

Geophysical Research Letters

Supporting Information for

QBO/Solar Modulation of the Tropical Madden-Julian Oscillation: A Mechanism Based on Extratropical Wave Forcing in Late Fall and Early Winter

Lon L. Hood¹, Natasha E. Trencham¹, and Thomas J. Galarneau, Jr.²

¹Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona

²NOAA/OAR/National Severe Storms Laboratory, Norman, Oklahoma

Contents of this file:

Figures S1 to S23

Tables S1 to S4

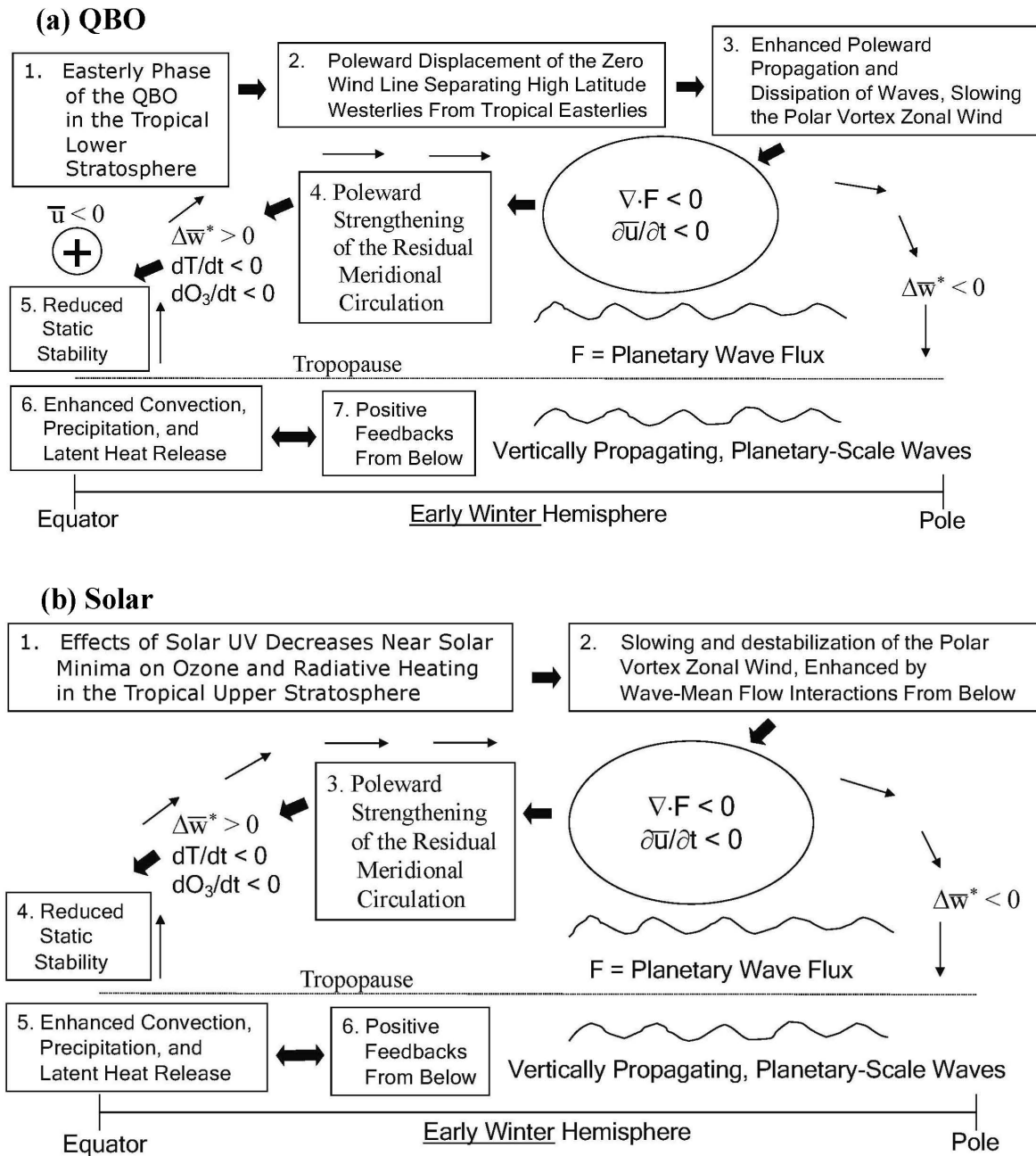


Figure S1. Schematic outlines of the proposed mechanisms by which the easterly phase of the stratospheric QBO and the minimum phase of the 11-year solar cycle can result in reduced static stability in boreal winter in the tropical lowermost stratosphere and enhanced convection, leading to increased MJO amplitudes. Heavy dark arrows indicate the flow of the proposed mechanisms; thin arrows represent the induced anomaly of the Brewer-Dobson circulation.

