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Supplement of

How does downward planetary wave coupling affect polar stratospheric ozone in the Arctic winter stratosphere?

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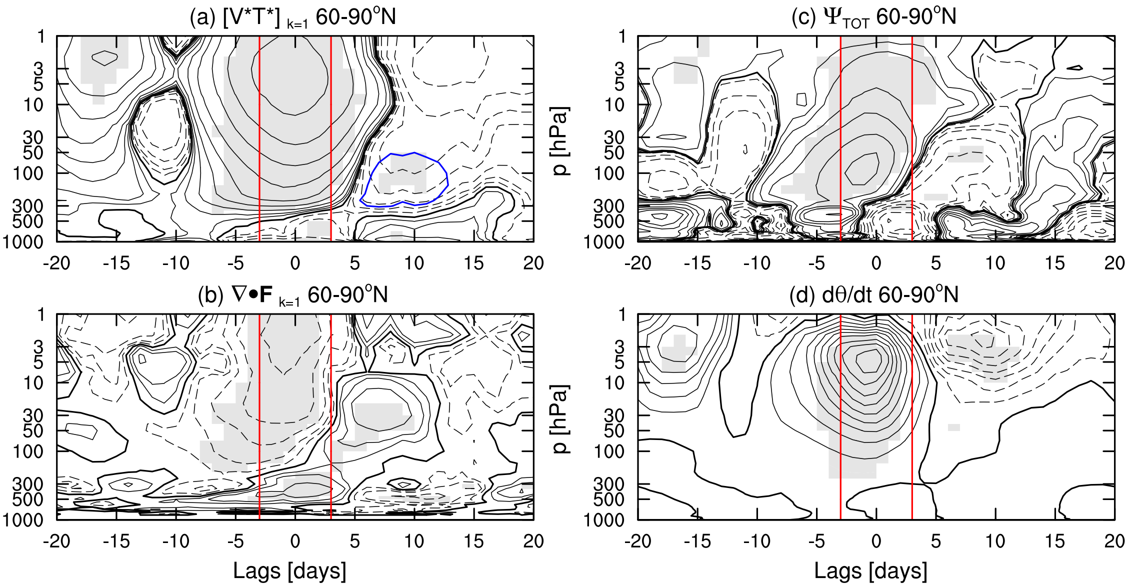

Figure S1. Evolution of the upward wave events as a function of time from days -20 to +20 and pressure: (a) wave-1 meridional heat flux anomaly (black contours) and zero contour of the total wave-1 meridional heat flux (blue contour), (b) wave-1 EP flux divergence anomaly, (c) residual mass-streamfunction anomaly, and (d) potential temperature tendency averaged from 60 to 90^0N. The black contour intervals are: $\pm$ 1 x 10^9 [0.5, 1, 2, 4, 8, 16, 32, 64,..] kg s^{-1} for Fig. S1c and $\pm$ 0.5 K day^{-1} for Fig. S1d. The gray shading indicates statistical significance at the 95% level using a 1000-trial Monte Carlo test. The periods of the maximum DWC event (days -3 to +3) are bounded by two vertical red lines.

