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Corrigendum to "The wave geometry of final stratospheric warming events" published in Weather Clim. Dynam., 2, 453–474, 2021

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A coding error was found by the authors that affects the final stratospheric warming (FSW) dates at the 50 hPa level only. This error was due to the "return to" value being defined at 0 m s^{-1}, while the threshold of the event itself was defined at 5 m s^{-1} in the Northern Hemisphere (NH) and 10 m s^{-1} in the Southern Hemisphere (SH).

While the code was supposed to detect the first date before 30 June (31 January) at which the daily mean zonal-mean zonal winds at 60° latitude and 50 hPa in the NH (SH) fell below 5 (10) m s^{-1} and did not return to westerly for more than 10 consecutive days, this is not what was actually calculated. In the NH, for example, the code is designed to first detect all the dates that fall below the 5 m s^{-1} threshold, then go through and test if there is an earlier date than the last one that has less than 10 d above zero (in which case it picks that date). The error occurred because the code did not check whether the time period after the last date then returns for less than 10 d above zero. This does not matter for 10 hPa because the threshold and the "return value" are the same, but it introduces an error for the 50 hPa dates.

An example is shown in panel a of the inclusion for the spring of 1958. The published paper states a final warming date of 27 April 1958 (marked by the red dot). However, note that following 27 April, the winds *do* return to above 0 m s^{-1} (dotted line) for more than 10 d during May, meaning that the FSW does not adhere to the stated definition. If we used the definition based on the 0 m s^{-1} "return value" as described in the uncorrected text, the FSW date should have been 20 May 1958. It turns out that 27 April 1958 is actually the first date that the winds fall below 5 m s^{-1} (dashed dotted line) and do not return to that *same* threshold for more than 10 consecutive days (what we would get if we used the corrected definition as described below).

To correct this issue, one option would be to re-calculate the dates using the original definition (using the "return to westerly" criteria), but there are issues with doing it this way. For one thing, it is not clear in this formulation when to apply the "does not return to zero" criteria since the events defined at 5 m s^{-1} could take some time to fall below 0 m s^{-1}. An example is shown in panel b of the inclusion for 1961. The winds fall below 5 m s^{-1} on 20 March 1961 (which again is the date that was published), but after that the winds stay above 0 m s^{-1} for more than 25 d (until around 30 April). The phrasing "return to westerly" thus does not make much sense since the winds have not fallen below 0 m s^{-1} in the first place.

For this reason, in this corrigendum we have changed the definition for the 50 hPa FSWs to have a "return value" that is the same as the date detection threshold (this is already the case for the 10 hPa FSWs). As it turns out this is what the code was actually doing to get most of the published dates.

Therefore, below we outline the changes that were made to fix this error.

- We have corrected the dates for the FSWs defined at 50 hPa using the following updated definition: "FSW events are detected as the first date before 30 June (31 January) when the daily mean zonal-mean zonal winds at 60° latitude and 50 hPa in the NH (SH) fall below a threshold of 5 (10) m s^{-1} and do not return to that same threshold for more than 10 consecutive days."
- Tables 1 and 2 list the corrected NH and SH FSW dates, respectively, using daily mean data from JRA-55 re-

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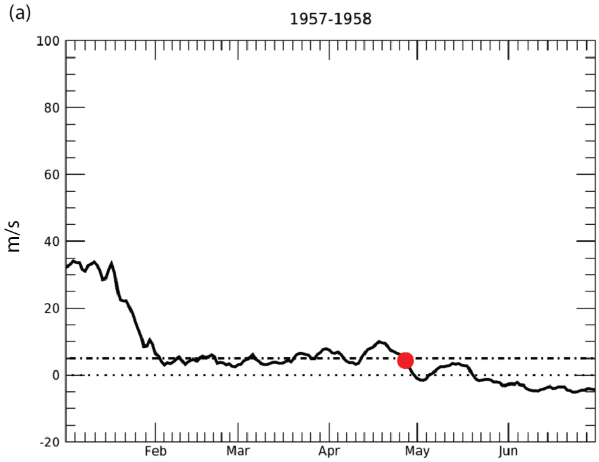

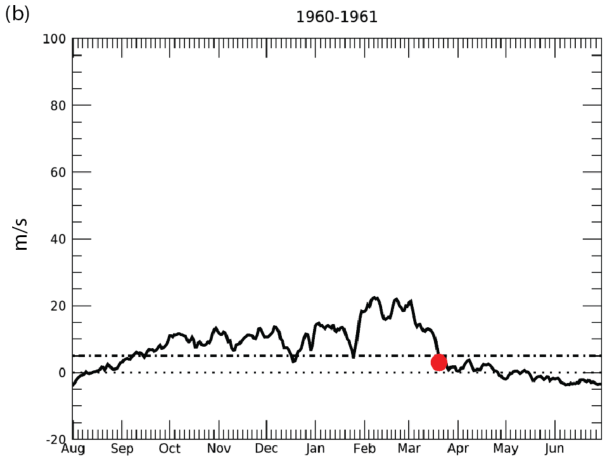

analysis for the January 1958–December 2019 period (note that the dates at 10 hPa are the same as in the published paper). This error affected 15 out of 62 dates in the NH (1971, 1973, 1974, 1985, 1989, 1992, 1998, 1999, 2005, 2007, 2008, 2010, 2012, 2015, 2018) and 3 out of 41 dates in the SH (2002, 2012, 2017). The error does not affect our conclusions or results but does slightly alter most of the figures (quantitatively, not qualitatively). The corrected figures are provided here along with corrected text related to the figures where applicable.

