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Supplement of

Australian bushfire emissions result in enhanced polar stratospheric clouds

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Supplementary

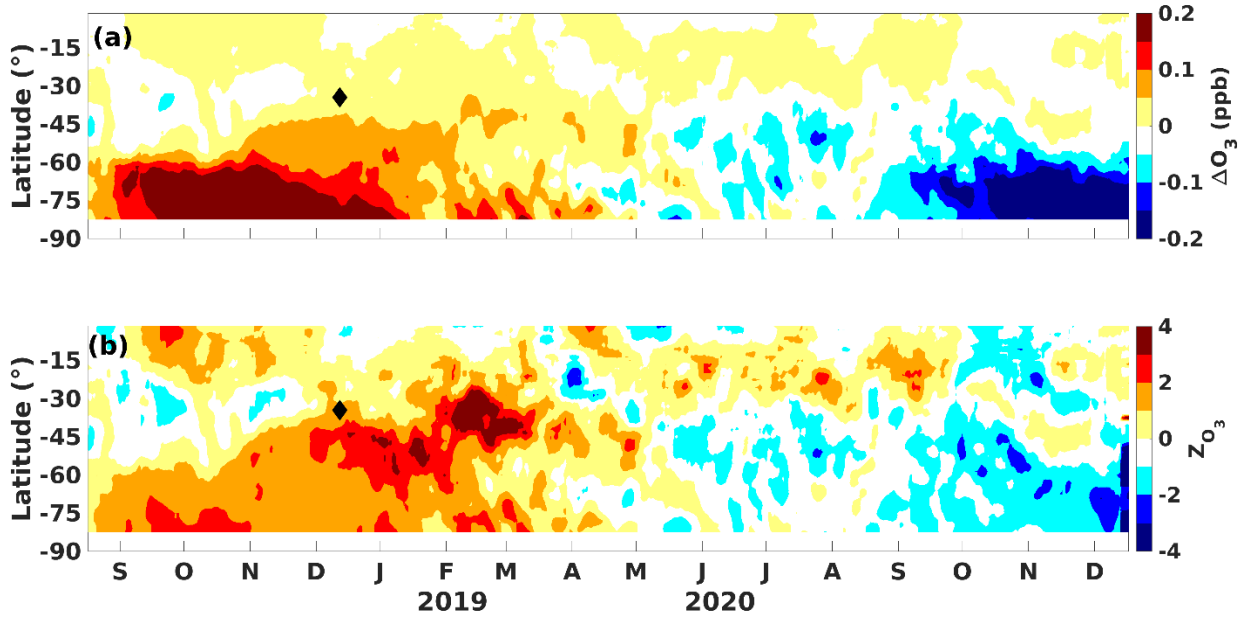

Figure S1. (a) Daily zonal mean anomaly (Δ) in MLS Ozone (O_3) mixing ratio, and (b) corresponding standardized anomaly (Z) at the altitude of 15 km from September 2019 to December 2020 are shown. The x-ticks mark the middle of each month. The black diamond in each plot marks the black summer event.

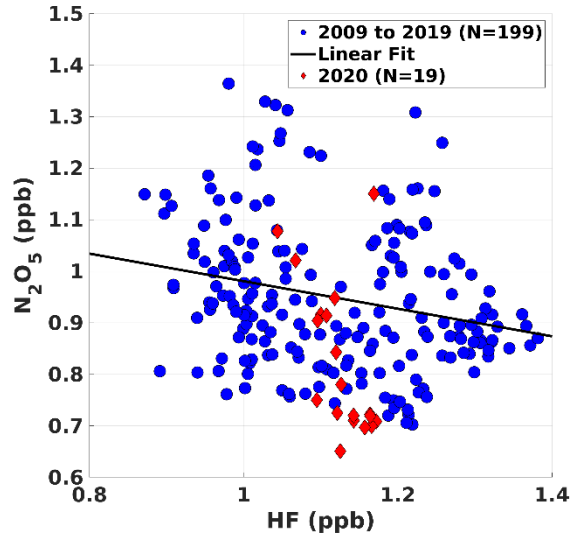

Figure S2. Tracer-Tracer correlation analysis between ACE-FTS HF and N_2O_5 for the altitude of 25 km is shown.

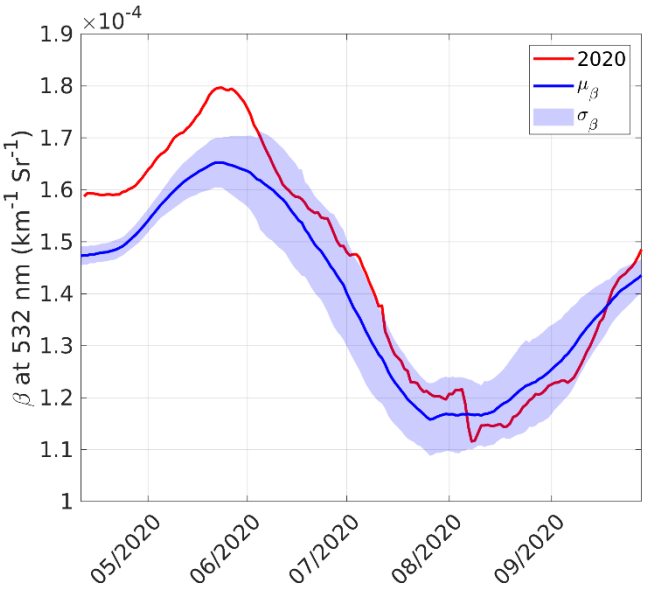

Figure. S3. Anomaly in CALIPSO observed total attenuated backscatter (β) at 532 nm corresponding to grids classified as 'No Cloud (NC)' at the temperature above T_{NAT}. Here, 'σ_β' (blue shading region) represents the standard deviation with respect to the background mean 'μ_β' (solid blue line) estimated for the period 2009–2019. The solid red line corresponds to the 2020 daily mean. The x-ticks mark the middle of each month.