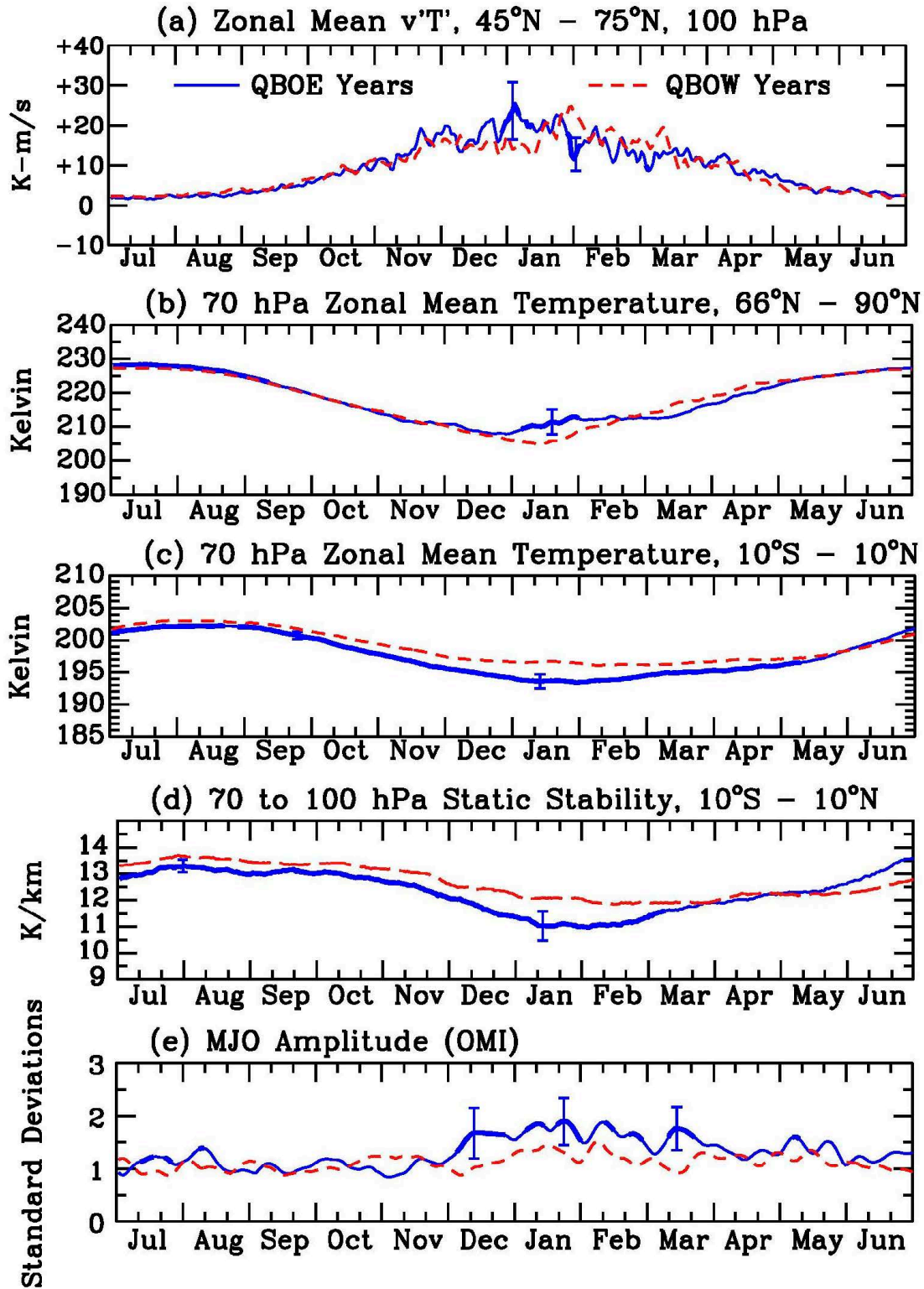


Figure S2. As in Figure 2 but using the relaxed Method 2 of QBO phase selection (15 QBOE winters and 25 QBOW winters).