– These changes affect the median date of year (DOY) of the 50 hPa events in each hemisphere, which is now DOY = 102 (12 April in a non-leap year) in the NH and DOY = 337 (3 December in a non-leap year) in the SH, which also changes which events are defined as early versus late. In particular, NH FSWs in the years 1960, 1963, 1969, 1970, 1982, 1992, 1993, 1996, 1998, 1999, 2000, 2010, 2012, 2015, 2017, and 2018 were reclassified by timing (most frequently from early to neutral, e.g., within ± 2 d of median DOY). SH FSWs in the years 1981, 1983, 1984, 1986, 1989, 1992, 1993, 2002, 2005, 2009, 2017, and 2018 were reclassified by timing (typically from either early to neutral or neutral to late). This means that the median FSW in the NH at 50 hPa occurs 22 d after the boreal spring equinox, but the median FSW in the SH at 50 hPa occurs 73 d after the austral spring equinox. In terms of wave classification, no changes to classification resulted in the SH; however, in the NH three wave-2 events were reclassified to wave-1 events (1989, 1992, and 2012), one wave-1 event was reclassified to a wave-2 event (1974), and one unclassified event was reclassified to a wave-1 event (1973) based on the modified 50 hPa dates. Thus for the 50 hPa dates in the NH, there are now 10 wave-2 events compared to 50 wave-1 events for 1958–2019. It remains the case that no statistical difference between the date of wave-1 and wave-2 FSW events at 50 hPa is observed in either hemisphere (Fig. 1b and d).

– Figure 1 reflects the corrected dates of the final warmings at 50 hPa. In the SH, the FSW date correction changes the linear trend for the 2001–2019 period for the 50 hPa dates to $-0.7 \pm 0.7\,\mathrm{d\,yr^{-1}}$ which is not statistically significant (the trend for the 50 hPa FSW dates for 1979–2000 is not affected because no dates changed during that time period). The correlation of the FSW dates at 10 and 50 hPa becomes $r = 0.57$ ($n = 62$, $\rho < 0.01$) in the NH (1958–2019) and $r = 0.81$ ($n = 41$, $\rho < 0.01$) in the SH (1979–2019). The standard deviations for the 50 hPa dates change to 17 d in the NH (1958–2019) and 14 d in the SH (1979–2019). For the FSWs at 50 hPa, the difference in median date for years with and without midwinter sudden stratospheric warmings (SSWs) changes to 7 d (years without an SSW show earlier FSWs than years with a SSW).

– Figure 2 is updated to reflect the new 50 hPa dates in the SH. The correlation coefficient between the 50 hPa FSW dates and austral spring polar cap total column ozone changes to $r = -0.60$ ($n = 41$, $\rho < 0.01$).

– Figure 3 shows the same cases as before with one exception (panel h). This previously showed the SH final warming in 2012 for the wave-2 example, but the change in date meant the wave-2 structure became less apparent (though it remains classified as a wave-2). Instead, we now show a different wave-2 example using the 22 November 1982 FSW at 50 hPa.

– No changes were needed for Fig. 4, which was based on the FSWs defined at 10 hPa.

– The updated Fig. 5 using the new dates at 50 hPa in both hemispheres looks almost identical to the composites in the original paper, and the text describing this figure does not need correction.

- The updated Fig. 6 for the corrected 50 hPa dates is very similar to the figure in the original paper with some differences in statistical significance particularly for the SH in panels d and h. The text describing this figure should be corrected to the following (changes in bold): "The average decrease in wind speed between the average over lags of −30 to −11 d before the FSW event and days 11 to 30 after the event is 25.2 $\mathrm{m\,s^{-1}}$ (36.7 $\mathrm{m\,s^{-1}}$) for the NH (SH) at 10 hPa. Further down at 50 hPa, these values are smaller, **i.e. 13.7 $\mathbf{m\,s^{-1}}$ (25.1 $\mathbf{m\,s^{-1}}$**) for the NH (SH)." For the comparison of early and late events, the text should be corrected to the following: "The decrease in wind speed between the average over lags of −30 to −11 d before the FSW event and days 11 to 30 after the event is 31.4 $\mathrm{m\,s^{-1}}$ (**14.6 $\mathbf{m\,s^{-1}}$**) at 10 (50) hPa for early events. For late events, the corresponding values are 18.8 $\mathrm{m\,s^{-1}}$ (**12.8 $\mathbf{m\,s^{-1}}$**) at 10 (50) hPa. In the SH, the winds exhibit similar strengths before the FSW event at both 10 and 50 hPa, although the deceleration at the time of the FSW event is stronger at 10 hPa compared to 50 hPa. The decrease in wind speed between the average over lags of −30 to −11 d before the FSW event and days 11 to 30 after the event is 39.3 $\mathrm{m\,s^{-1}}$ (**29.1 $\mathbf{m\,s^{-1}}$**) at 10 (50) hPa for early events. For late events, the corresponding values are 33.4 $\mathrm{m\,s^{-1}}$ (22.8 $\mathrm{m\,s^{-1}}$) at 10 (50) hPa. The wind speeds at 10 hPa between early and late events are significantly different from each other for most lags before the FSW event, **while the winds speeds at 50 hPa between early and late events are significantly different only for roughly half of the time steps before the FSW event**. After the FSW event, significant differences can only be detected between early and late events for the first few days at 10 hPa in the NH **and at longer lags at 50 hPa in both hemispheres**."

- Figure 7 did not need to be updated as it was composited based on 10 hPa FSW dates. The corresponding figure for the 50 hPa FSW dates in the Appendix (Fig. A1) was updated and the results are not qualitatively different from the original paper.

- Figure 8 was updated using the corrected 50 hPa FSW dates. The comparable figure for 10 hPa dates (Fig. A2) did not need to be corrected. Qualitatively Fig. 8 does not change much and our conclusions remain the same. We had noted a significant difference over the North Pacific between wave-1 and wave-2 events which is no longer significant using the corrected dates. However, there are more significant differences over the North Pacific and western North America for early versus late events in the corrected figure. Few qualitative differences are noted for the SH in the updated figure.

- Figure 9 was updated using the corrected 50 hPa FSW dates. The text should be corrected as follows: "[North Atlantic Oscillation, NAO] values significantly different from zero are observed primarily for wave-1 events for lags between 20 and 30 d before the FSW event and for wave-2 events for lags between 5 and 15 d before the FSW event."