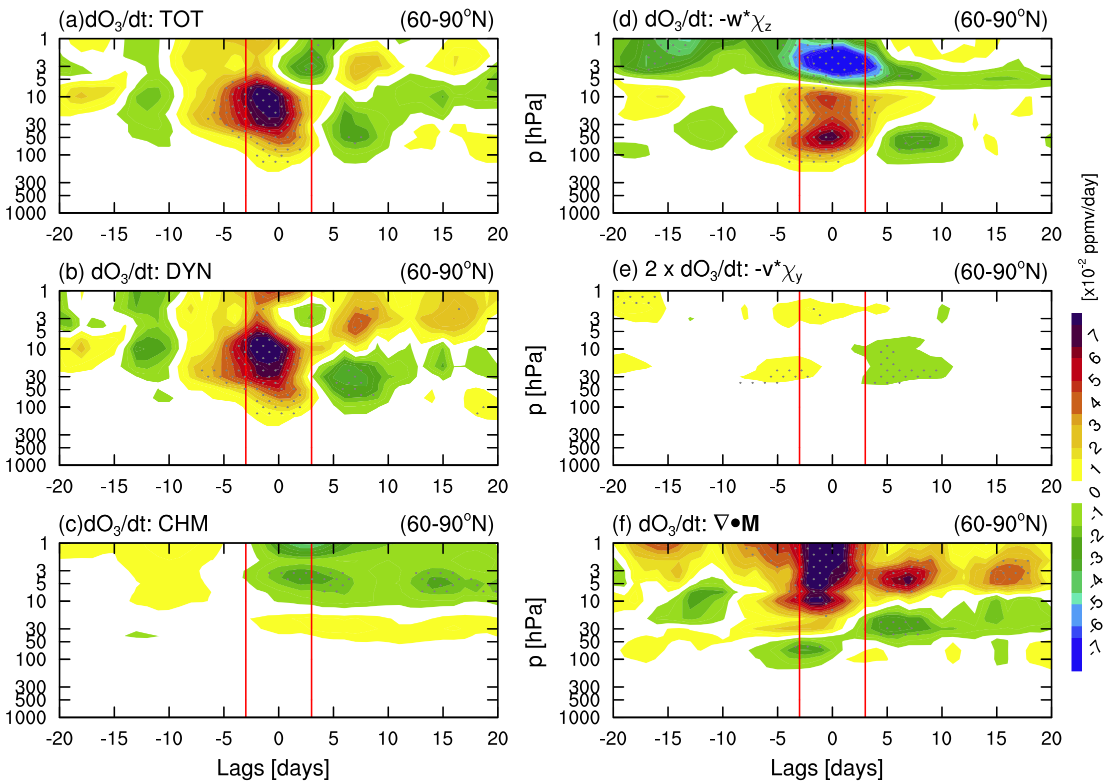

Figure S2. Evolution of the ozone tendencies for the composite upward wave event as a function of time and pressure, averaged from 60 to 90°N: (a) total ozone tendency, (b) ozone tendency anomaly due to dynamics and (c) due to parameterized chemistry. Tendency from the dynamics is decomposed into (d) vertical advection, (e) meridional advection, and (f) eddy transport effects based on Eq.1. The periods of the maximum DWC event (days -3 to +3) are bounded by two vertical red lines. Stippling indicates statistical significance at the 95% level using a 1000-trial Monte Carlo test.

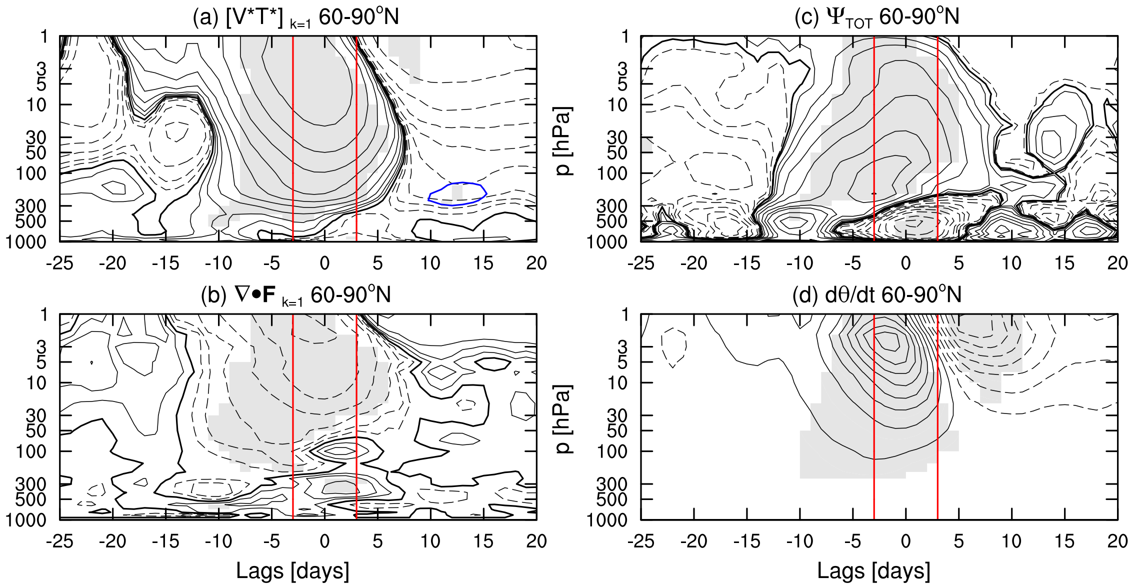

Figure S3. As in Fig. S1, but from a 100-yr CESM1(WACCM) simulation. The gray shading indicates statistical significance at the 95% level using a 1000-trial Monte Carlo test. The periods of the maximum DWC event (days -3 to +3) are bounded by two vertical red lines.