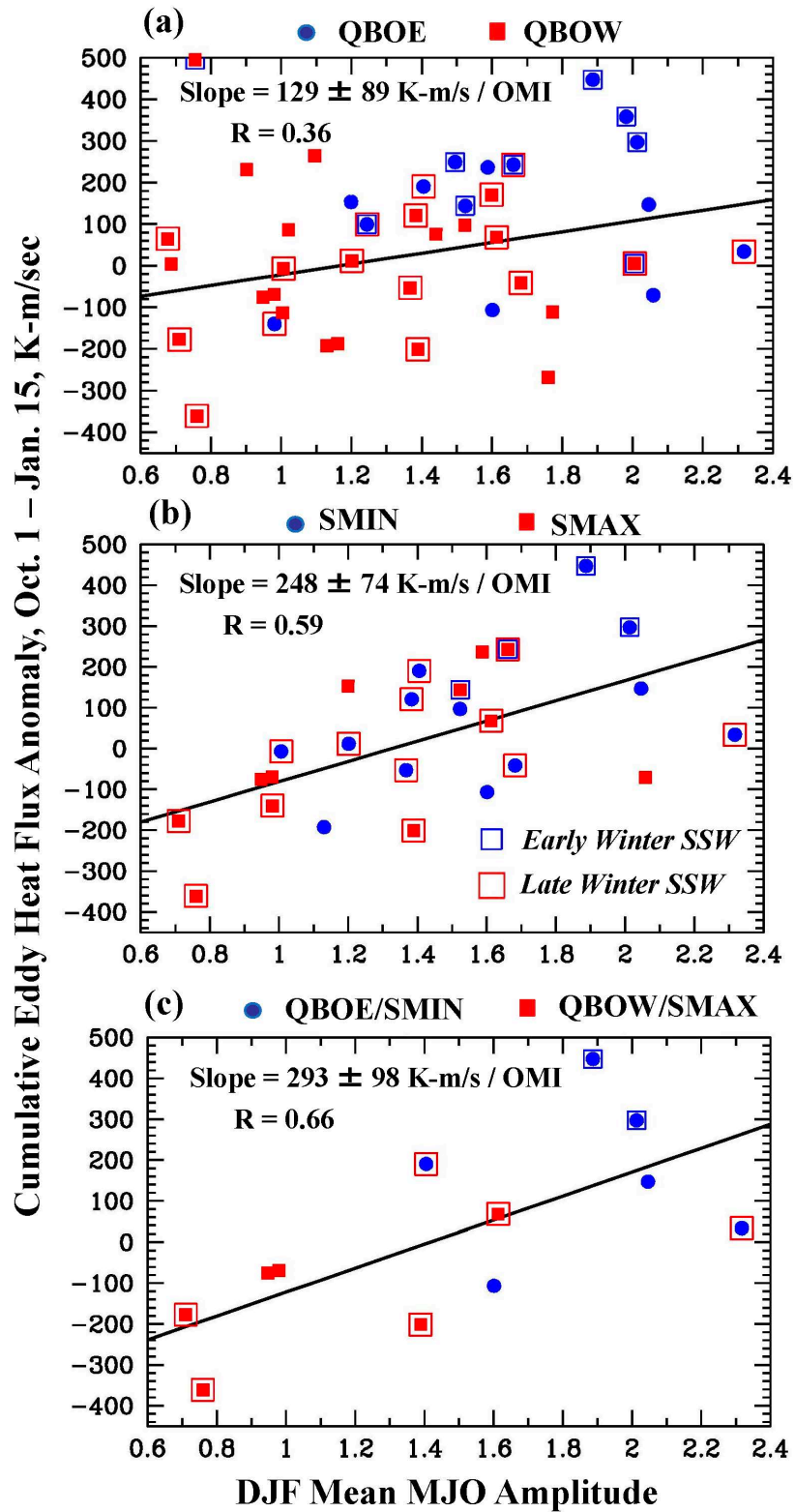


Figure S3. As in Figure 3 but using the relaxed Method 2 of QBO phase selection (15 QBOE winters and 25 QBOW winters; 6 QBOE/SMIN winters and 6 QBOW/SMAX winters).