Table 1. Dates and classifications for FSW events in the Northern Hemisphere according to JRA-55 reanalysis. Early (late) events are indicated in bold (cursive), referring to a day of year (DOY) before (after) the median DOY of 102 (corresponding to 12 April in a non-leap year) at both 10 and 50 hPa. DOYs that fall within ±2 d of the median DOY are not classified as early or late. U = unclassified (methods did not agree according to the criterion). Superscripts indicate the ERA-interim classification if it was not in agreement with JRA-55 during the 1979–2019 period.

Year	Date 10 hPa	Type	Date 50 hPa	Type	Year	Date 10 hPa	Type	Date 50 hPa	Type
1958	*3 May*	wave-2	*27 Apr*	wave-1	1989	*15 Apr*	wave-2	**9 Mar**	wave-1
1959	**18 Mar**	wave-1	**4 Apr**	wave-1	1990	*8 May*	wave-1	*12 May*	wave-1
1960	**2 Apr**	wave-2	12 Apr	wave-1	1991	10 Apr	wave-1	14 Apr	wave-1
1961	**11 Mar**	wave-1	**20 Mar**	wave-1	1992	**22 Mar**	wave-1	9 Apr	wave-1
1962	*28 Apr*	wave-1	*30 Apr*	wave-1	1993	12 Apr	wave-1	*15 Apr*	wave-1
1963	*3 May*	wave-1	12 Apr	wave-2	1994	**2 Apr**	wave-1	13 Apr	wave-2
1964	**19 Mar**	wave-1	**19 Mar**	wave-1	1995	**8 Apr**	wave-1	**7 Apr**	wave-1
1965	*19 Apr*	wave-2	*19 Apr*	wave-2	1996	10 Apr	wave-1	10 Apr	wave-1
1966	**9 Apr**	wave-1	**7 Apr**	wave-1	1997	*30 Apr*	wave-1	*6 May*	wave-1
1967	14 Apr	wave-1	*27 Apr*	wave-1	1998	**28 Mar**	wave-1	**3 Apr**	wave-1
1968	*21 Apr*	wave-1	*3 May*	wave-1	1999	*2 May*	wave-1	**3 Mar**	wave-1
1969	13 Apr	wave-1	*16 Apr*	wave-1	2000	9 Apr	wave-1	11 Apr	wave-1
1970	12 Apr	wave-1	12 Apr	wave-1	2001	*10 May*	wave-1	*28 Apr*	U
1971	*24 Apr*	wave-1	**19 Mar**	wave-1	2002	*2 May*	U^2	*30 Apr*	wave-1
1972	**25 Mar**	wave-1	**2 Apr**	wave-1	2003	14 Apr	wave-2	14 Apr	wave-2
1973	*6 May*	wave-1	**30 Mar**	wave-1	2004	*29 Apr*	wave-2	*28 Apr*	wave-2
1974	**12 Mar**	wave-2	**13 Mar**	wave-2	2005	**13 Mar**	wave-1	**13 Mar**	wave-1
1975	**17 Mar**	wave-1	**20 Mar**	wave-1	2006	*7 May*	wave-1	*1 May*	wave-2
1976	**30 Mar**	wave-2	**3 Apr**	wave-2	2007	*19 Apr*	wave-1	*20 Apr*	wave-1
1977	**1 Apr**	wave-1	**4 Apr**	wave-1	2008	*1 May*	wave-1	**26 Mar**	wave-1
1978	**12 Mar**	wave-1	**26 Mar**	wave-1	2009	*10 May*	wave-2	*1 May*	wave-3
1979	**8 Apr**	wave-2	**5 Apr**	wave-2	2010	*30 Apr*	wave-2	**25 Mar**	wave-1
1980	**8 Apr**	wave-1	**5 Apr**	wave-1	2011	**5 Apr**	wave-1	13 Apr	wave-1
1981	*13 May*	wave-2	*7 May*	wave-1	2012	*18 Apr*	wave-2	**1 Apr**	wave-1
1982	**4 Apr**	wave-1	*16 Apr*	wave-1	2013	*3 May*	wave-1	*10 May*	wave-1^U
1983	**1 Apr**	wave-1	**23 Mar**	wave-1	2014	**27 Mar**	wave-1	*18 Apr*	wave-1
1984	*25 Apr*	wave-1	**11 Mar**	wave-1	2015	**28 Mar**	wave-1	**5 Apr**	wave-1
1985	**24 Mar**	wave-1	**25 Mar**	wave-1	2016	**5 Mar**	wave-1	**12 Mar**	wave-1
1986	**19 Mar**	wave-1	**31 Mar**	wave-2	2017	**8 Apr**	wave-1	10 Apr	wave-1
1987	*2 May*	wave-1	*24 Apr*	wave-1	2018	*15 Apr*	wave-1^U	**4 Apr**	wave-1
1988	**6 Apr**	wave-1	13 Apr	wave-1	2019	*23 Apr*	wave-1	*28 Apr*	wave-1

Table 2. Dates and classifications for FSW events in the Southern Hemisphere according to JRA-55 reanalysis. Early (late) events are indicated in bold (cursive), referring to a day of year (DOY) before (after) the median DOY of 321 (17 November in a non-leap year) at 10 hPa and DOY 337 (3 December in a non-leap year) at 50 hPa. Dates that fall within ±2 d of the median DOY are not classified as early or late. U = unclassified (methods did not agree according to the criterion outlined). Superscripts indicate the ERA-interim classification if it was not in agreement with JRA-55 during the 1979–2018 period.