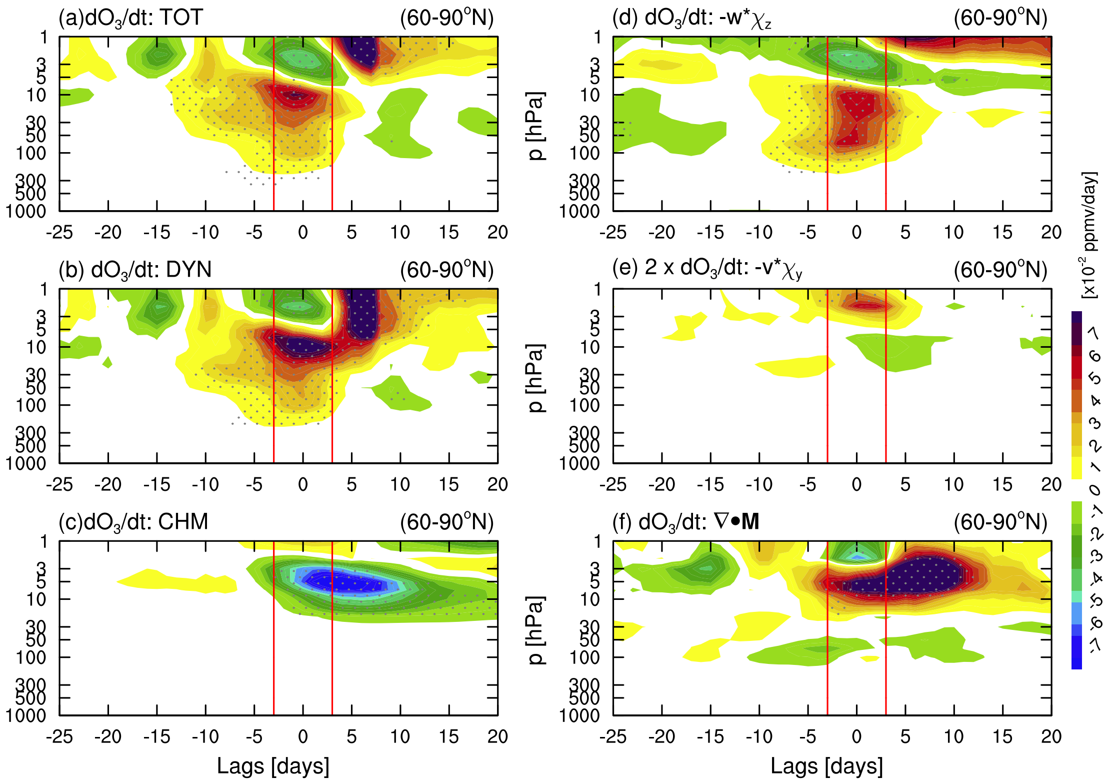

Figure S4. As in Fig. S2, but from a 100-yr CESM1(WACCM) simulation. The periods of the maximum DWC event (days -3 to +3) are bounded by two vertical red lines. Stippling indicates statistical significance at the 95% level using a 1000-trial Monte Carlo test.