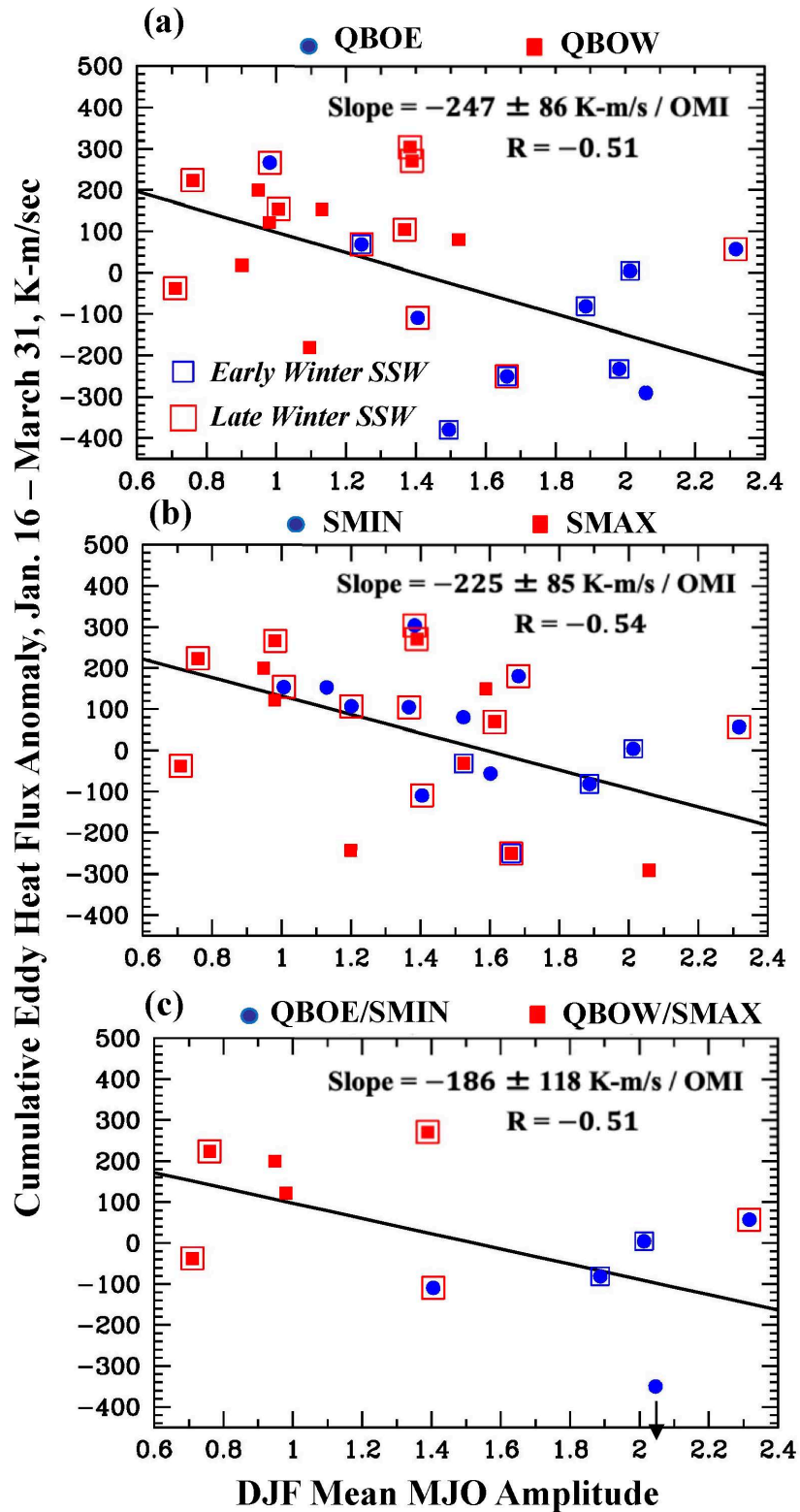


Figure S4. As in Figure 3 but the cumulative daily 100 hPa 45°N to 75°N meridional eddy heat flux anomalies are calculated over the Jan. 16 to March 31 period for each winter.

