**2**	**1.56**
2116.08	**77.586**	**77.513**	**232.82**	**3**	**1.97**
2116.73	**77.785**	**77.721**	**240.83**	**3**	**1.24**
2120.16	**78.809**	**78.795**	**235.51**	**2**	**0.11**
2122.78	**79.604**	**79.628**	**238.65**	**2**	**4.76**
2125.62	**80.449**	**80.515**	**240.08**	**3**	**1.03**
2126.13	**80.635**	**80.708**	**233.00**	**3**	**1.69**
2130.20	**82.116**	**82.248**	**250.22**	**2**	**4.72**
2130.67	**82.399**	**82.539**	**246.47**	**2**	**0.04**
2130.78	**82.466**	**82.607**	**244.08**	**2**	**2.06**
2131.99	**83.195**	**83.354**	**250.70**	**2**	**0.33**
2132.50	**83.503**	**83.669**	**248.75**	**2**	**2.37**
2132.66	**83.600**	**83.766**	**237.44**	**2**	**2.38**
2134.46	**84.687**	**84.855**	**240.19**	**2**	**1.00**
2134.70	**84.828**	**84.996**	**240.36**	**2**	**1.19**
2135.22	**85.133**	**85.301**	**233.84**	**2**	**0.20**
2135.97	**85.572**	**85.740**	**241.73**	**2**	**1.76**
2136.25	**85.734**	**85.902**	**220.23**	**2**	**5.01**
2136.93	**86.127**	**86.295**	**225.72**	**2**	**1.15**
2137.57	**86.498**	**86.666**	**228.99**	**3**	**1.73**
2138.02	**86.764**	**86.932**	**229.26**	**2**	**1.58**
2138.32	**86.942**	**87.110**	**218.37**	**2**	**0.94**
2138.79	**87.221**	**87.389**	**222.25**	**2**	**1.43**
2143.57	**90.075**	**90.266**	**236.19**	**5**	**2.31**
2144.02	**90.342**	**90.534**	**235.65**	**2**	**2.86**
2144.72	**90.759**	**90.953**	**242.07**	**3**	**4.54**

[†]Depth-age scale from ref. S4. BP = Before 1950

[‡]Depth-age scale for this study

*CO_2 data of the depths of 1894.8 ~ 2055.9 m are from ref. S1.

**The uncertainty is estimated from the standard deviation of the mean for 2~5 ice samples

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