Year	Date 10 hPa	Type	Date 50 hPa	Type	Year	Date 10 hPa	Type	Date 50 hPa	Type
1979	17 Nov	wave-1	**20 Nov**	wave-1	2000	**4 Nov**	wave-1	**18 Nov**	wave-1
1980	17 Nov	wave-1	**22 Nov**	wave-1	2001	*7 Dec*	wave-2	*26 Dec*	wave-2
1981	17 Nov	wave-2	3 Dec	wave-1	2002	**1 Nov**	wave-1	**3 Nov**	wave-1
1982	18 Nov	wave-2	**22 Nov**	wave-2	2003	15 Nov	wave-1	**28 Nov**	wave-1
1983	**7 Nov**	wave-1	*6 Dec*	wave-1	2004	16 Nov	wave-1	**28 Nov**	wave-1
1984	**6 Nov**	wave-1	1 Dec	wave-1	2005	**10 Nov**	wave-1	*8 Dec*	wave-1
1985	*25 Nov*	wave-1	*12 Dec*	U[1]	2006	*3 Dec*	wave-1	*17 Dec*	wave-1
1986	**13 Nov**	wave-1	1 Dec	wave-1	2007	*27 Nov*	wave-1	*24 Dec*	wave-2
1987	*1 Dec*	wave-1	*12 Dec*	wave-1	2008	*1 Dec*	wave-1	*24 Dec*	wave-1
1988	**27 Oct**	wave-1	**19 Nov**	wave-1	2009	16 Nov	wave-2	3 Dec	wave-1
1989	**10 Nov**	wave-1	*7 Dec*	wave-1	2010	*11 Dec*	wave-1	*21 Dec*	wave-1
1990	*4 Dec*	U[1]	*14 Dec*	wave-1	2011	*25 Nov*	wave-1	*17 Dec*	wave-1
1991	**14 Nov**	wave-1	**20 Nov**	wave-1	2012	**5 Nov**	wave-1[U]	**8 Nov**	wave-2
1992	*20 Nov*	U	*8 Dec*	wave-1	2013	**2 Nov**	wave-1	**27 Nov**	wave-1
1993	*22 Nov*	wave-1	*7 Dec*	wave-1	2014	*22 Nov*	wave-1	*13 Dec*	wave-1
1994	**11 Nov**	wave-1	**24 Nov**	wave-1	2015	*11 Dec*	wave-1	*13 Dec*	wave-1
1995	*23 Nov*	wave-1	*19 Dec*	wave-1	2016	**10 Nov**	wave-1	**21 Nov**	wave-1
1996	*3 Dec*	wave-1	*9 Dec*	wave-1	2017	**9 Nov**	wave-1	1 Dec	wave-1
1997	17 Nov	wave-1	**25 Nov**	U	2018	*24 Nov*	wave-1	1 Dec	wave-2
1998	*7 Dec*	wave-1[U]	*22 Dec*	wave-1	2019	**30 Oct**	wave-1	**9 Nov**	wave-1
1999	*5 Dec*	wave-1	*2 Jan (2000)*	wave-1					

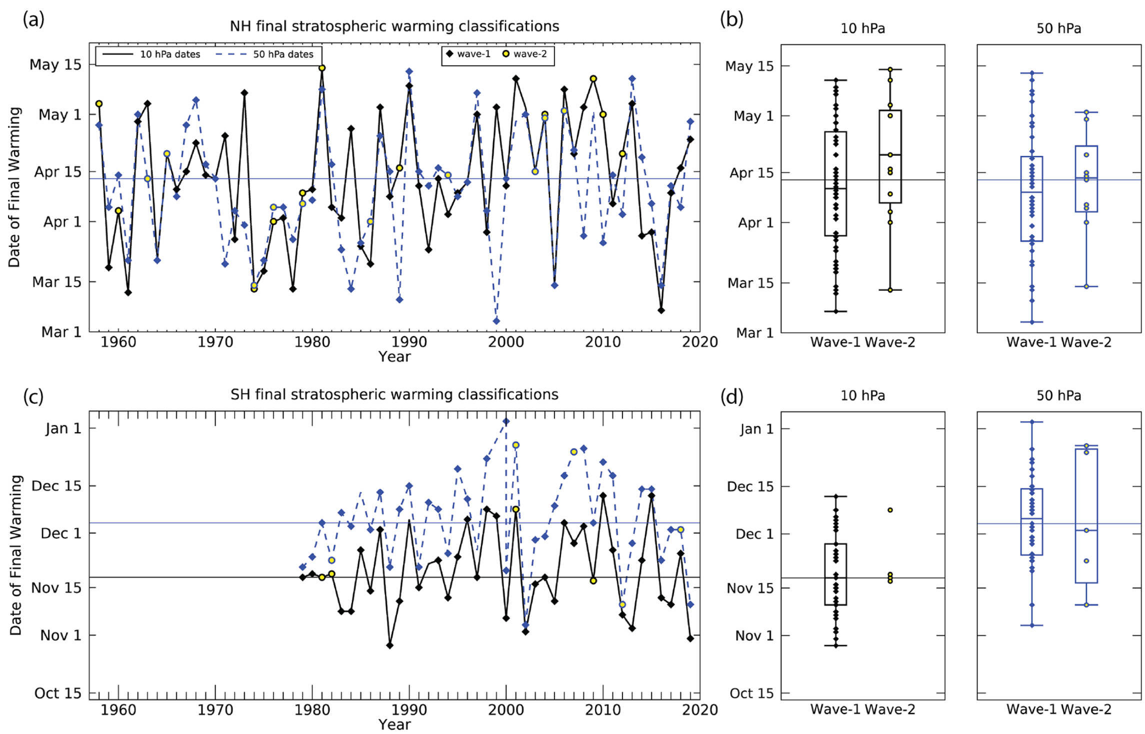

Figure 1. (a, c) Dates of FSWs in the NH (1958–2019) and SH (1979–2019), using JRA-55 reanalysis based on zonal-mean zonal winds below 0 m s^{-1} at 10 hPa (solid black line) and below 5 (10) m s^{-1} at 50 hPa in the NH (SH) (dashed blue line). Symbols indicate the wave classification of the event. **(b, d)** Dates of FSWs at 10 and 50 hPa grouped by either wave-1 or wave-2 classification. The whiskers show the earliest/latest dates, the top/bottom of the box shows the upper and lower quartiles, and the solid line shows the median date (in a non-leap year) for each classification. The horizontal lines indicate the median date (based on the 1979–2019 period) for all final warmings in each hemisphere.

