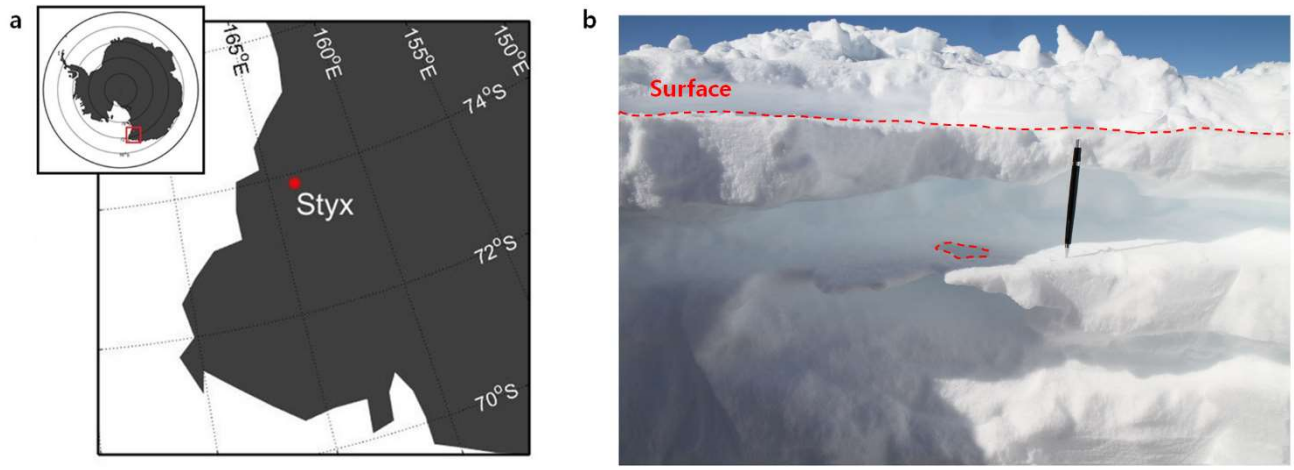

Figure 1. (a) Location map of study site, Styx Glacier, Antarctica and (b) a photo of surface snow density layers. The thickness of the snow density layers varies horizontally. The top boundaries of the high-density layers are sharp (horizontal red-dashed line). A hole on a high-density layer surface is indicated by a red-dashed circle. The length of the black sharp pencil in (b) is 14.3 cm.