Table S1. The CALIPSO observed the onset of each PSC type from 2009 to 2020 (excluding 2015)

Year	**Ice**	**Liquid-NAT mixture**	**STS**	**Enhanced NAT mixture**
2009	23-May	16-May	16-May	22-May
2010	25-May	21-May	21-May	22-May
2011	28-May	22-May	22-May	27-May
2012	04-Jun	23-May	23-May	25-May
2013	29-May	29-May	29-May	29-May
2014	27-May	20-May	20-May	26-May
2016	26-May	23-May	23-May	24-May
2017	22-May	16-May	17-May	18-May
2018	29-May	15-May	16-May	22-May
2019	27-May	17-May	17-May	25-May
2020	26-May	23-May	26-May	26-May

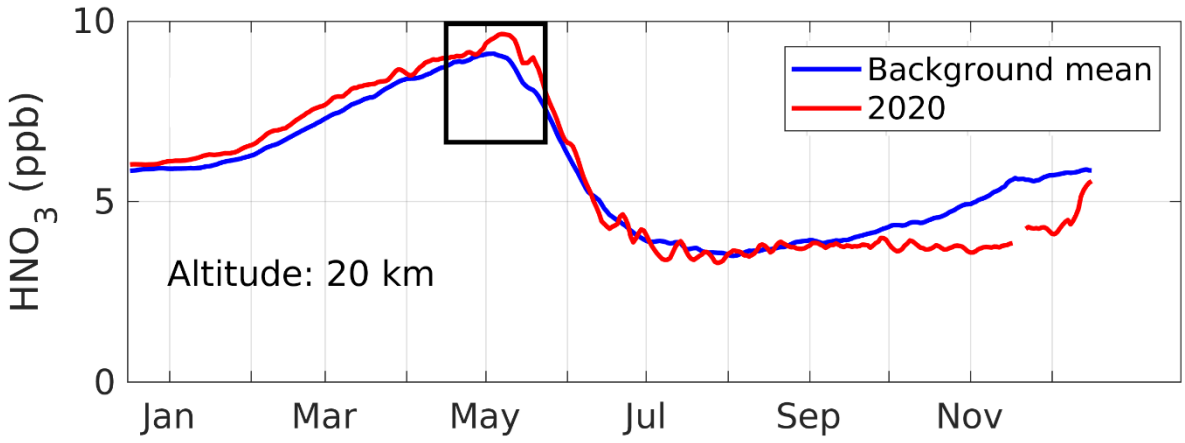

Figure S4. MLS obtained daily mean HNO_3 mixing ratio (ppb) averaged over high latitude (60°S to 90°S) is shown for the year 2020 (red line), and the background period of 2009-2019 (blue line) at the altitude of 20 km. The x-tick marks the middle of each month. The black rectangle box shows the period when depletion in HNO3 occurs leading to PSC formation every year.

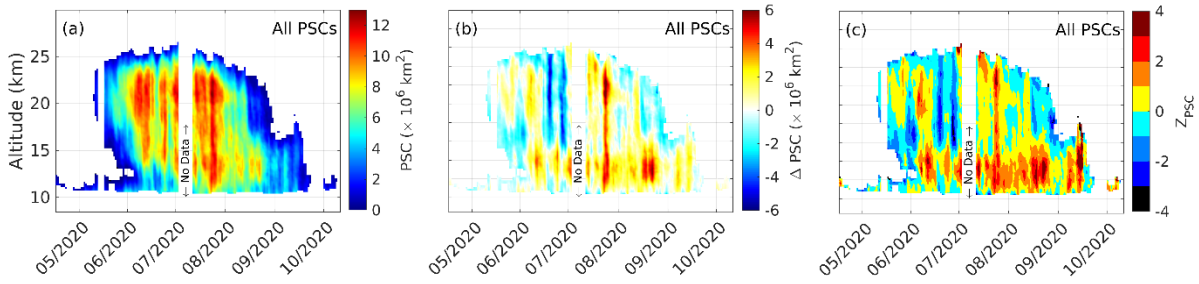

Figure S5. CALIPSO Antarctic PSC areal coverage (panel a), anomaly (panel b), and standardized anomaly (panel c) for the year 2020.