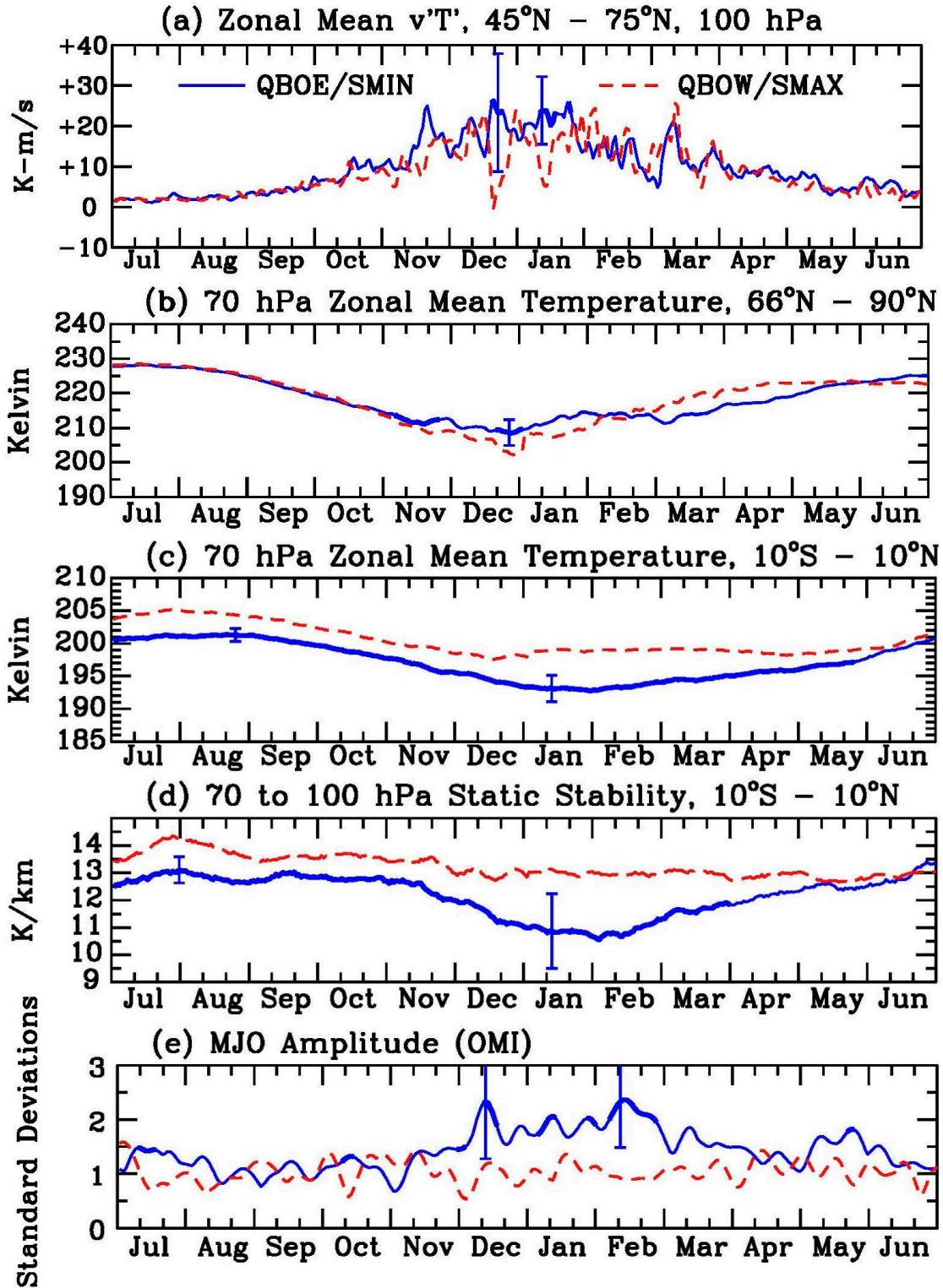


Figure S5. As in Figure 2 but comparing composites for the 5 QBOE/SMIN (Method 1) years versus the 5 QBOW/SMAX years.