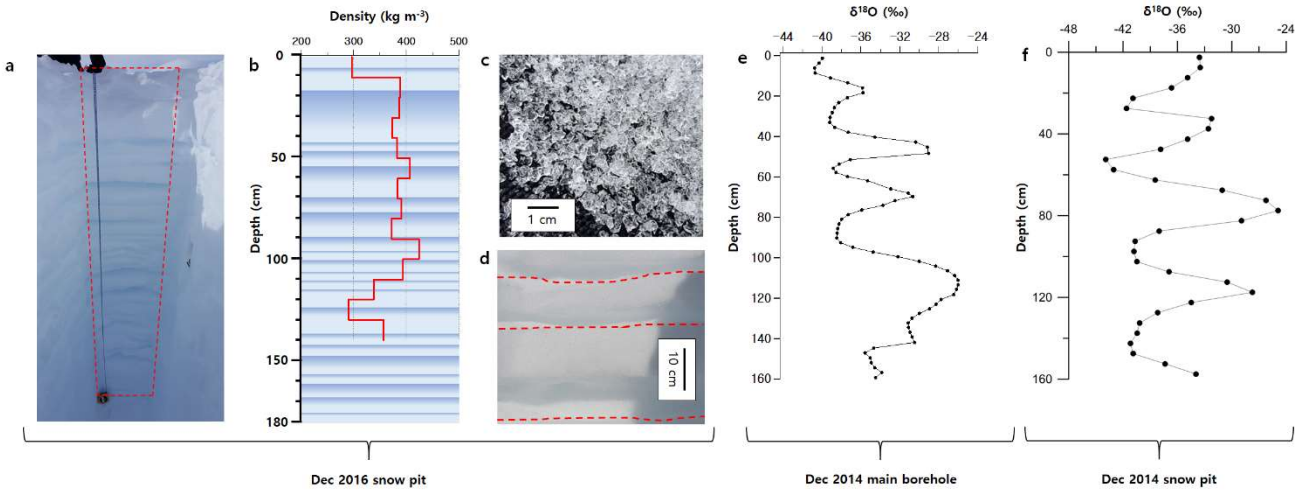

Figure 2. Snow-pit photos at Styx Glacier. (a) The snow pit with dimensions of 280 × 65 × 220 cm (length × width × height). (b) The illustration of qualitatively defined hard (dark blue) and soft (pale blue) layers observed in the top 180-cm-depth interval. Progressive blue color changes indicate a gradual density decrease with depth. Red line is a 10-cm-resolution density profile. (c) Coarse grains observed in a soft layer. (d) Enlarged snow layers. Dashed red lines indicate top boundaries of fine-grained hard layers. (e) and (f) Stable isotope ratio ($\delta^{18}O$) of snow profiles at the main core and a snow pit 100 m away from the main ice core borehole, respectively.