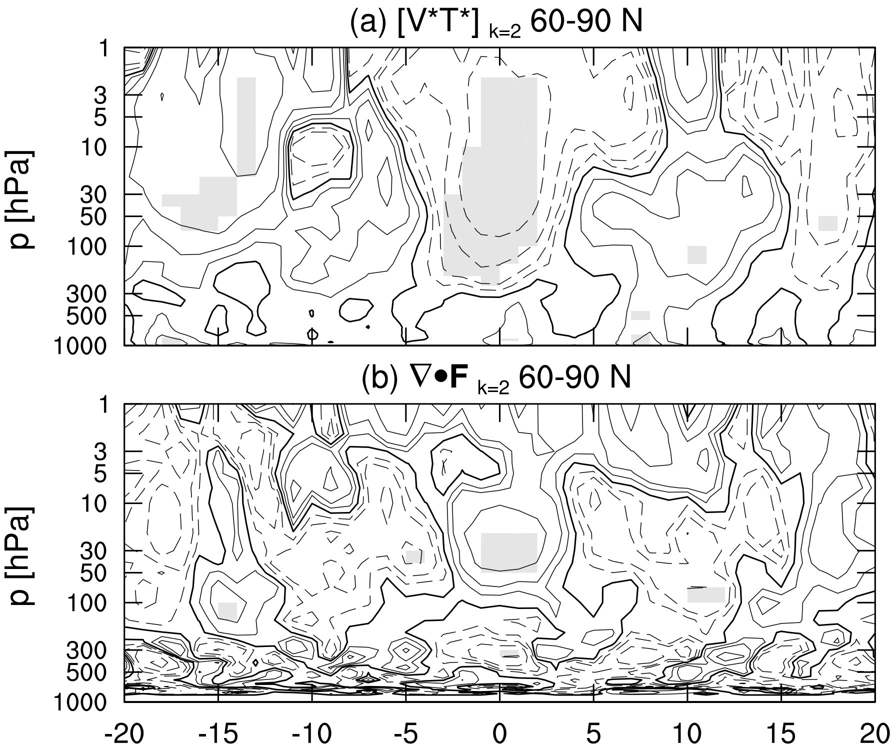

Figure S5. Evolution of the downward wave (k=2) events as a function of time from days -20 to +20 and pressure: (a) wave-2 meridional heat flux anomaly (black contours) and (b) wave-2 EP flux divergence anomaly. The black contour intervals are: $\pm$ 1 x 10^9 [0.5, 1, 2, 4, 8, 16, 32, 64,..] kg s^{-1} for Fig. S5a and $\pm$ 0.5 K day^{-1} for Fig. S5b. The gray shading indicates statistical significance at the 95% level using a 1000-trial Monte Carlo test.

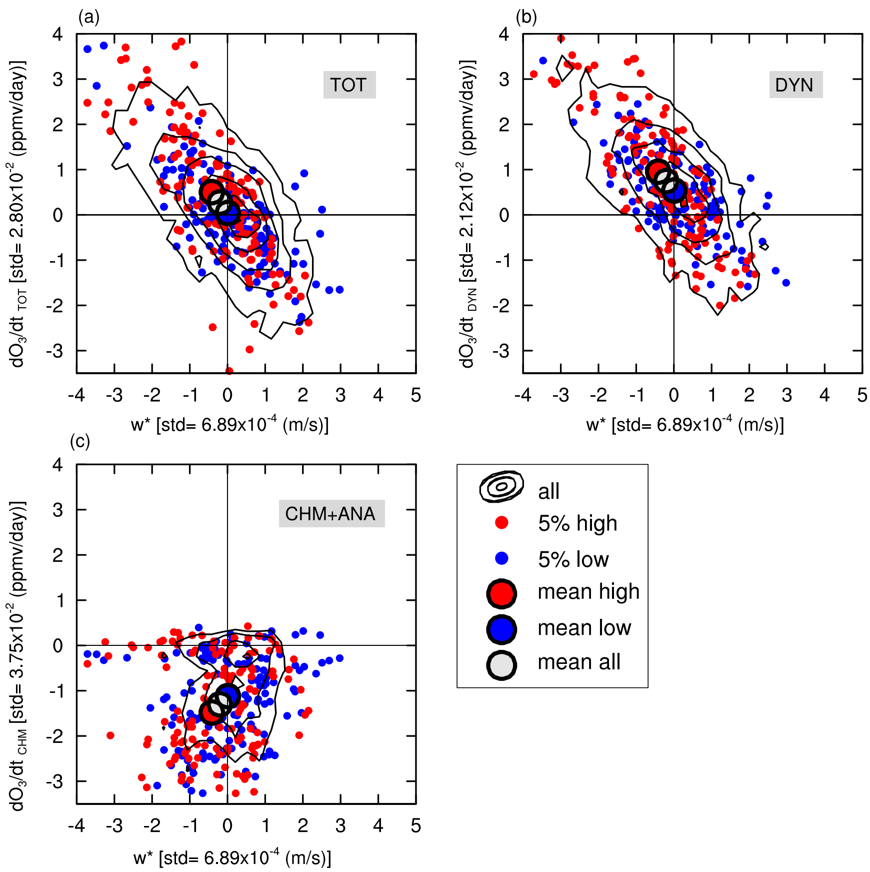

Figure S6. As in Fig. 3, but for wave 2.