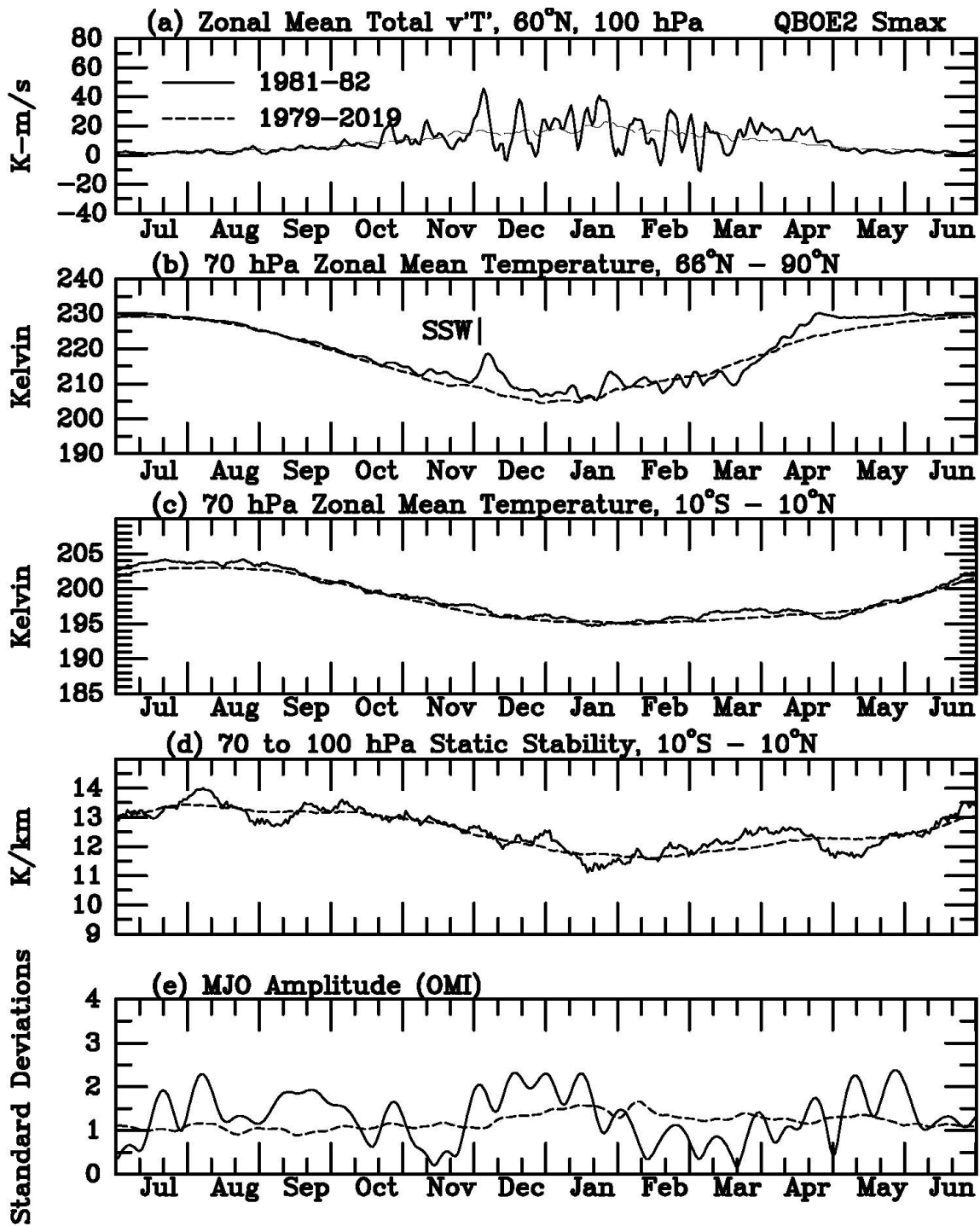


Figure S6. Annual time series in a format similar to Figure 2 but for the 1981-1982 winter, which included an early winter SSW. The central date of the SSW is indicated in panel (b). 1979-2019 means are shown for comparison.