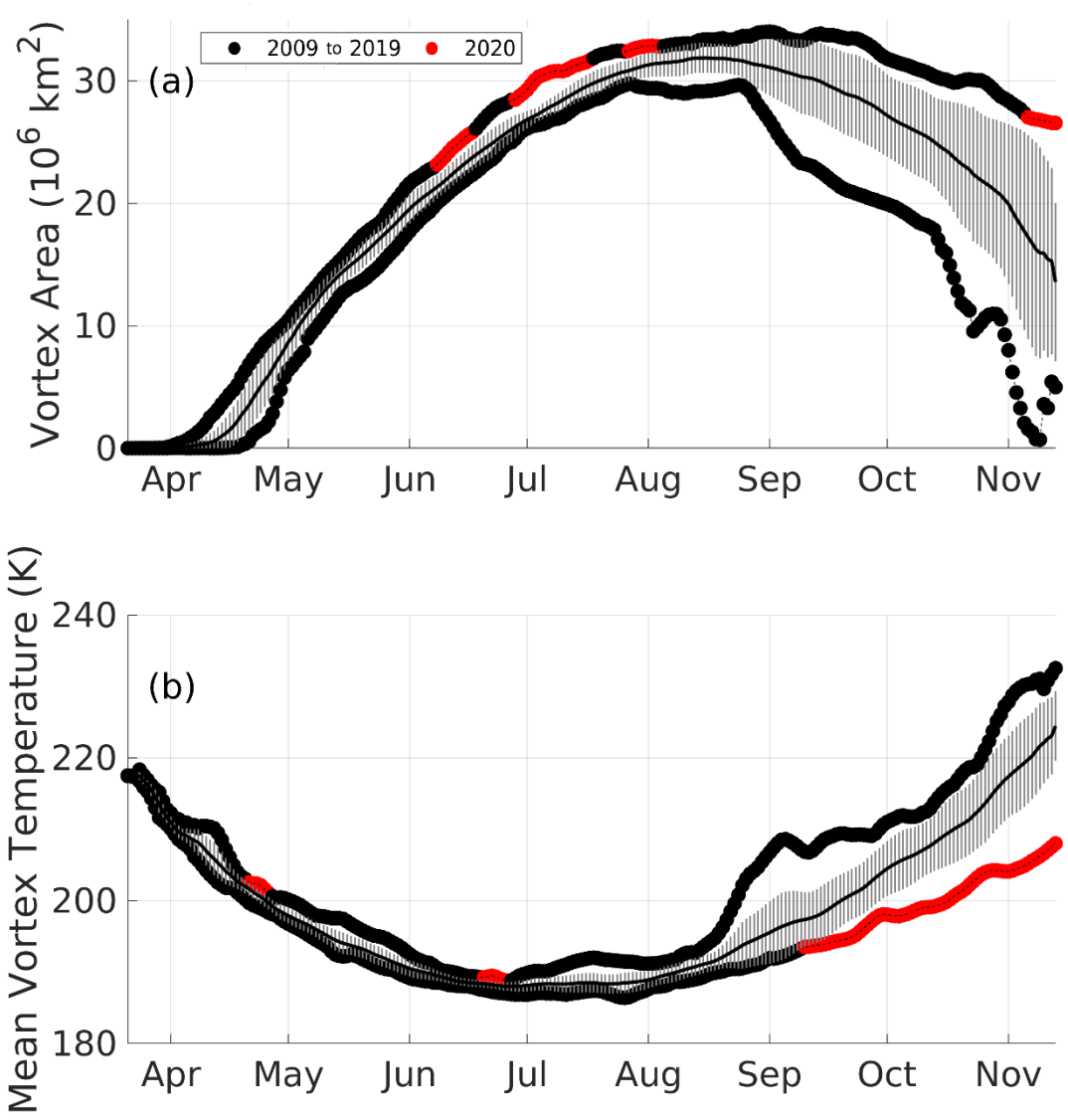

Figure S6: Time series of (a) Antarctic polar vortex area and (b) mean vortex temperature over the Antarctic from 2009 to 2020 (excluding 2015) are shown. The black solid line represents the vortex area/mean vortex temperature and the vertical lines represent the standard deviation. The daily maximum and minimum values are color-coded according to the period in which they occurred. The red-filled circles mark the anomalous high/low value in vortex area and mean vortex temperature during 2020 and black-filled circles mark the period from 2009 to 2019..

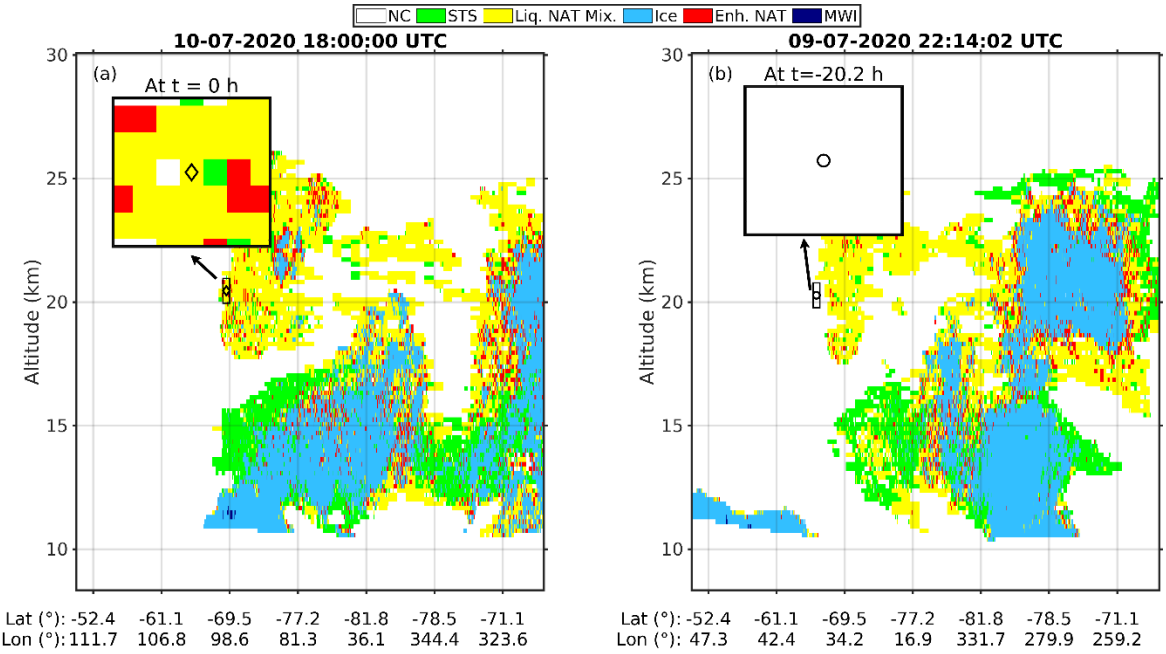

Figure S7. CALIPSO PSC orbit curtain plots are shown. Panel (a) and (b) correspond to the CALIPSO scan tracks marked with solid grey and magenta line shown in Fig. 10a, respectively. The insets of each panel show the zoomed-in region marked with a black rectangle. The yellow diamond in panel (a) marks the liquid-NAT mixture, and the white circle in panel (b) marks 'NC' (No Cloud).