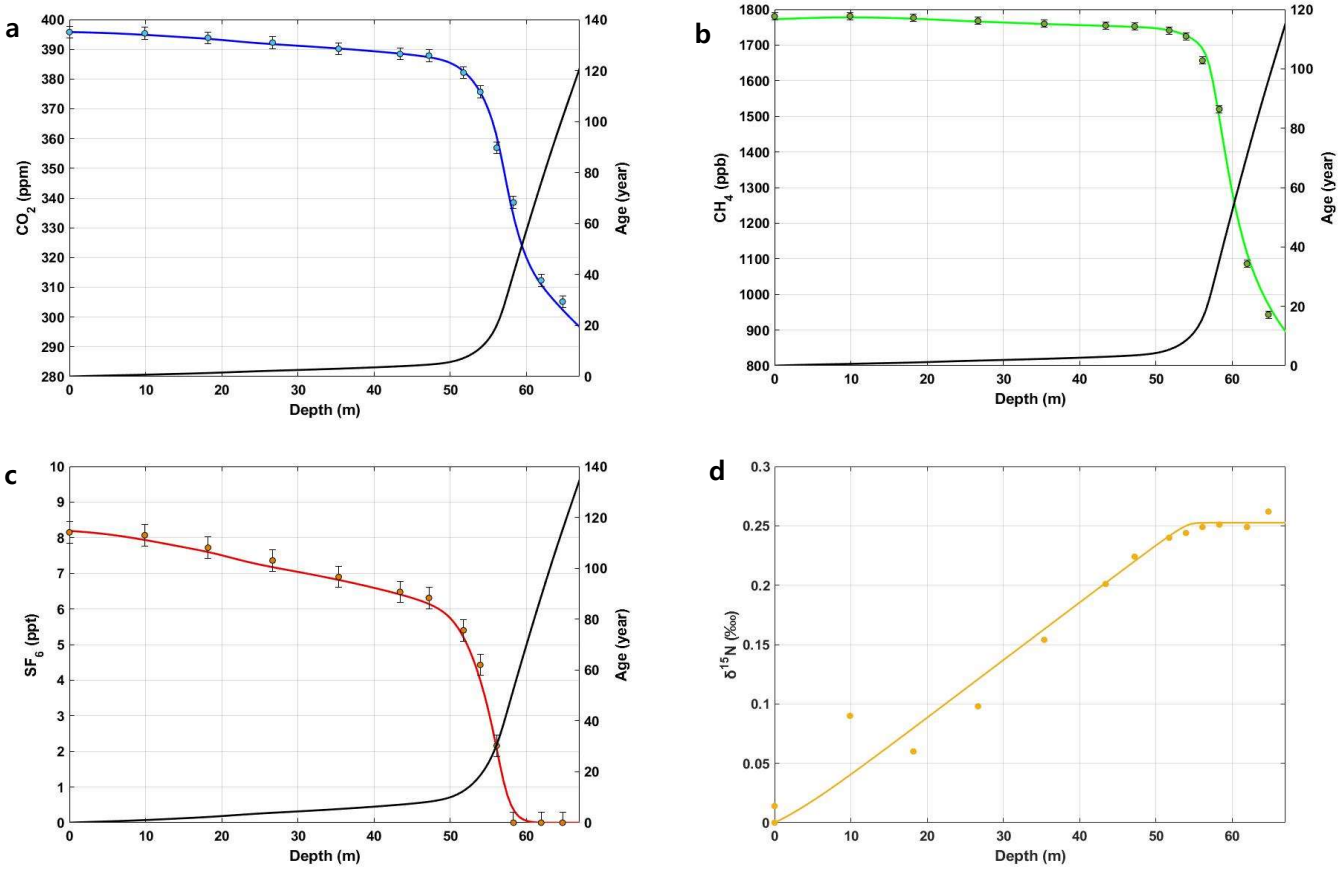

Figure 3. CO_2, CH_4, SF_6 mole fractions and $\delta^{15}N$ of N_2 measurements (circles), and model results (solid line) for the Styx firn air (air in open porosity). Black lines are modeled ages for the gas species.

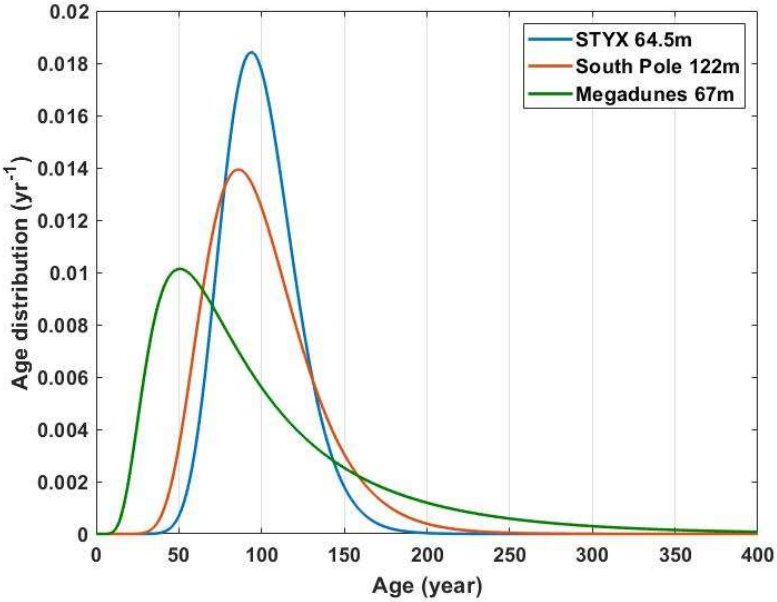

Figure 4. Comparison of model-simulated CO_2 age distributions at Styx (this study), South Pole (Battle et al., 1996), and Megadunes (Severinghaus et al., 2010).