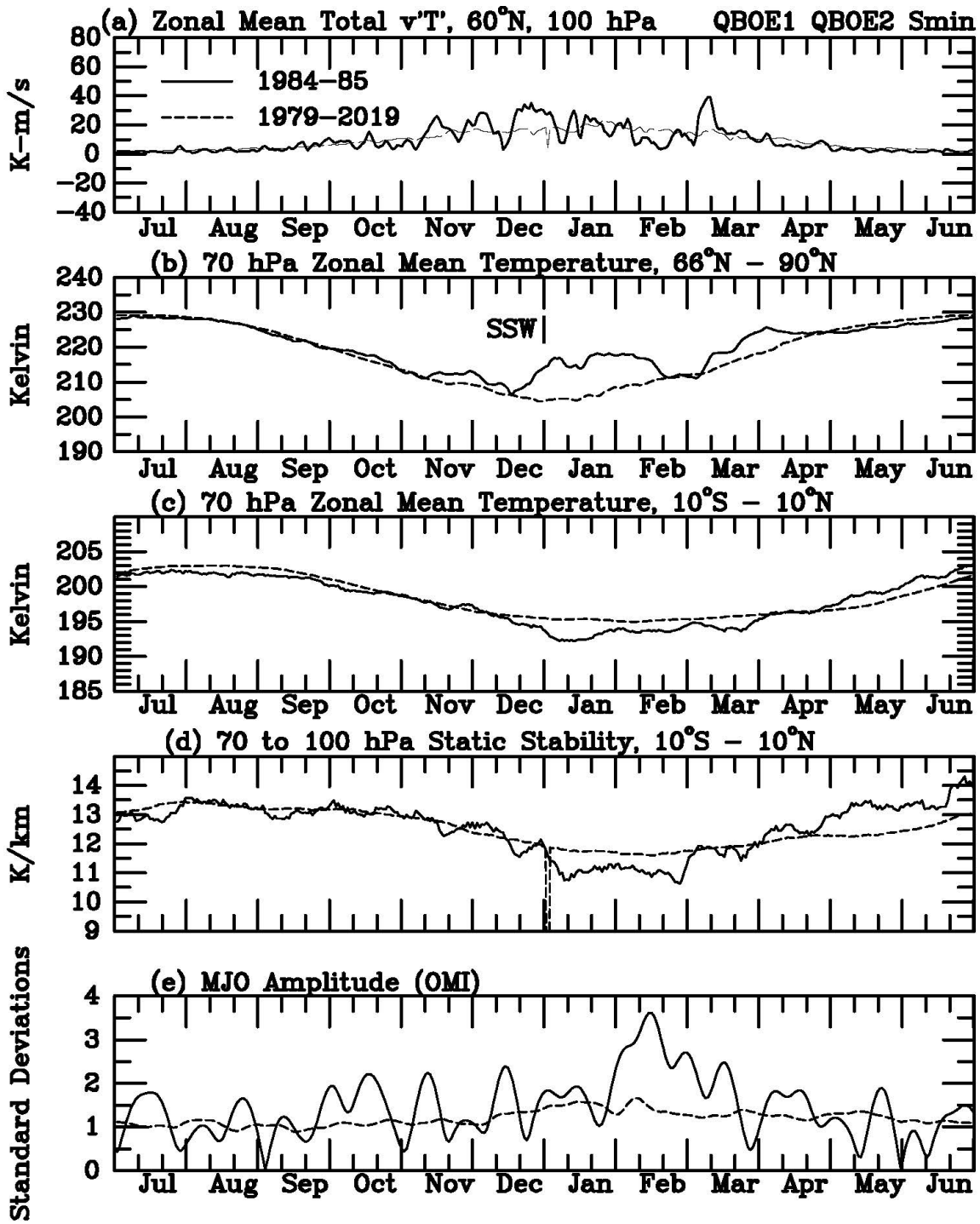


Figure S7. As in Figure S6 but for the 1984-1985 winter.