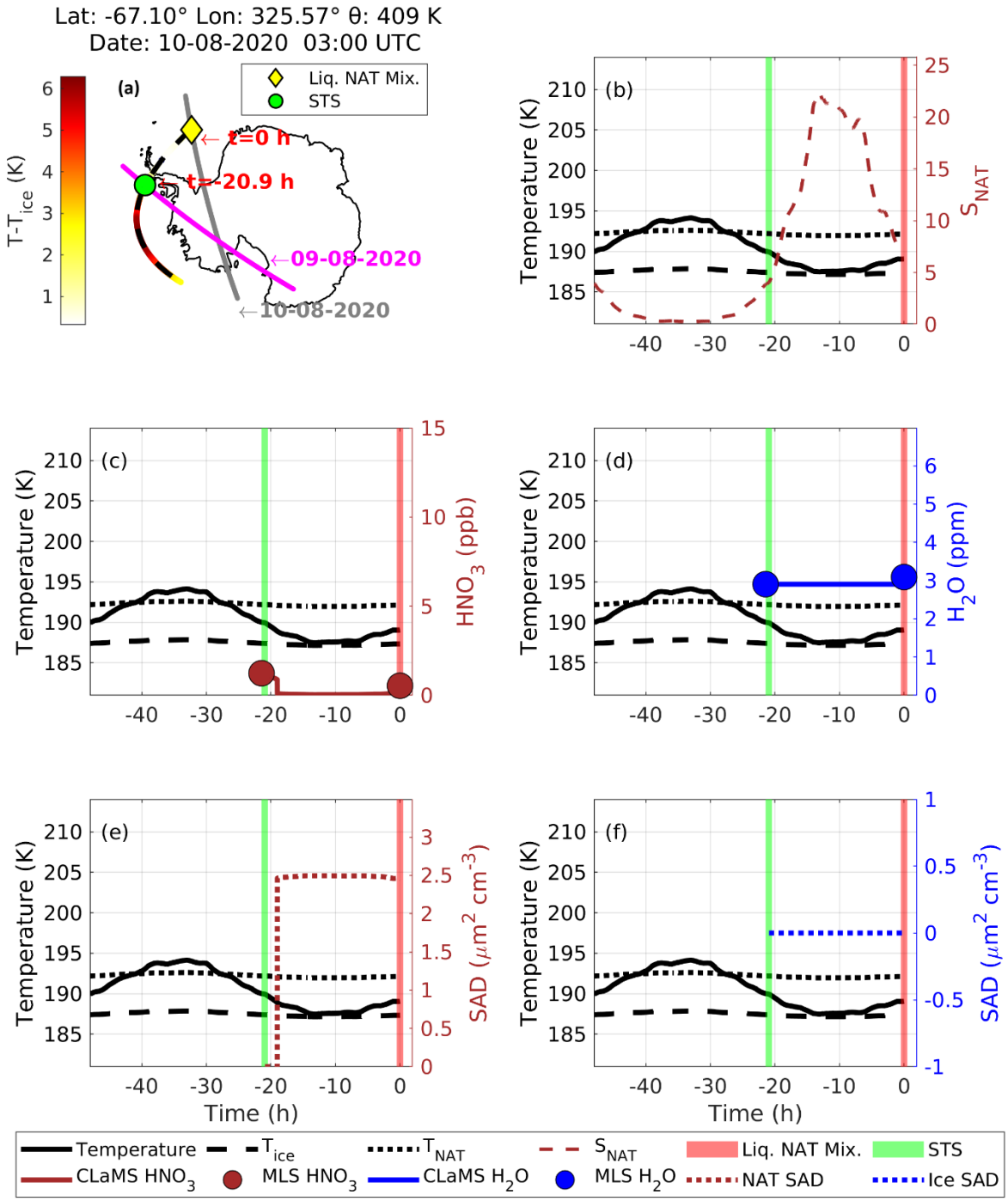

Figure S8. (a) The Lagrangian backward trajectory for a 48 h period starting at time, t = 0 h (corresponding to 03:00 UTC 10-08-2020) is shown. Here, the dashed black line is the backward trajectory and the color along this trajectory is the temperature at the T-T_{ice} coordinate. The yellow diamond represents the observed liquid-NAT mixture from the CALIPSO scan track (solid grey line) corresponding to 10-08-2020. The complete coordinate of this liquid-NAT mixture is given in the title. The green circle represents the observed STS at the time, t = -20.9 h from the CALIPSO scan track (solid magenta line) corresponding to 09-08-2020. (b) shows the saturation ratio over ice (S_{ice}) (dashed blue line) and vertical bars mark the liquid-NAT mixture (red) and STS (green). (c) The brown circle marks the MLS HNO_3, and the solid brown line represents the CLaMS HNO_3. (d) The blue circle marks the MLS H_2O, and the solid blue line represents the CLaMS H_2O. (e) shows the NAT surface area density (SAD) (dotted brown line). Panel (f) shows the ice surface area density (SAD) (dotted blue line).

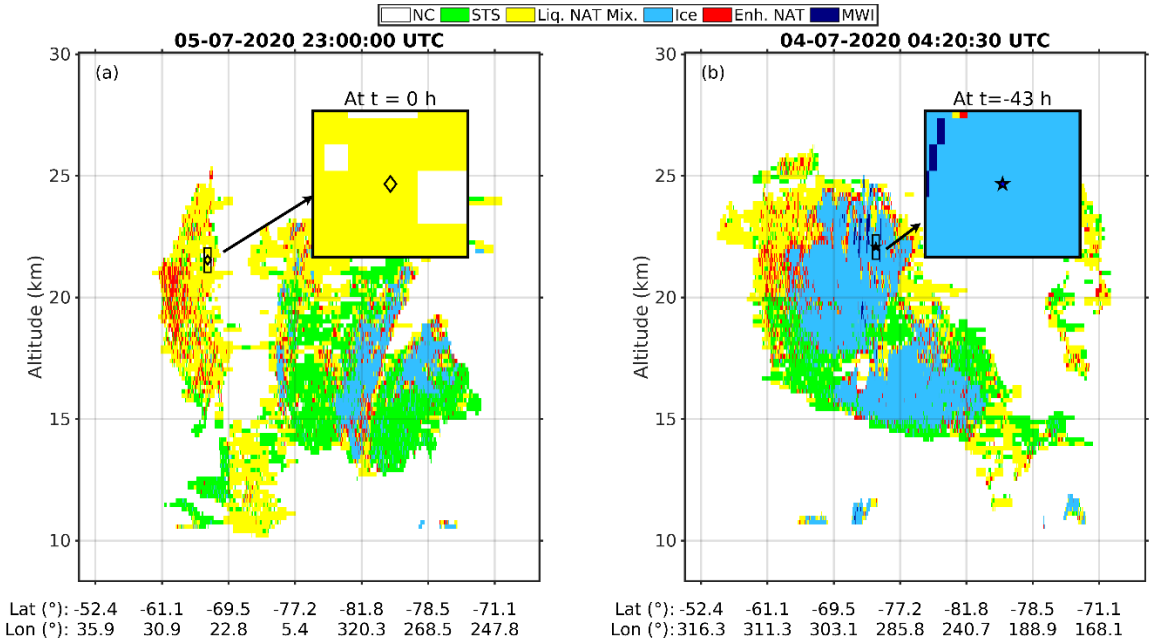

Figure S9. CALIPSO PSC orbit curtain plots are shown. Panel (a) and (b) correspond to the CALIPSO scan tracks marked with solid grey and magenta line shown in Fig. 11a, respectively. The insets of each panel show the zoomed-in region marked with a black rectangle. The yellow diamond in panel (a) marks the liquid-NAT mixture, and the blue star in panel (b) marks ice PSC.