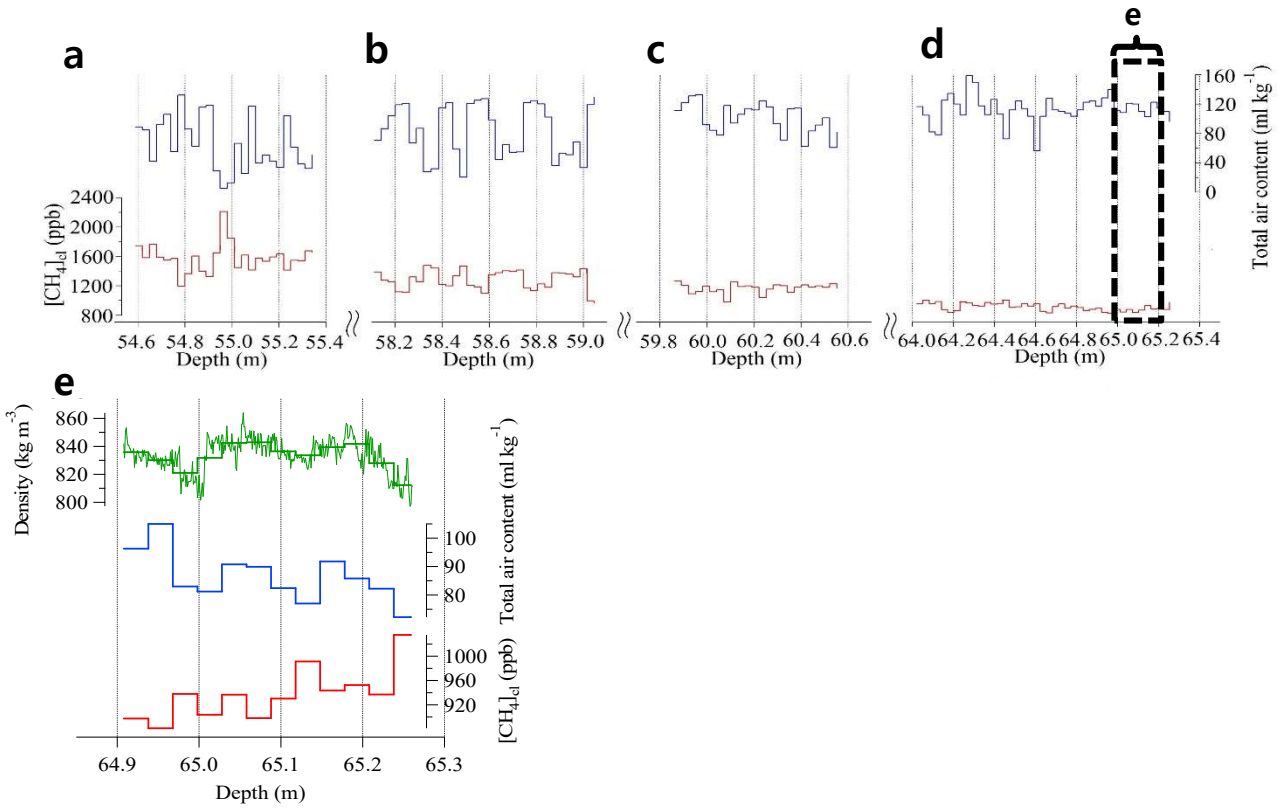

Figure 5. (a-d) CH_4 mole fraction in closed pores ($[CH_4]_{cl}$) (red line) and total air content (air volume per ice weight) (blue line) in the lock-in zone of Styx Glacier. (e) Comparison of density with $[CH_4]_{cl}$ and total air content near z_{COD}. A small dashed-box in (d) indicates the depth interval of Fig. 5e.