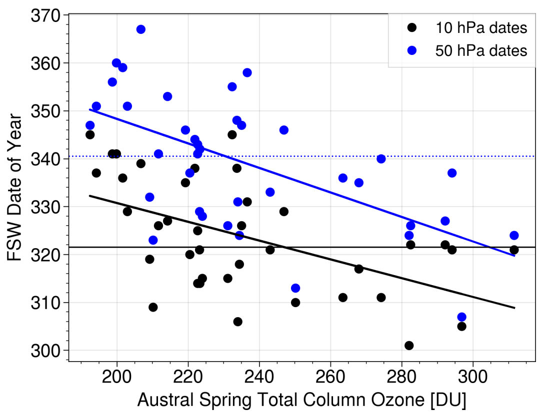

Figure 2. Polar cap total column ozone (TCO) (Dobson units) averaged from 7 September–13 October for each year versus the FSW date in the SH (1979–2019), using zonal-mean zonal winds below $0\,\mathrm{m\,s^{-1}}$ at 10 hPa (black) or below $10\,\mathrm{m\,s^{-1}}$ at 50 hPa (blue). The solid (dashed) horizontal line indicates the median date for FSW dates defined at 10 (50) hPa. TCO data are from the Bodeker Scientific filled total column ozone (TCO) database (Version 3.4)

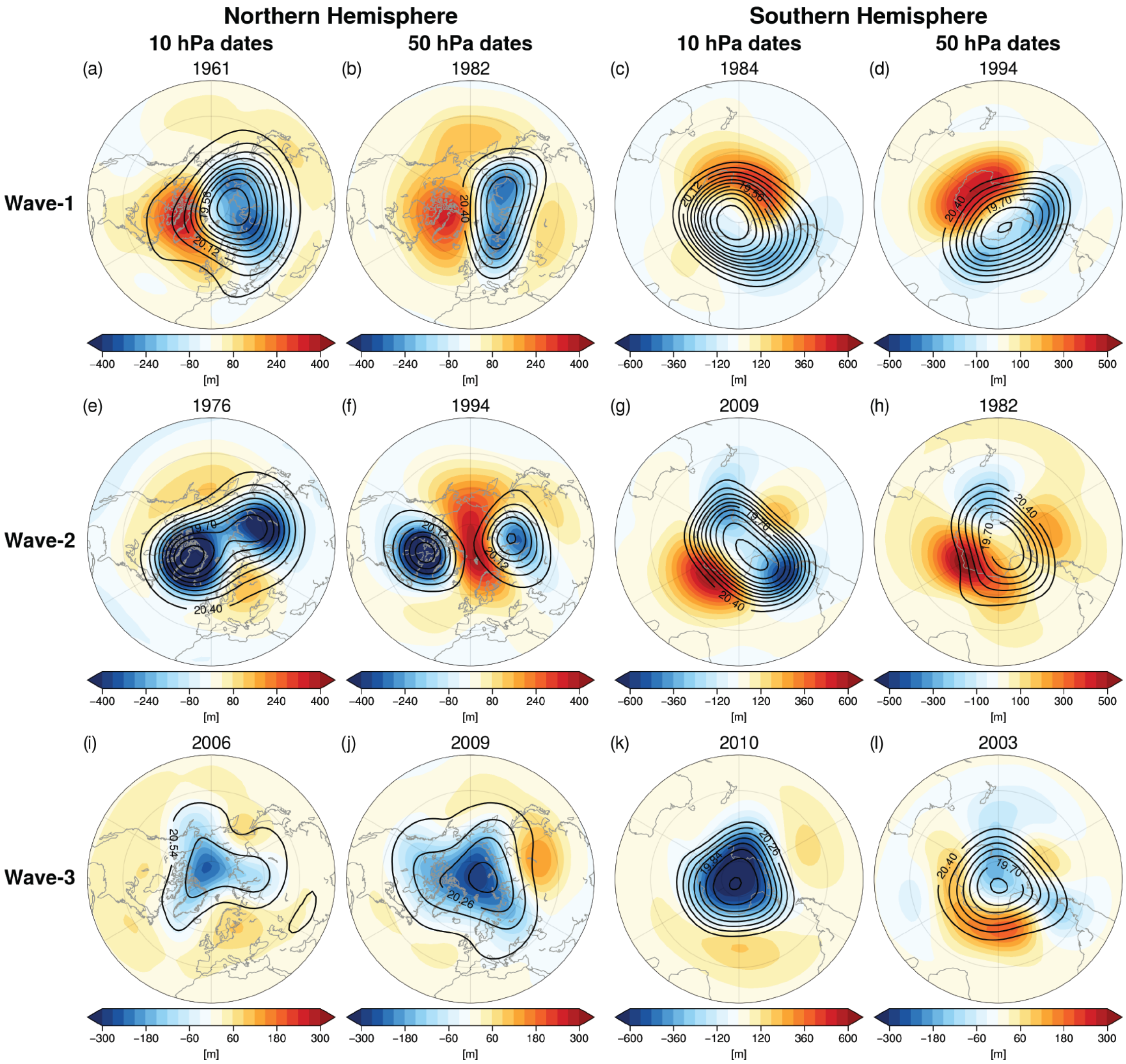

Figure 3. The 50 hPa geopotential heights (contours, km) and anomalies (shading, m) from JRA-55 reanalysis averaged over the 10 d prior to the final warming for selected case studies that show a clear wave structure for **(a–d)** wave-1, **(e–h)** wave-2, and **(i–l)** wave-3 for both hemispheres and for FSWs dates at both 10 and 50 hPa. Note the different color bars.