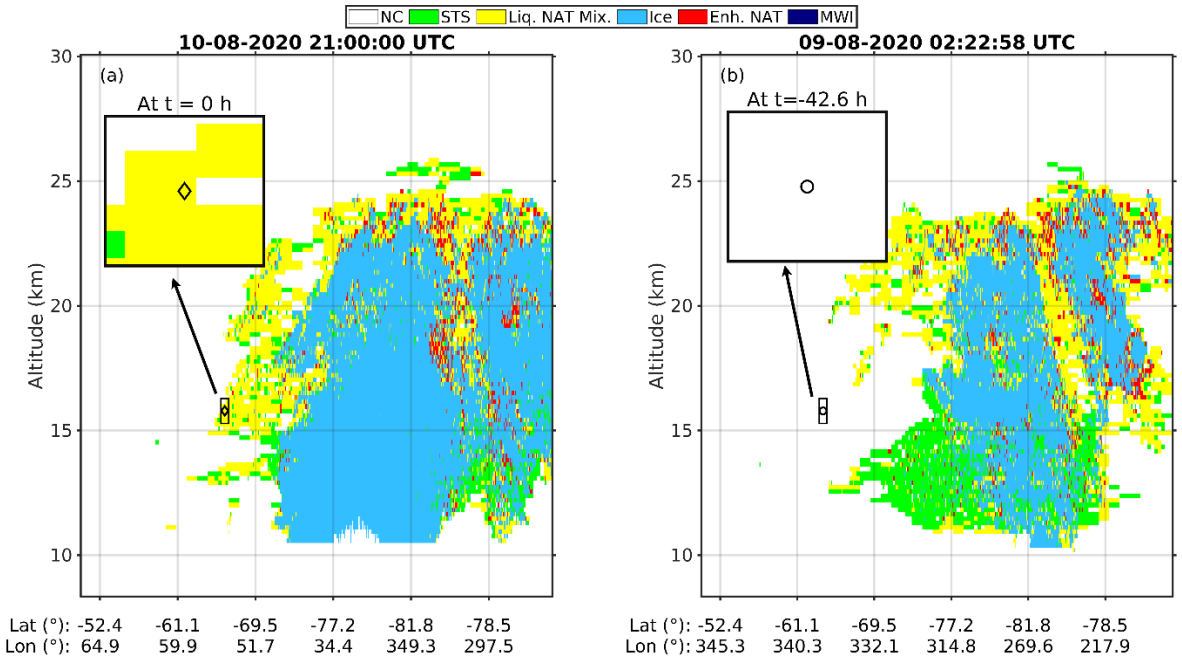

Figure S10. CALIPSO PSC orbit curtain plots are shown. Panel (a) and (b) correspond to the CALIPSO scan tracks marked with solid grey and magenta line shown in Fig. 11a, respectively. The insets of each panel show the zoomed-in region marked with a black rectangle. The yellow diamond in panel (a) marks the liquid-NAT mixture, and the white circle in panel (b) marks 'NC' (No Cloud).

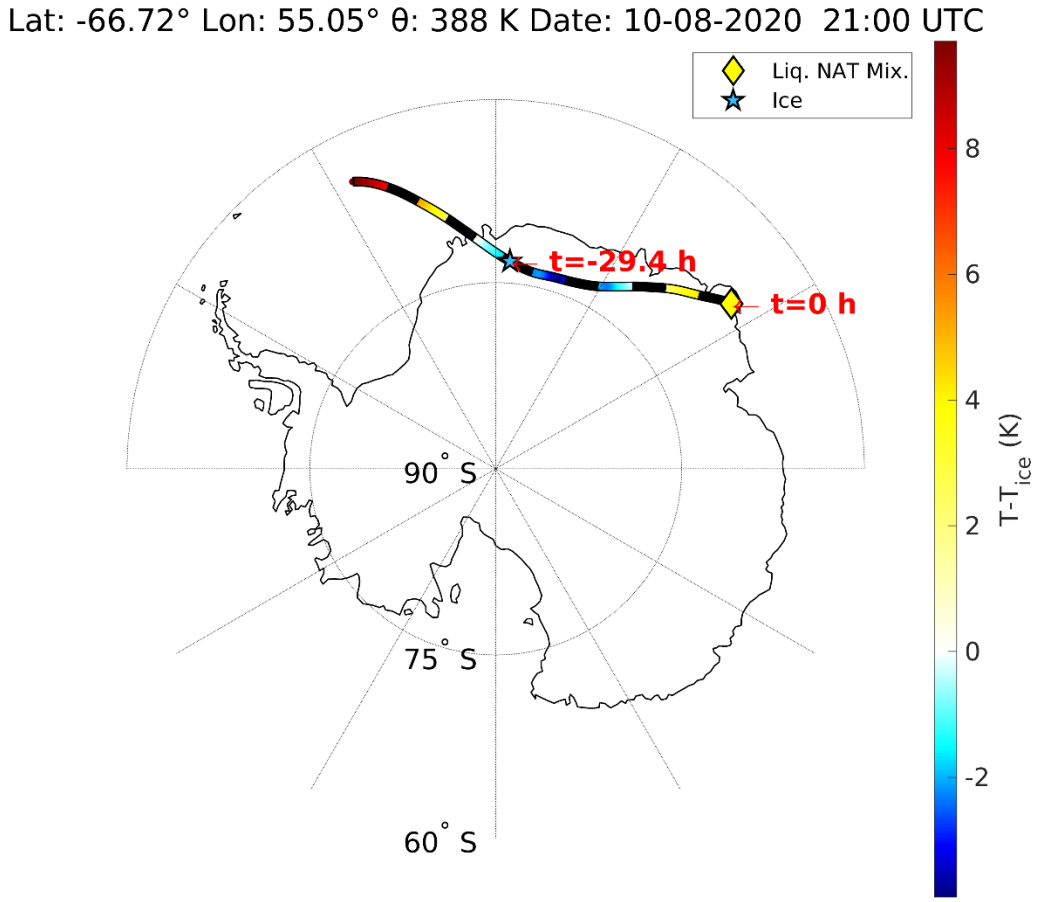

Figure. S11. The backward trajectory of the liquid-NAT mixture and the presence of the ice PSC along the trajectory is shown.