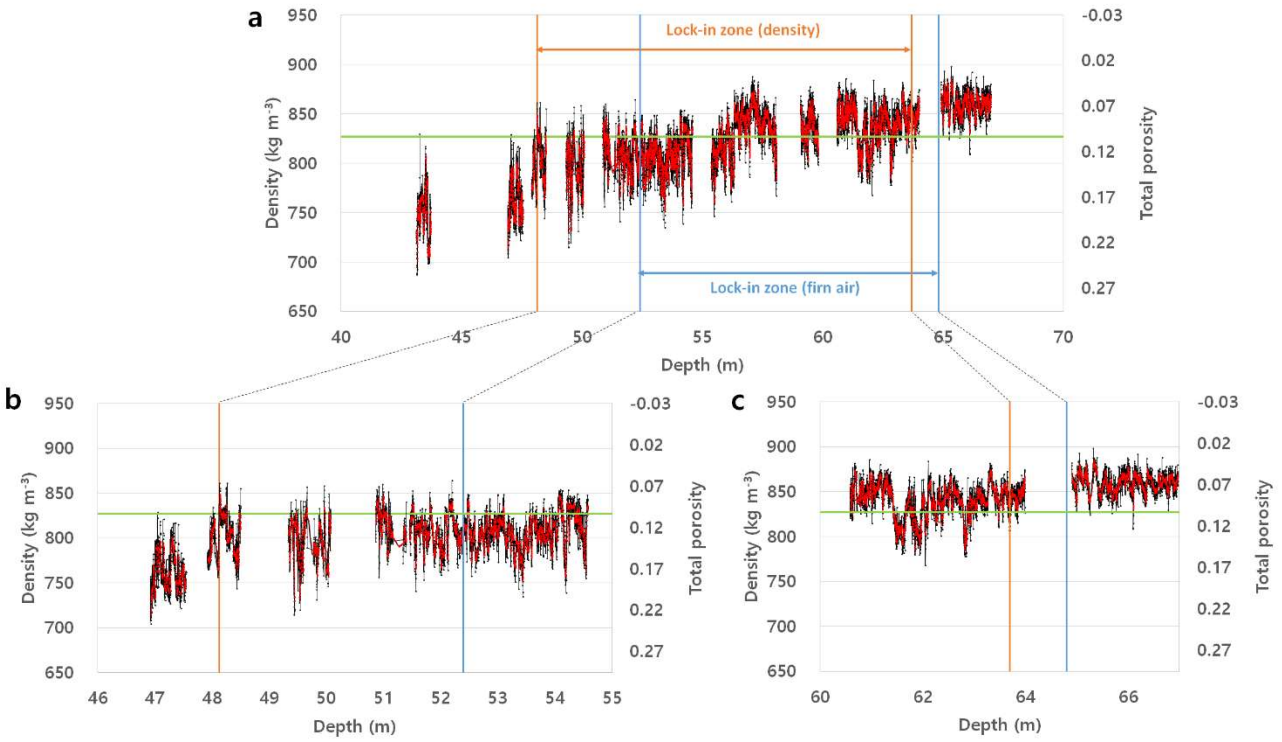

Figure 6. X-ray high-resolution density data obtained from the lock-in zone. (b) and (c) are enlarged portion of (a). Black lines show individual density data, while the red lines are 1-cm running means. Blue and orange lines represent the boundaries of the LIZ estimated from the gas compositions (between two vertical blue lines) and the critical porosity thresholds (between two orange vertical lines), respectively (see section 3.4).