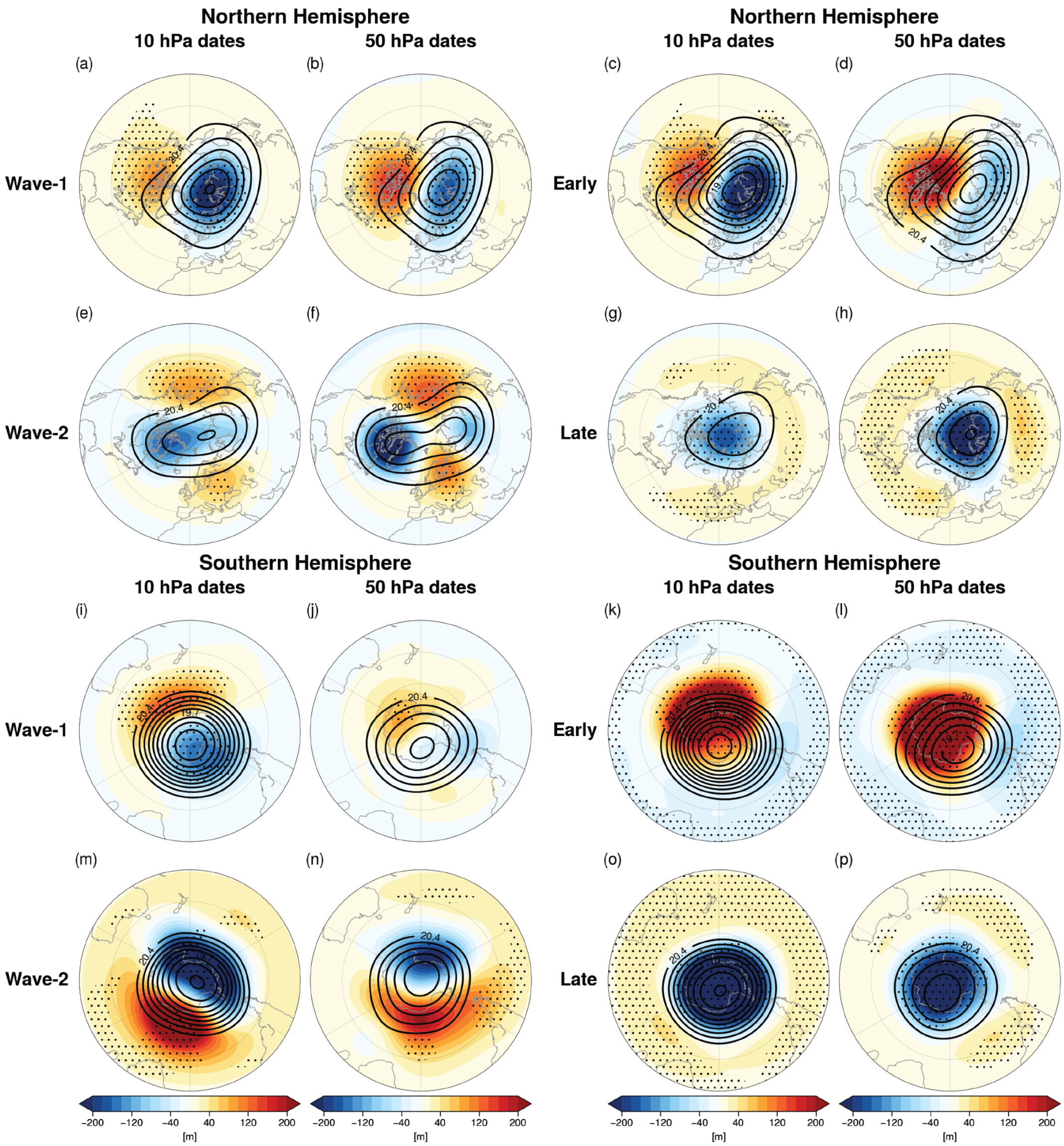

Figure 5. The 50 hPa geopotential heights (contours, km) and anomalies (shading, m) from JRA-55 reanalysis averaged over the 10 d prior to the final warming at both 10 and 50 hPa for **(a–h)** the NH and **(i–p)** the SH. Panels show the composites based on wave-1 or wave-2 classification, or early or late classification. Stippling indicates regions where the anomaly composites are significantly different from zero at the 95 % confidence level according to a two-tailed t test.