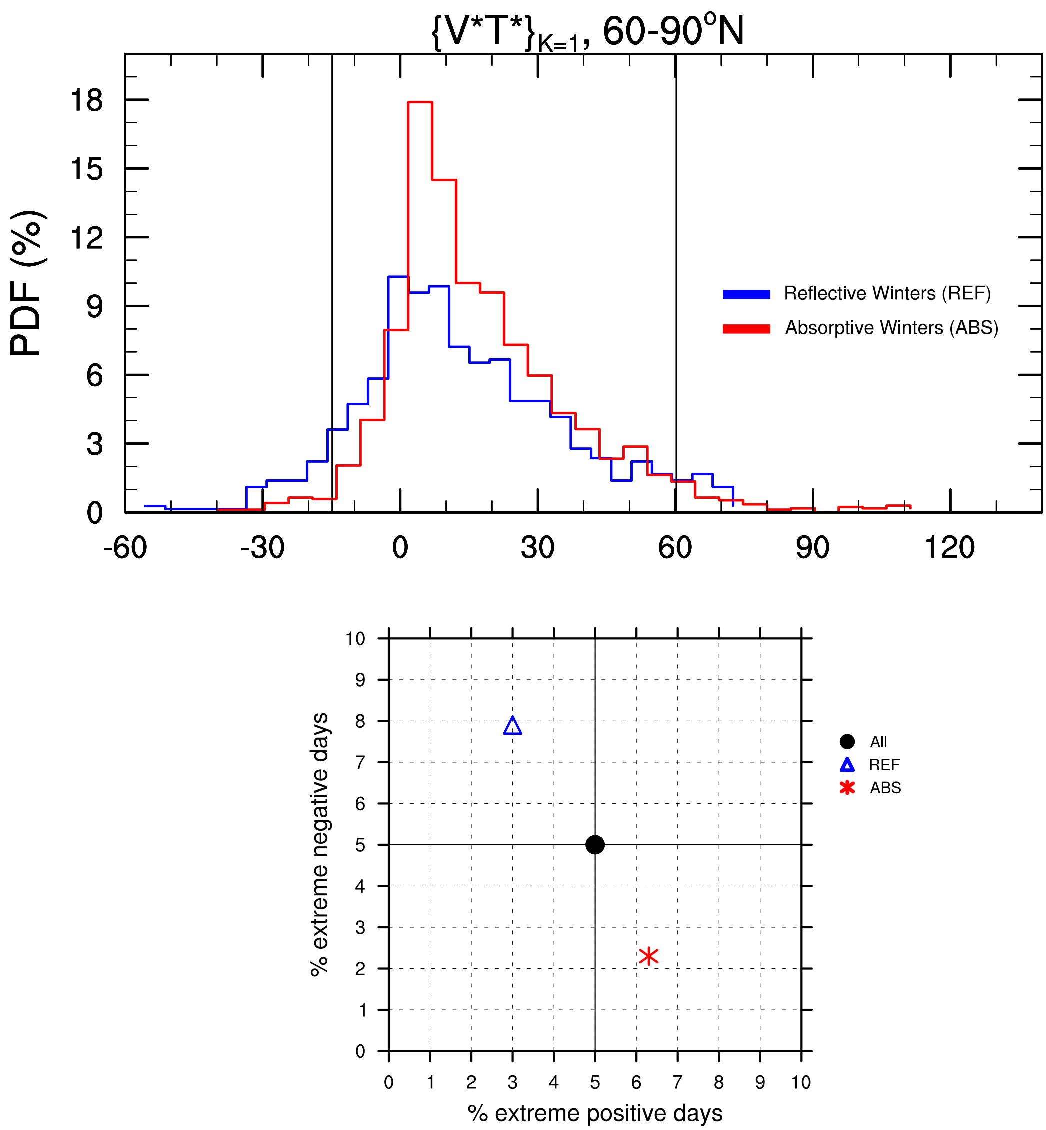

Figure S7. (a). Probability distribution functions of reflective (blue) and absorptive (red) winters. The vertical black lines represent the 5th (-17.5 Kms^{-1}) and 95th (63.6 Kms^{-1}) percentile values of the daily distribution from all years. (b) Percentage (frequency) of extreme negative high-latitude averaged wave-1 heat flux events at 50-hPa level vs extreme positive events at the same levels during JFM for all years (black circle), reflective years (blue triangle) and absroptive years (red asterisk).