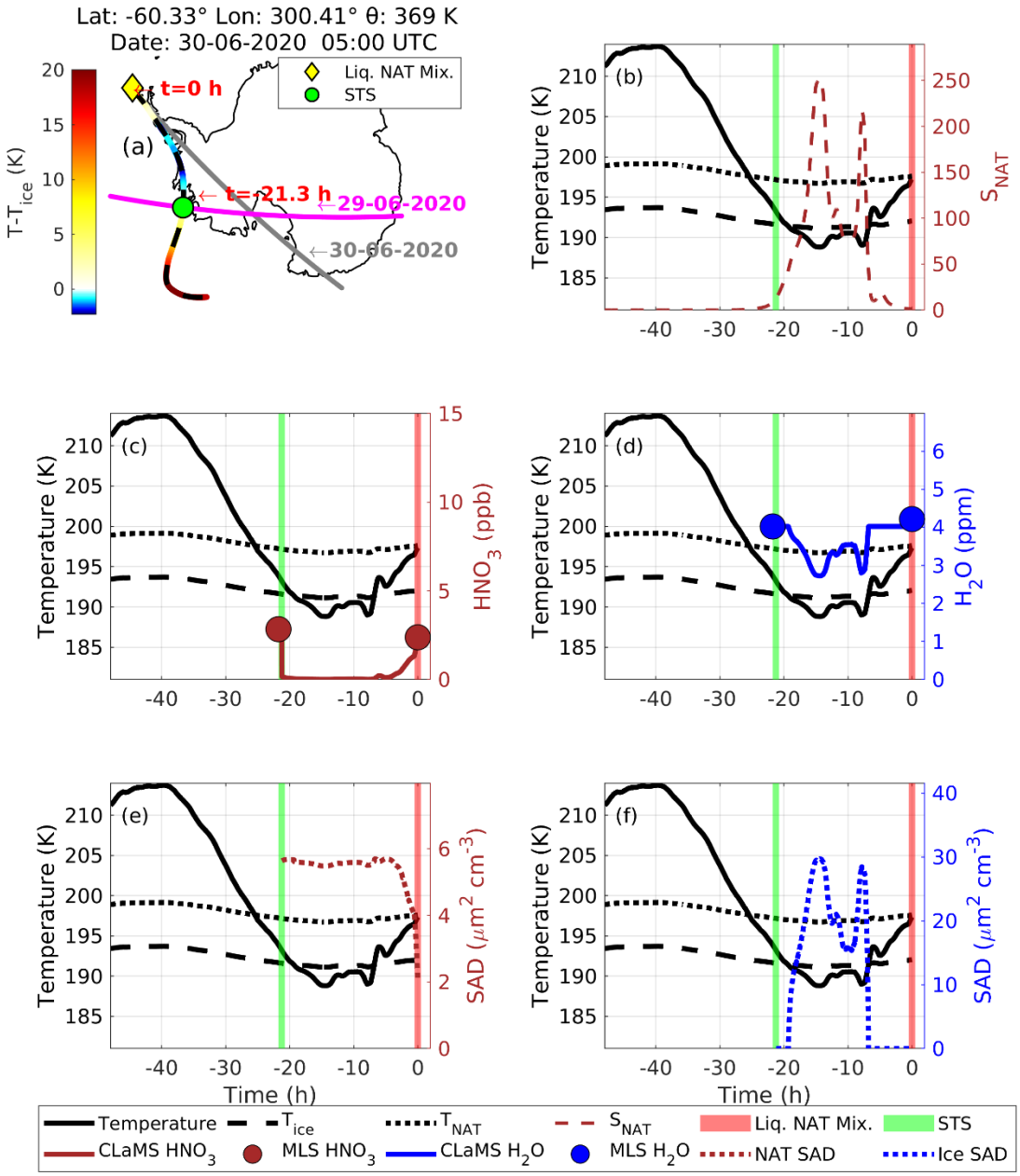

Figure S12. (a) The Lagrangian backward trajectory for a 48 h period starting at time, t = 0 h (corresponding to 05:00 UTC 30-06-2020) is shown. Here, the dashed black line is the backward trajectory and the color along this trajectory is the temperature at the T-T_{ice} coordinate. The yellow diamond represents the observed liquid-NAT mixture from the CALIPSO scan track (solid grey line) corresponding to 30-06-2020. The complete coordinate of this liquid-NAT mixture is given in the title. The green circle represents the observed STS at the time, t = -21.3 h from the CALIPSO scan track (solid magenta line) corresponding to 29-06-2020. (b) shows the saturation ratio over ice (S_{ice}) (dashed blue line) and vertical bars mark the liquid-NAT mixture (red) and STS (green). (c) The brown circle marks the MLS HNO_3, and the solid brown line represents the CLaMS HNO_3. (d) The blue circle marks the MLS H_2O, and the solid blue line represents the CLaMS H_2O. (e) shows the NAT surface area density (SAD) (dotted brown line). Panel (f) shows the ice surface area density (SAD) (dotted blue line).