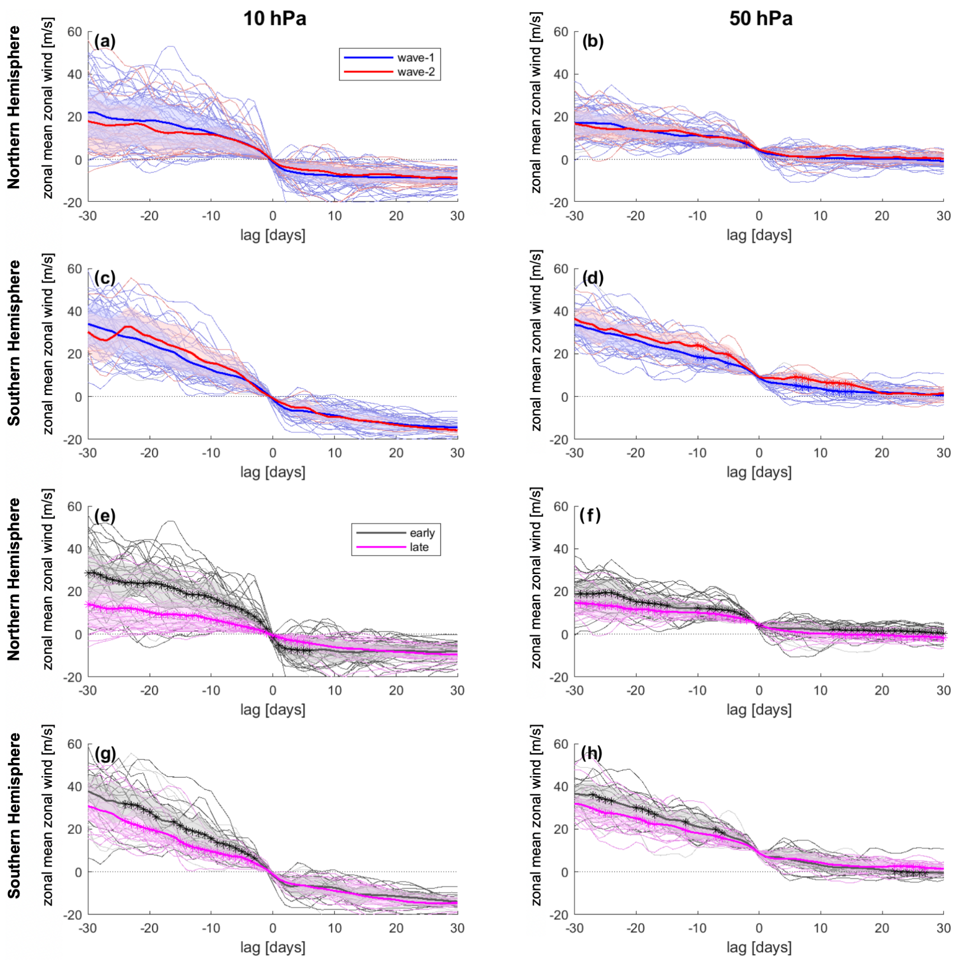

Figure 6. Composites of zonal mean zonal wind ($m\,s^{-1}$) at 60° latitude and 10 hPa (left) and 50 hPa (right) for the NH **(a, b, e, f)** and the SH **(c, d, g, h)** for 1958–2019 (NH) and 1979–2019 (SH) for lags of -30 to $+30$ d around all final warming event dates defined at the indicated level. **(a–d)** Thin blue (red) lines correspond to a wave-1 (wave-2) classification. Thin gray lines (if applicable) correspond to FSW events unclassified by wavenumber. The bold blue (red) lines indicate the average of all events classified as wave-1 (wave-2) at the depicted level. The blue (red) shading indicates the area between the 25th and 75th percentile for the wave-1 (wave-2) classification. **(e–h)** Same as **(a–d)** but for early (black) versus late (pink) FSW events; see text for definition. Thin gray lines correspond to FSW events classified as neither early nor late at the depicted level. Stars denote lags for which the composites for wave-1 and wave-2 or early and late events, respectively, are significantly different from each other at the 95 % level according to a t test.

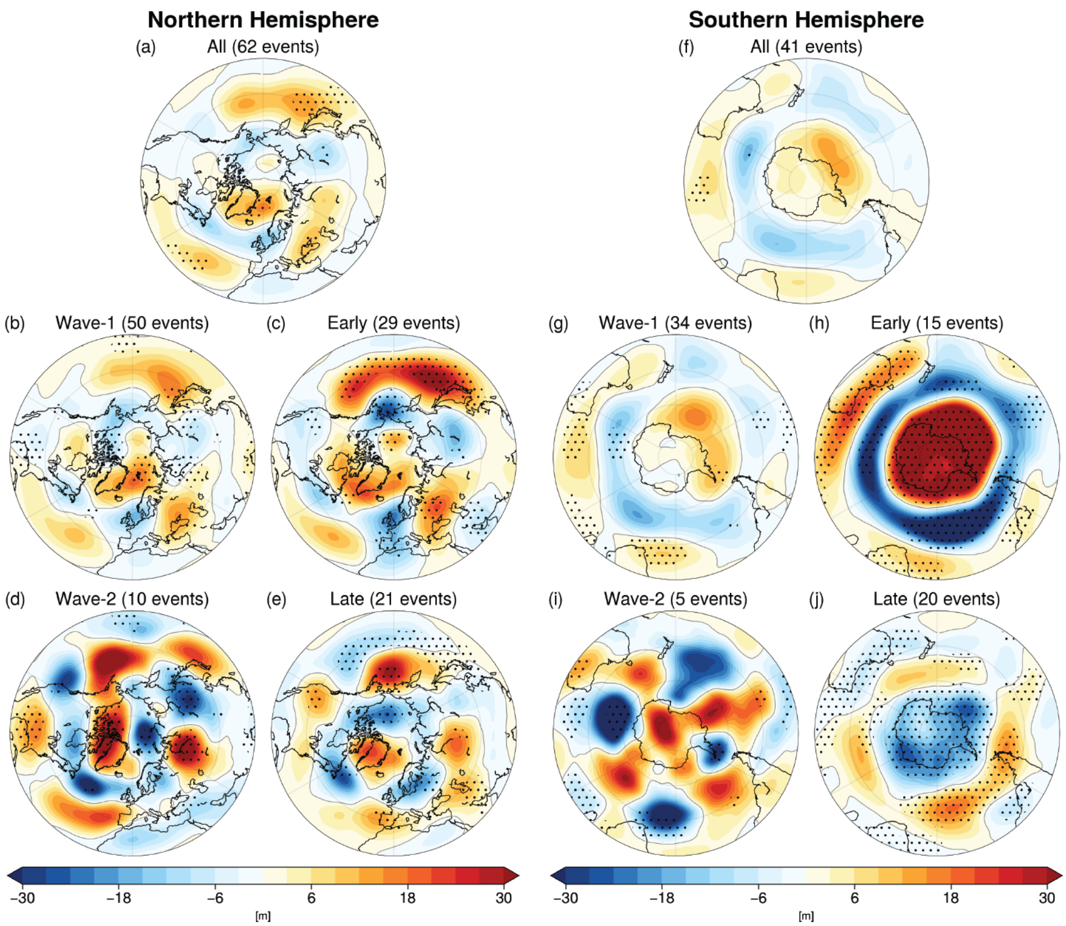

Figure 8. Composite of the linearly detrended 500 hPa geopotential height anomalies (m) from JRA-55 data for **(a, f)** all FSW events based on the 50 hPa dates and classified as **(b, g)** wave-1, **(d, i)** wave-2, **(c, h)** early, or **(e, j)** late averaged over the 7–30 d after the central FSW date (i.e., lags of 7–30 d) for **(a–e)** the NH and **(f–j)** the SH extratropics. Stippling in **(a, f)** indicates regions where the anomaly composites are significantly different from zero at the 95 % confidence level according to a *t* test, while stippling in other panels shows where composites are significantly different from each other (e.g., wave-1 versus wave-2, early versus late) according to a 1000-sample bootstrap analysis (with replacement).