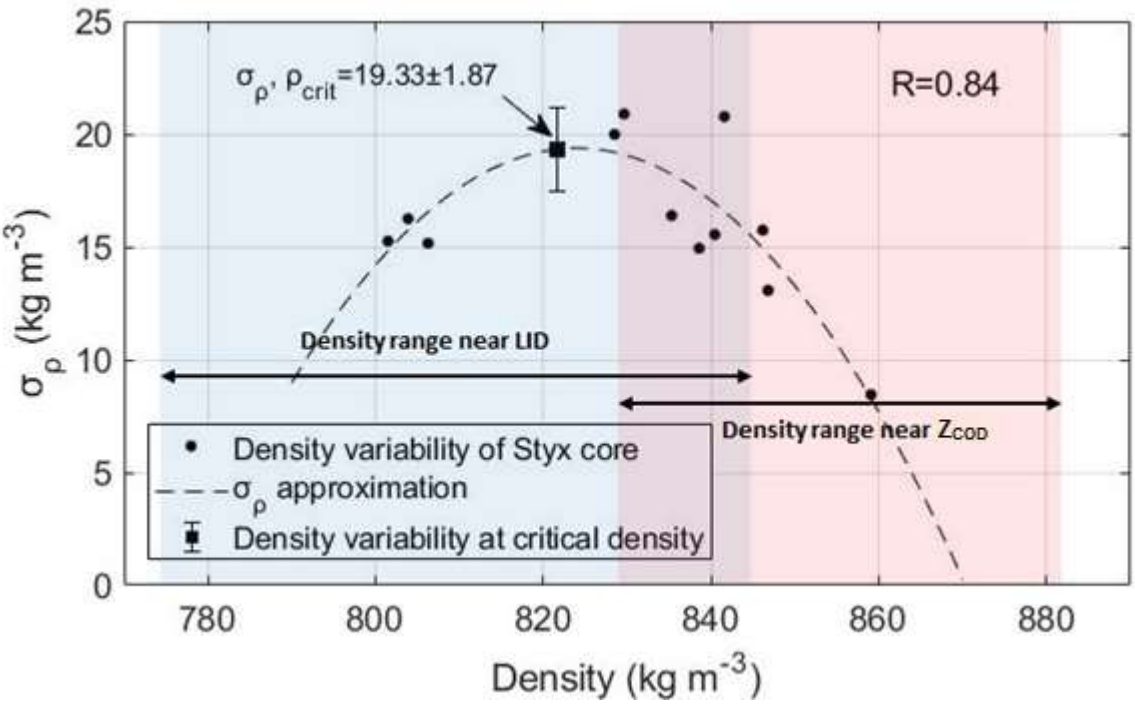

Figure 7. Density variability calculated from 1000 depth points and their average density. The standard deviation at the critical density (821.68 kg m^{-3}) calculated from the approximate second order polynomial (R = 0.84) is 19.33 ± 1.87 kg m^{-3}. The blue and red areas are the density ranges near the LID (52.38 - 52.48 m) and the z_{COD} (64.91 - 65.01 m), respectively.

Table 1. Glaciological characteristics of Styx Glacier and other firn air sampling sites.

Site	T (°C)	A (cm ice yr^{-1})	Effective CO_2 age (year)	LID (m)	COD (m)	LIZ thickness (m)	References
Styx	-31.7	10	93	52.4	64.8	12.4	This study, Yang et al. (2018)
Megadunes	-49	~0	129	64.5	68.5	4	Severinghaus et al. (2010)
South Pole	-51.0	8	91	115	125	10	Severinghaus et al. (2001)
Siple Dome	-25.4	13	59	49	58	9	Severinghaus et al. (2001)
Dome C	-54.5	2.7	33	97	100	3	Landais et al. (2006)
WAIS Divide	-31	22	39	~67	76.5	9.5	Battle et al. (2011)
NEEM	-28.9	22	50	63	78	15	Buizert et al. (2012a)
NGRIP	-31.1	19	45	67.5	78	11.5	Kawamura et al. (2006)
Summit	-32	23	26	70	80.8	10.8	Witrant et al. (2012)
DE-08	-19	120	13	71.8	88.5	16.8	Etheridge et al. (1996)

57 **Table 2. Comparison of standard deviation of density (σ_ρ) at critical density (ρ_{crit}). For data from all other**

58 **sites, except the Styx, refer to Hörhold et al. (2011).**

59

Campaign/Region	Core name	ρ_{crit} (kg m^{-3})	σ_ρ, ρ_{crit} (kg m^{-3})	T (°C)	A(cm ice yr^{-1})
Styx	Styx	821.68	19.33±1.87	-31.7	10
NGT	B16	819.27	12.26	-27	15.5
NGT	B18	820.81	12.81	-30	11.3
NGT	B21	820.81	12.91	-30	11.8
NGT	B26	820.85	13.23	-30.6	20
NGT	B29	821.32	10.50	-31.6	16.7
Berkner Island	B25	819.16	14.57	-27	15
DML	B31	827.00	10.27	-42	6.9
DML	B32	827.00	11.28	-42	6.7
DML	B36/37	827.50	8.12	-44.6	7.3
Pre-IPICS	B38	815.00	16.59	-18.1	136
Pre-IPICS	B39	814.91	17.11	-17.9	84
Pre-IPICS	DML95	815.51	13.42	-19.2	60
Pre-IPICS	DML97	816.07	10.03	-20.4	53
Dome C	EDC2	832.02	4.59	-53	2.7
WAIS Divide	WDC06A	820.81	10.35	-31	22