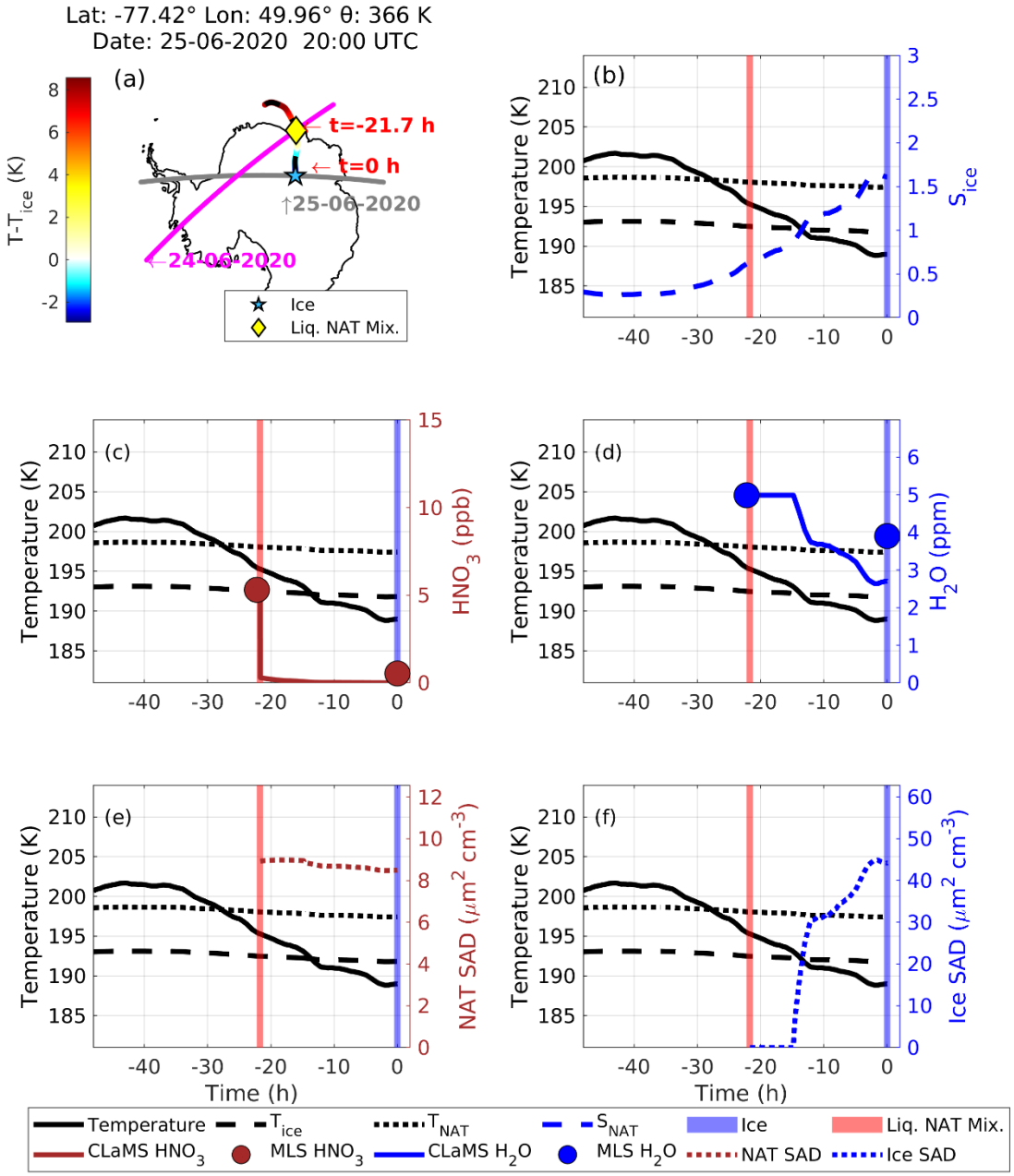

Figure S13. (a) The Lagrangian backward trajectory for a 48 h period starting at time, t = 0 h (corresponding to 18:00 UTC 19-06-2020) is shown. Here, the dashed black line is the backward trajectory and the color along this trajectory is the temperature at the T-T_{ice} coordinate. The blue star represents the observed ice PSC from the CALIPSO scan track (solid grey line) corresponding to 19-06-2020. The complete coordinate of this liquid-NAT mixture is given in the title. The white circle represents the presence of no cloud (NC) at the time, t = -37.6 h from the CALIPSO scan track (solid magenta line) corresponding to 18-06-2020. (b) shows the saturation ratio over ice (S_{ice}) (dashed blue line) and vertical bars mark the ice (blue) and NC (grey). (c) The brown circle marks the MLS HNO_3, and the solid brown line represents the CLaMS HNO_3. (d) The blue circle marks the MLS H_2O, and the solid blue line represents the CLaMS H_2O. (e) shows the NAT surface area density (SAD) (dotted brown line). Panel (f) shows the ice surface area density (SAD) (dotted blue line).

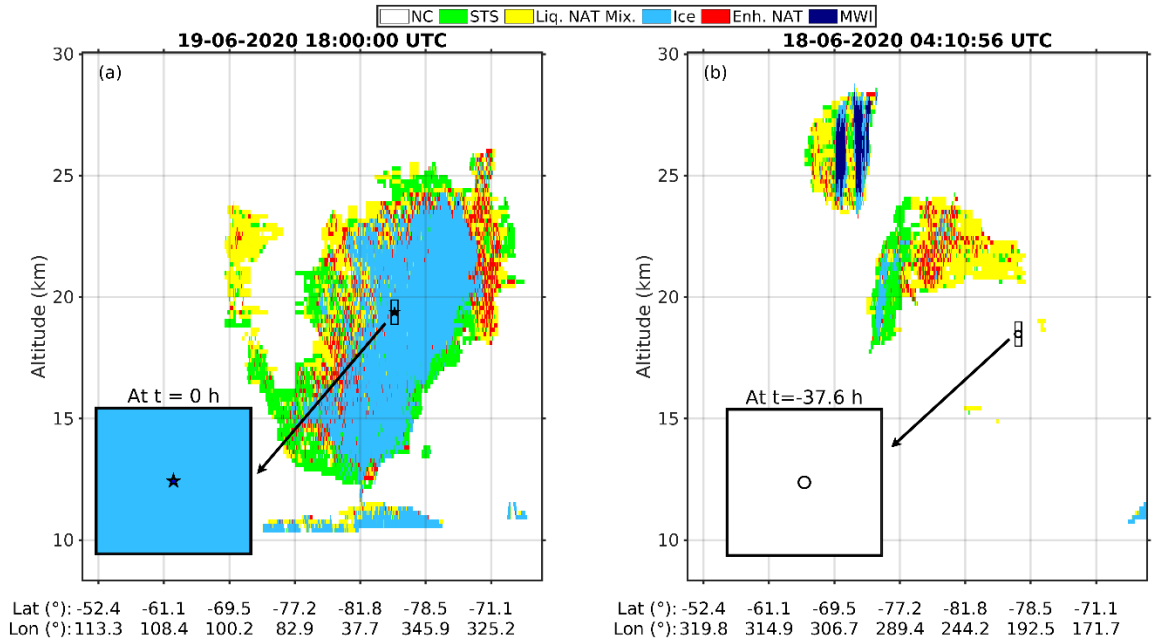

Figure S14. CALIPSO PSC orbit curtain plots are shown. Panel (a) and (b) correspond to the CALIPSO scan tracks marked with solid grey and magenta line shown in Fig. 15a, respectively. The insets of each panel show the zoomed-in region marked with a black rectangle. The blue star in panel (a) marks the ice PSC, and the white circle in panel (b) marks 'NC' (No Cloud).