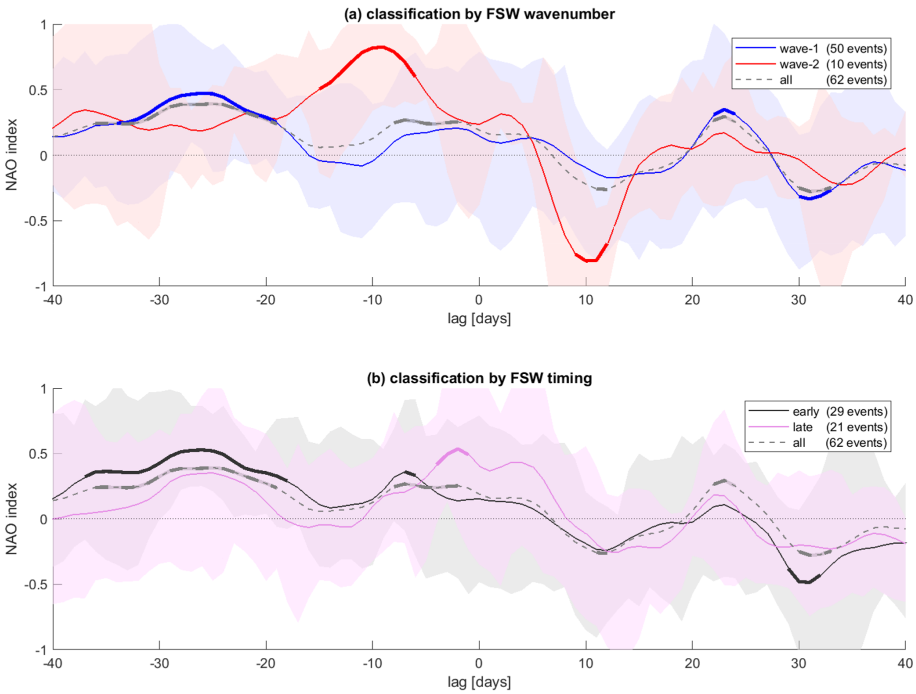

Figure 9. Composite of the NAO index (using a 3 d running mean) for lags of −40 to +40 d around the final warming dates at 50 hPa for 1958–2019. **(a)** The blue (red) lines indicate the average values for the wave-1 (wave-2) classification. The dashed gray line is the average over all FSW events from 1958–2019, including unclassified events. Bold parts of the lines indicate values significantly different from zero at the 95 % level according to a *t* test. The blue (red) shading indicates the 25th and 75th percentiles for the wave-1 (wave-2) classification. **(b)** Same as **(a)** but for early (black) versus late (purple) FSW events.

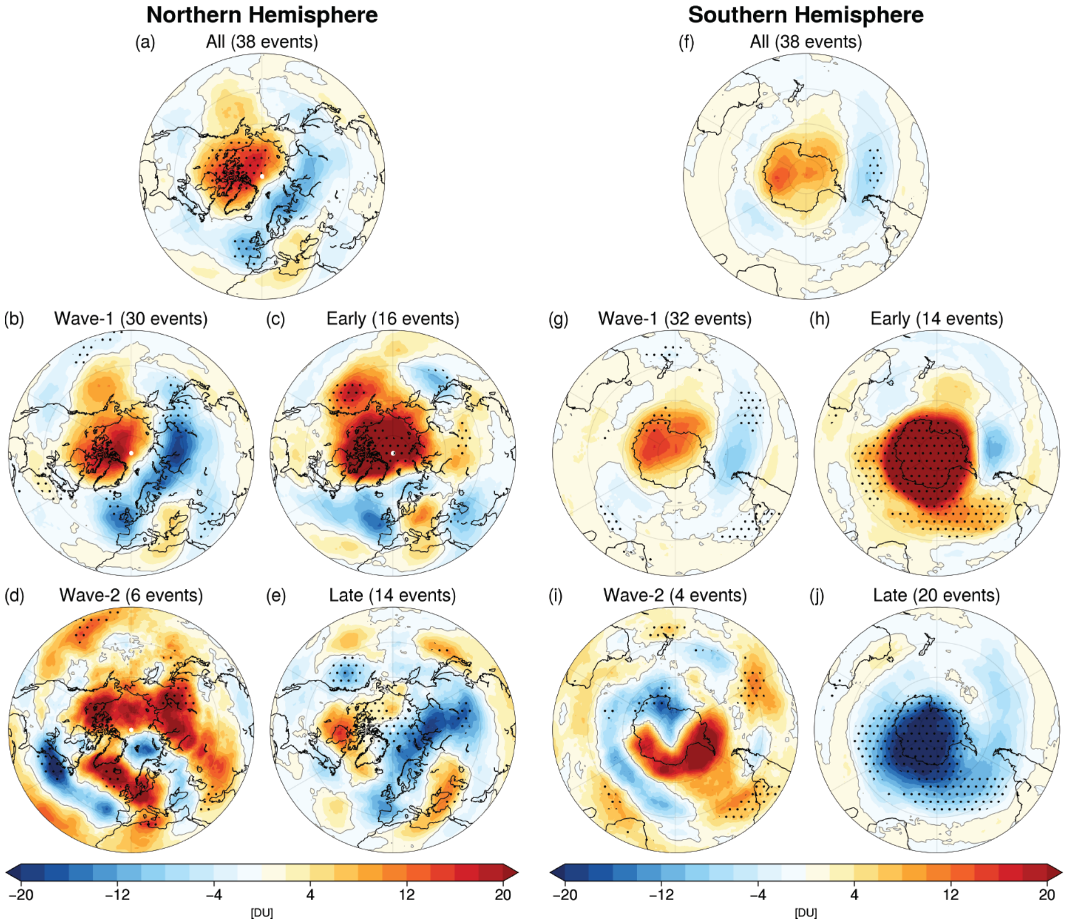

Figure A1. Composite total column ozone anomaly (Dobson units) averaged over the 10 d prior to FSWs at 50 hPa for **(a–e)** the NH and **(f–j)** the SH. Panels show the composites based on **(a, f)** all events from 1979–2016 (the period of the TCO dataset), **(b, g)** wave-1 or **(d, i)** wave-2 classification, or **(c, h)** early or **(e, j)** late classification. Stippling in **(a, f)** indicates regions where the anomaly composites are significantly different from zero at the 95 % confidence level on a two-tailed *t* test; stippling in other panels shows where composites are significantly different from each other (e.g., wave-1 versus wave-2, early versus late) using a *t* test for two samples of unequal variance.