60

61

Supplement Materials

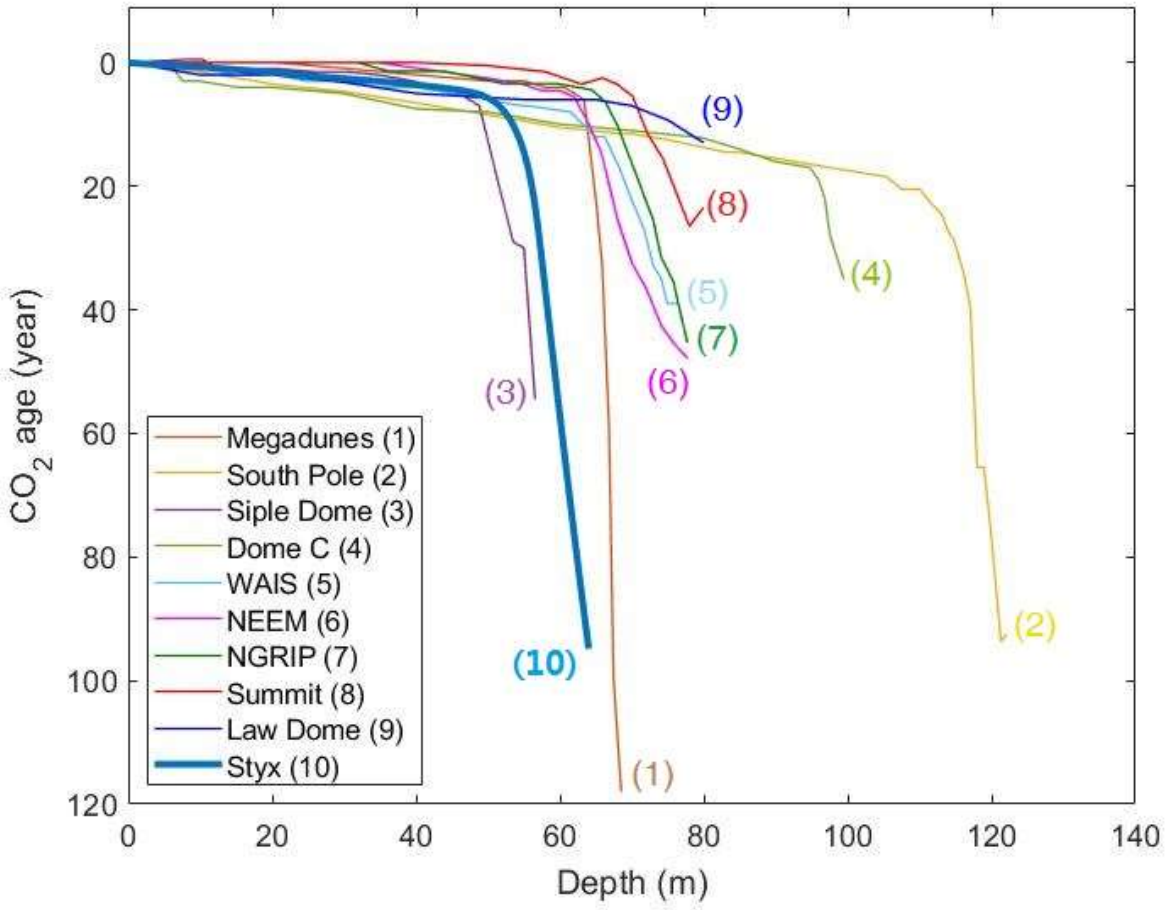

Figure S1. Comparison of CO_2 ages at several firn air sampling sites in Antarctica and Greenland. Old firn air (>55 years) is reported only in inland sites, where temperatures and snow accumulation rates are relatively low. However, 93-year old firn air was observed at Styx Glacier, where the coast is near and snow accumulation rates are high. References: (1) Severinghaus et al. (2010); (2) Battle et al. (1996); (3) Severinghaus and Battle. (2006); (4) Landis et al. (2006); (5) Battle et al. (2011); (6) Buizert et al. (2012a); (7) Kawamura et al. (2006); (8) Witrant et al. (2012); (9) Etheridge et al. (1996); (10) this study.