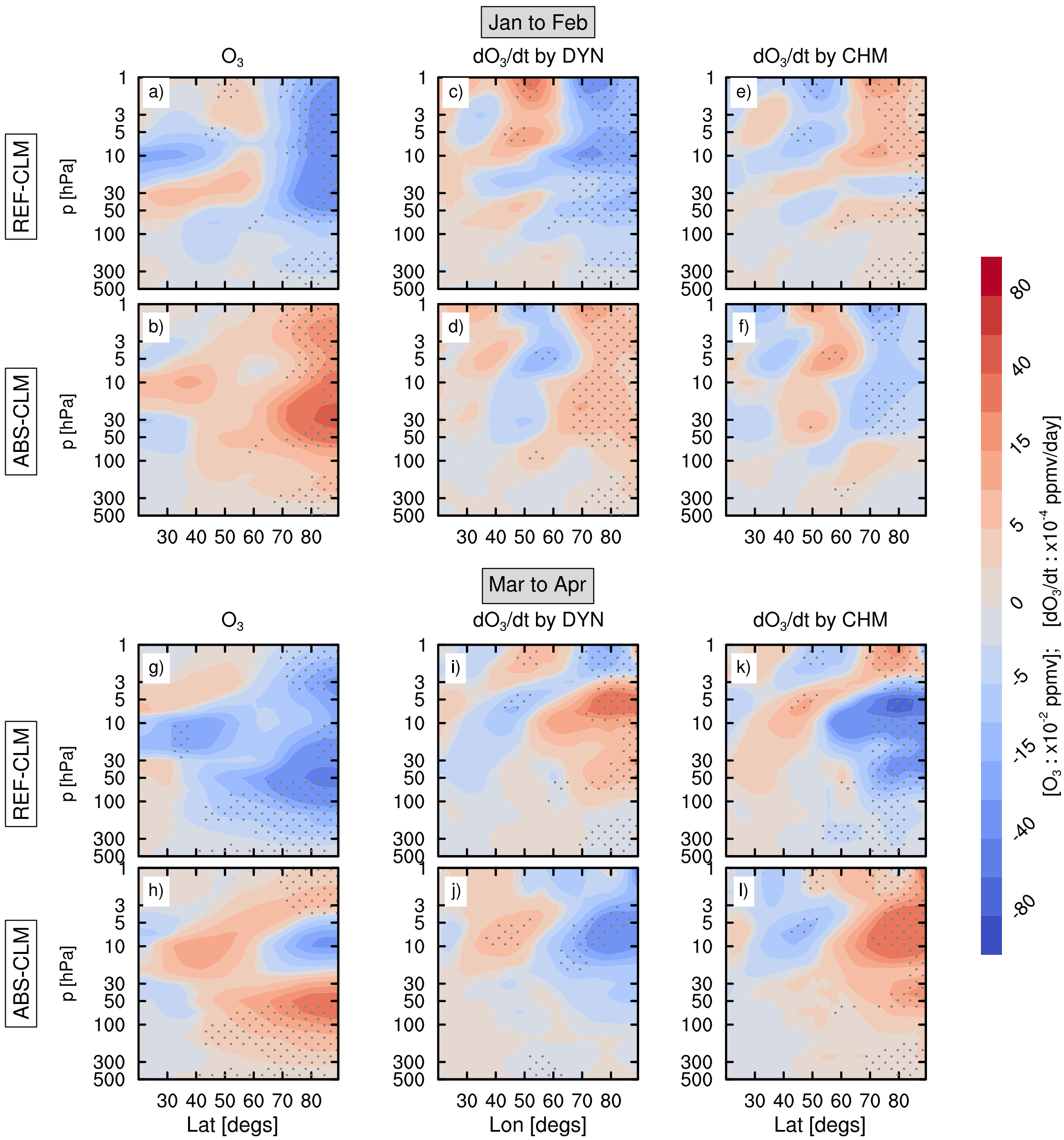

Figure S8. Composite-mean difference (REF or ABS minus climatological mean (CLM)) of the (a,b,g,h) zonal mean ozone, (c,d,i,j) ozone tendency due to dynamics, and (e,f,k,l) ozone tendency due to chemistry from MERRA, averaged between January-February and March-April. Stipplings denote differences significant at the 95% confidence level.