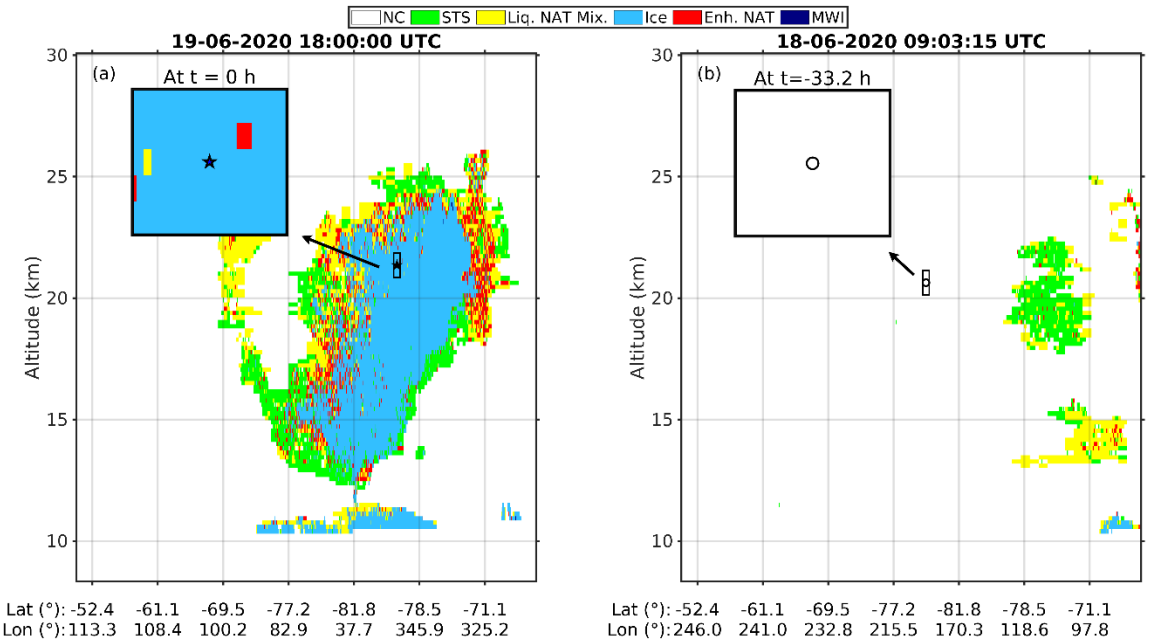

Figure S15. CALIPSO PSC orbit curtain plots are shown. Panel (a) and (b) correspond to the CALIPSO scan tracks marked with solid grey and magenta line shown in Fig. 16a, respectively. The insets of each panel show the zoomed-in region marked with a black rectangle. The blue star in panel (a) marks the ice PSC, and the white circle in panel (b) marks 'NC' (No Cloud).

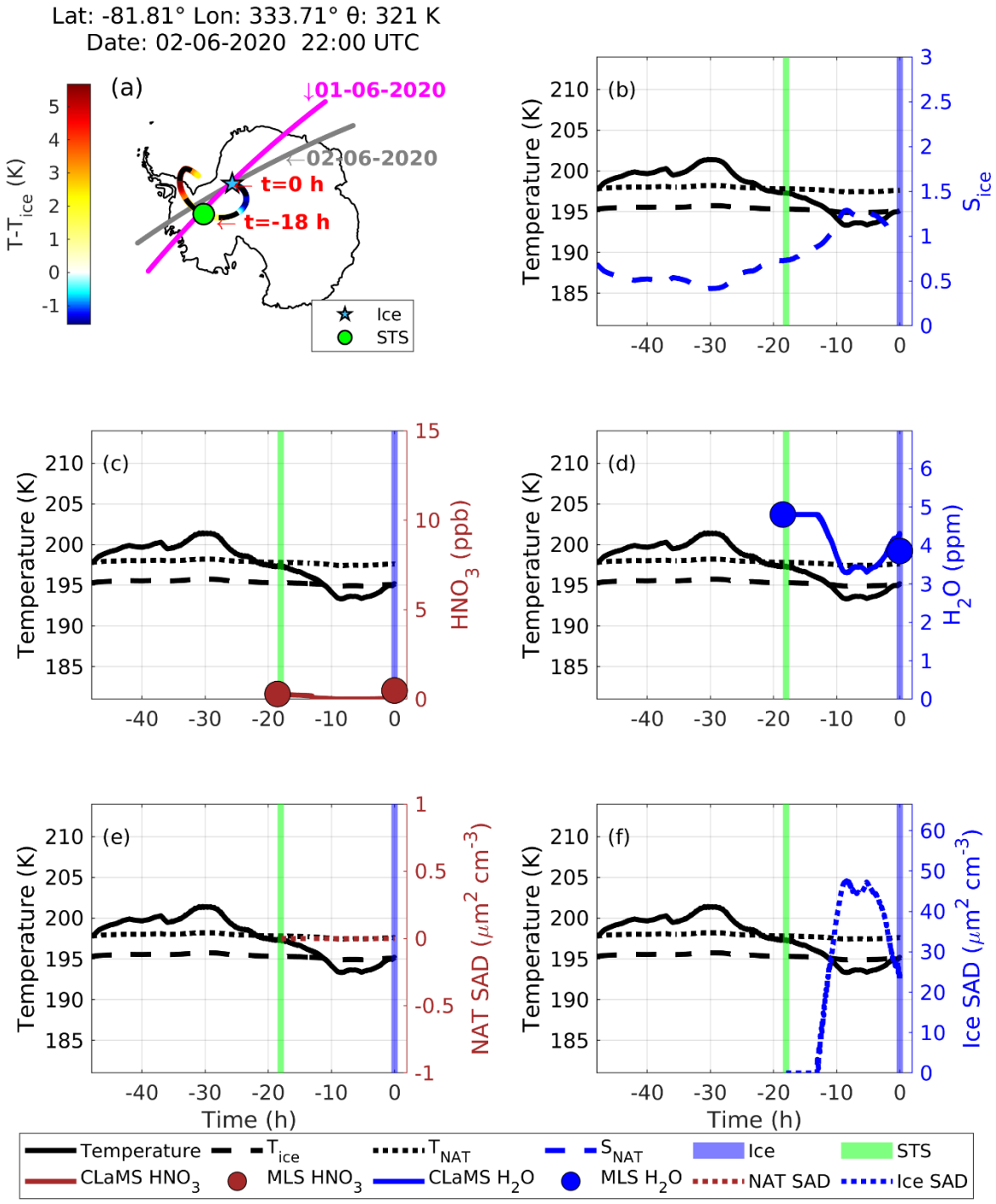

Figure S16. (a) The Lagrangian backward trajectory for a 48 h period starting at time, t = 0 h (corresponding to 22:00 UTC 02-06-2020) is shown. Here, the dashed black line is the backward trajectory and the color along this trajectory is the temperature at the T-T_{ice} coordinate. The blue star represents the observed ice PSC from the CALIPSO scan track (solid grey line) corresponding to 02-06-2020. The complete coordinate of this liquid-NAT mixture is given in the title. The green circle represents the observed STS at the time, t = -18 h from the CALIPSO scan track (solid magenta line) corresponding to 01-06-2020. (b) shows the saturation ratio over ice (S_{ice}) (dashed blue line) and vertical bars mark the ice (blue) and STS (green). (c) The brown circle marks the MLS HNO_3, and the solid brown line represents the CLaMS HNO_3. (d) The blue circle marks the MLS H_2O, and the solid blue line represents the CLaMS H_2O. (e) shows the NAT surface area density (SAD) (dotted brown line). Panel (f) shows the ice surface area density (SAD) (dotted blue line).