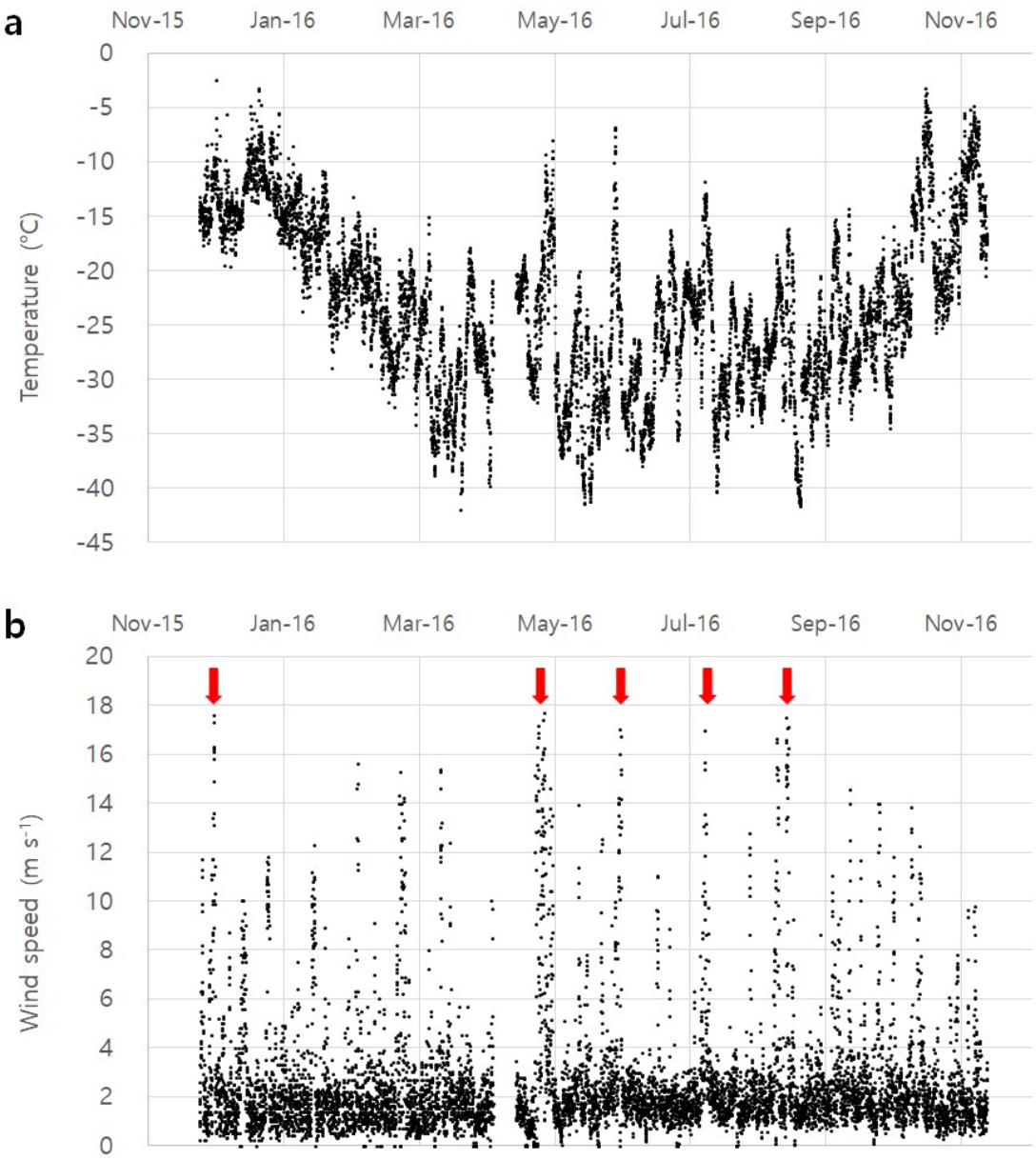

Figure S2. (a) Surface air temperature and (b) wind speed data from AWS (Automatic Weather System) at Styx Glacier during December 2015 to December 2016. Red arrows indicate blizzard events.