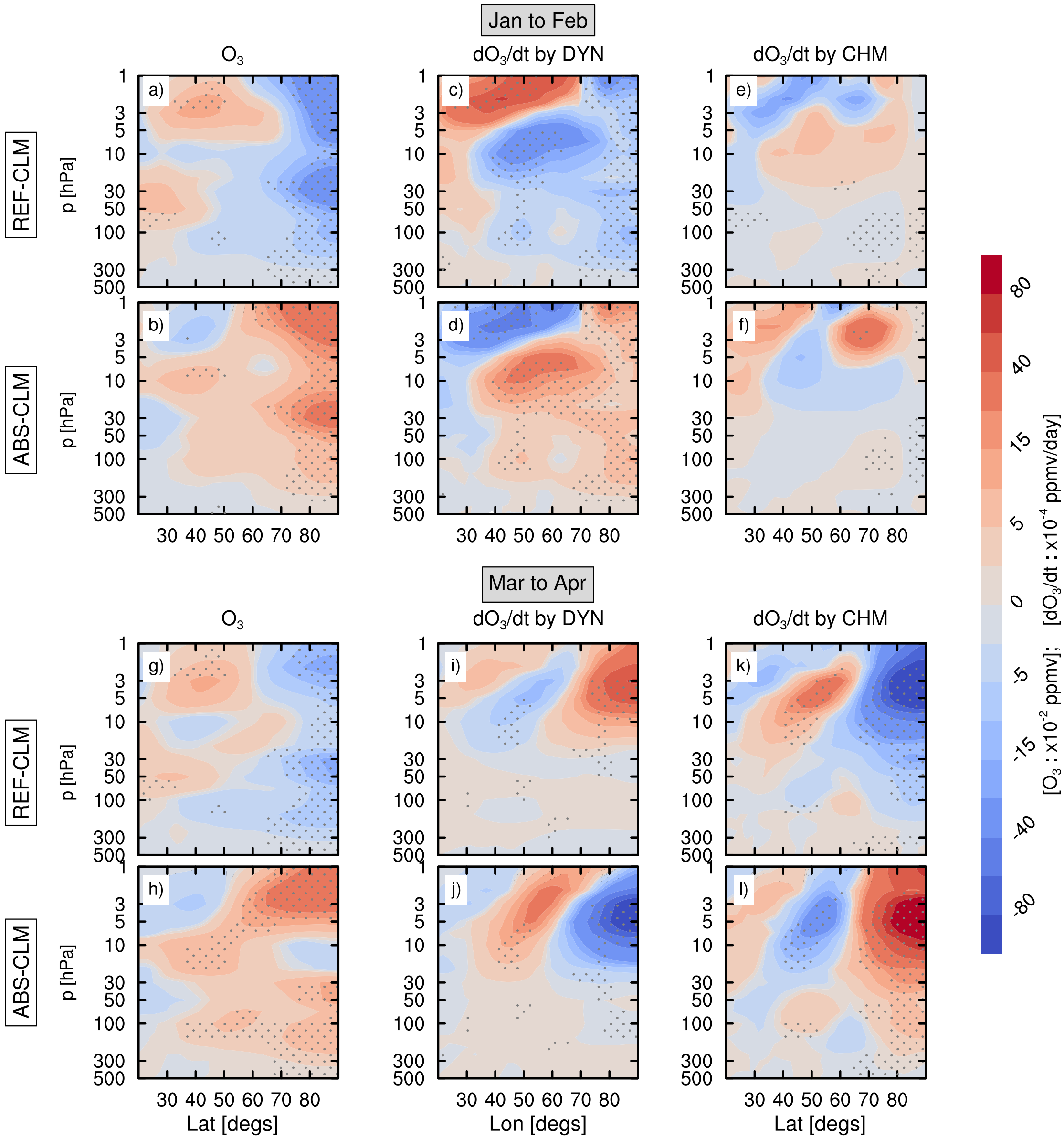

Figure S9. As in Fig. S8, but from 100-yr CESM1(WACCM) simulation. Stipplings denote differences significant at the 95% confidence level.

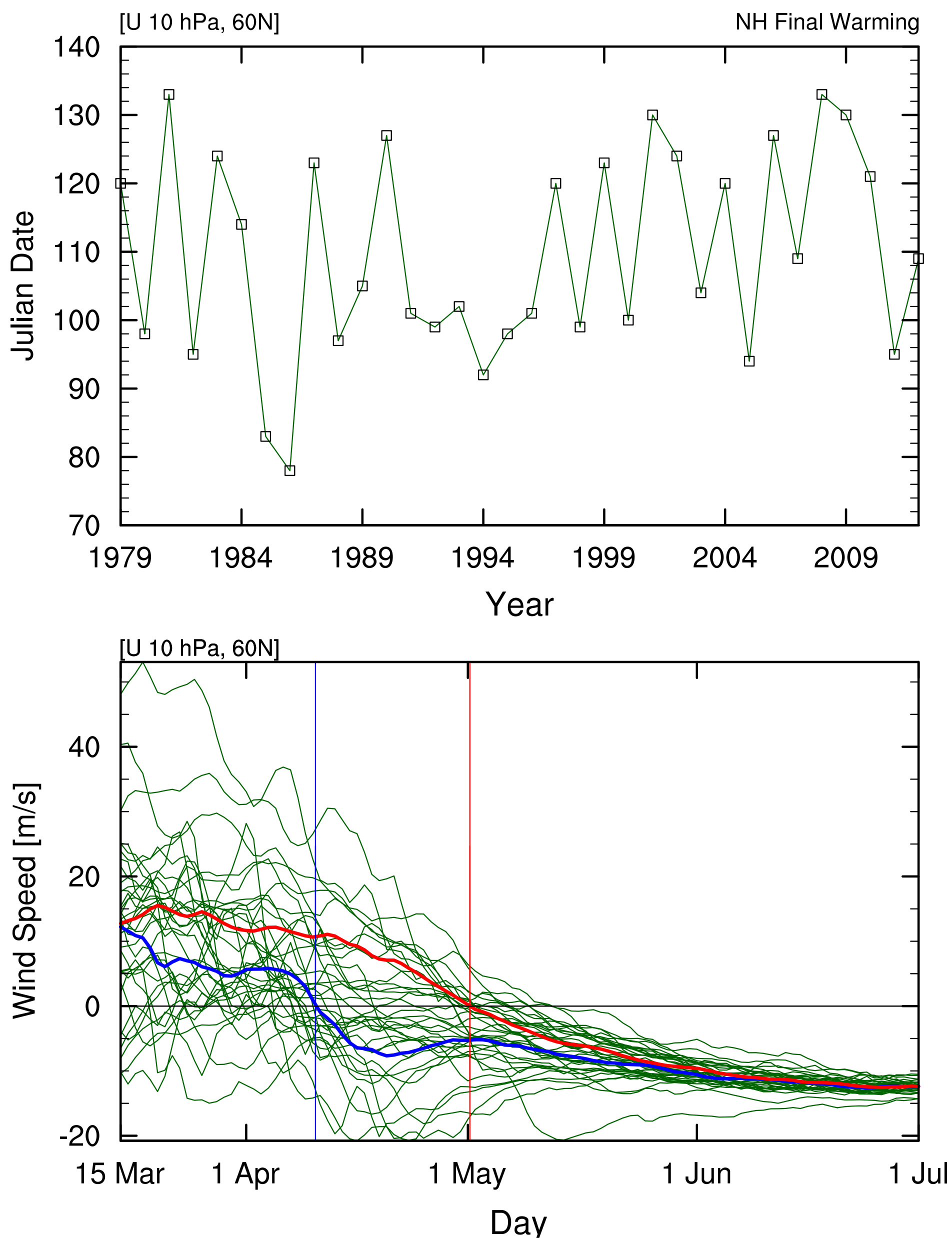

Figure S10. (top) Time series of the polar vortex evolution during the time of final vortex breakup in the NH from MERRA2. The final breakup day is defined as the first day when the is negative, and never recovers. (bottom) Composites of the vortex for REF (blue) and ABS (red) winters. Dark green contour lines denote the time series of zonal mean wind from all years.

Table S1. As in Table 1, but for the CESM1(WACCM) simulation.

Dates	$\min_{60-90^oN}\overline{v'T'}_{k=1}$	$\min_{60-90^oN} dO_3/dt$	Dates	$\min_{60-90^oN}\overline{v'T'}_{k=1}$	$\min_{60-90^oN} dO_3/dt$
18 Mar 1956	-41.41	-23.91	19 Feb 2007	-88.41	-10.96
6 Feb 1958	-61.16	-25.89	28 Feb 2008	-104.6	-12.3
12 Jan 1959	-54.95	-7.81	16 Jan 2010	-71.58	-4.94
14 Jan 1961	-125.9	-5.68	5 Mar 2010	-19.27	-9.61
28 Jan 1962	-92.87	-32.55	3 Feb 2011	-37.05	-7.15
31 Mar 1964	-68.39	-3.13	26 Mar 2011	-157.2	-16.95
10 Feb 1965	-144.5	-47.87	5 Jan 2012	-46.41	-7.46
10 Feb 1966	-64.27	-9.84	29 Jan 2012	-71.7	-54.92
4 Feb 1968	-59.48	-4.51	1 Jan 2014	-37.47	-16.45
28 Mar 1969	-54.76	-16.64	16 Feb 2015	-88.92	-11.65
5 Feb 1970	-91.87	-16.12	25 Jan 2016	-40.82	-9.69
1 Feb 1972	-38.3	-4.73	17 Mar 2016	-70.51	-26.1
6 Jan 1974	-44.33	-8.27	8 Jan 2018	-81.6	-13.93
21 Jan 1977	-63.08	-5.09	15 Feb 2019	-47.7	-22.88
9 Mar 1981	-45.79	-17.27	23 Mar 2019	-55.67	-9.63
5 Feb 1982	-69	-28.15	15 Feb 2023	-70.42	-31.56
27 Mar 1982	-43.4	-25.63	3 Mar 2023	-82.45	-56.34
17 Jan 1984	-62.91	-8.39	13 Jan 2024	-38.01	-13.94
4 Mar 1984	-50.41	-9.26	2 Feb 2025	-103.6	-6.57
20 Jan 1985	-56.24	-9.08	10 Jan 2029	-87.6	-16.32
14 Feb 1985	-120.2	-15.66	29 Jan 2030	-101.3	-8.91
15 Jan 1986	-48	-9.79	31 Jan 2031	-93.74	-5.11
2 Feb 1987	-38.41	-6.21	29 Mar 2034	-69.24	-9.68
10 Mar 1987	-94.01	-19.39	3 Mar 2037	-59.01	-10.83
26 Feb 1990	-84.78	-14.46	2 Mar 2038	-71.45	-19.67
19 Jan 1999	-55.01	-87.78	6 Feb 2042	-73.8	-5.08
11 Feb 1999	-115.7	-23.19	3 Feb 2049	-65.93	-15.85
3 Jan 2004	-73.3	-24.37	20 Jan 2054	-47.82	-34.82
11 Jan 2005	-77.26	-8.04			
16 Feb 2006	-90.56	-47.08			