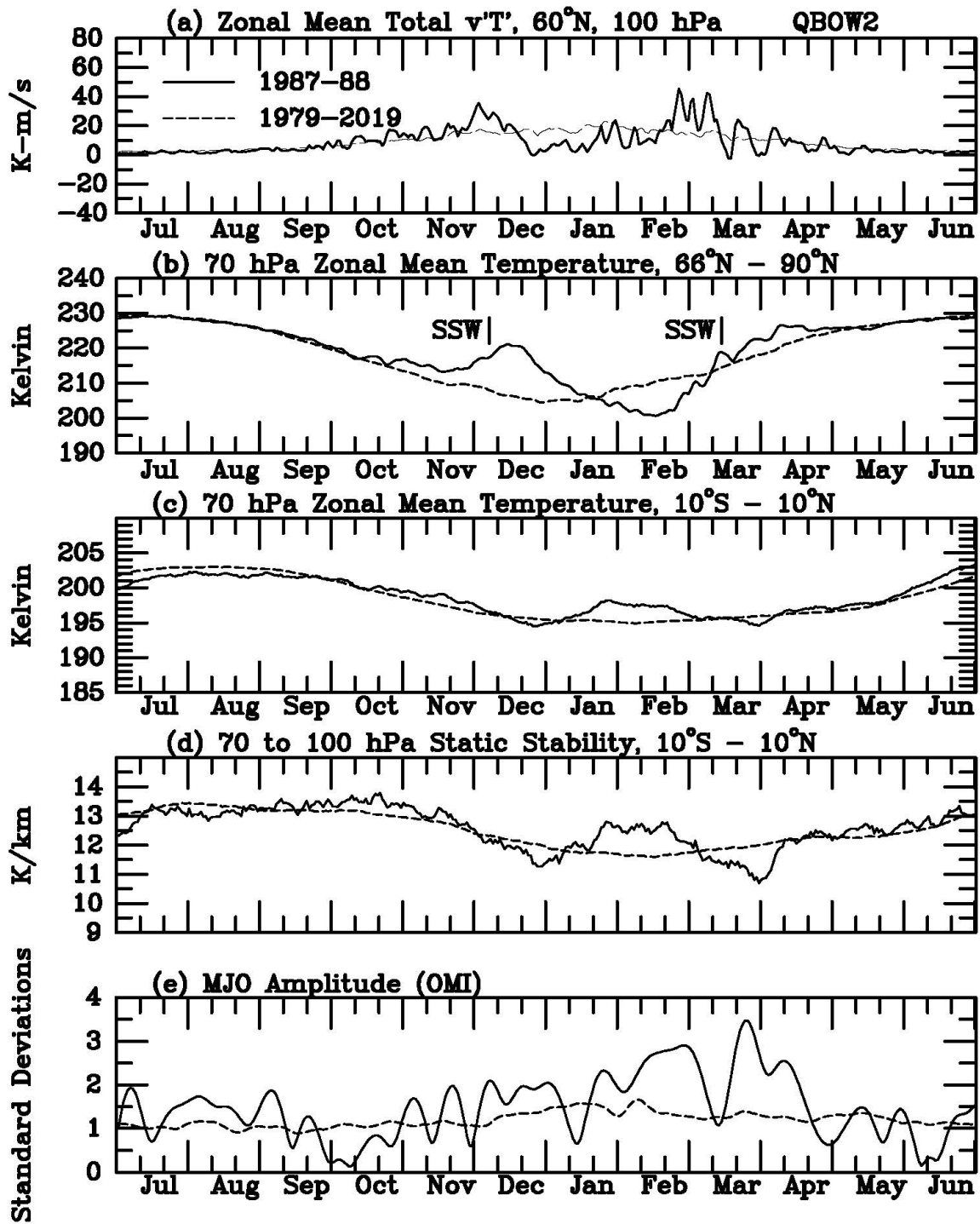


Figure S8. As in Figure S6 but for the 1987-1988 winter.

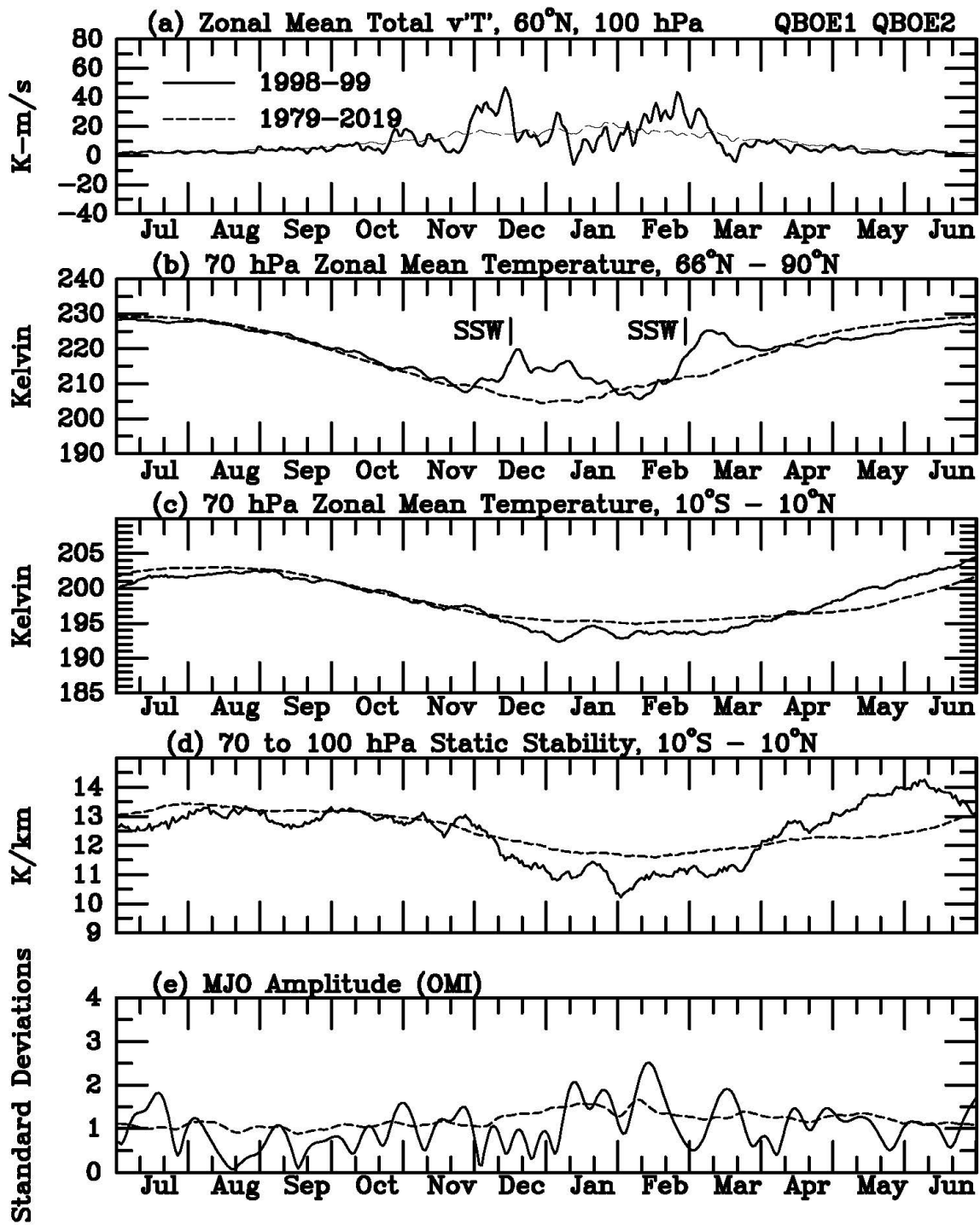


Figure S9. As in Figure S6 but for the 1998-1999 winter.

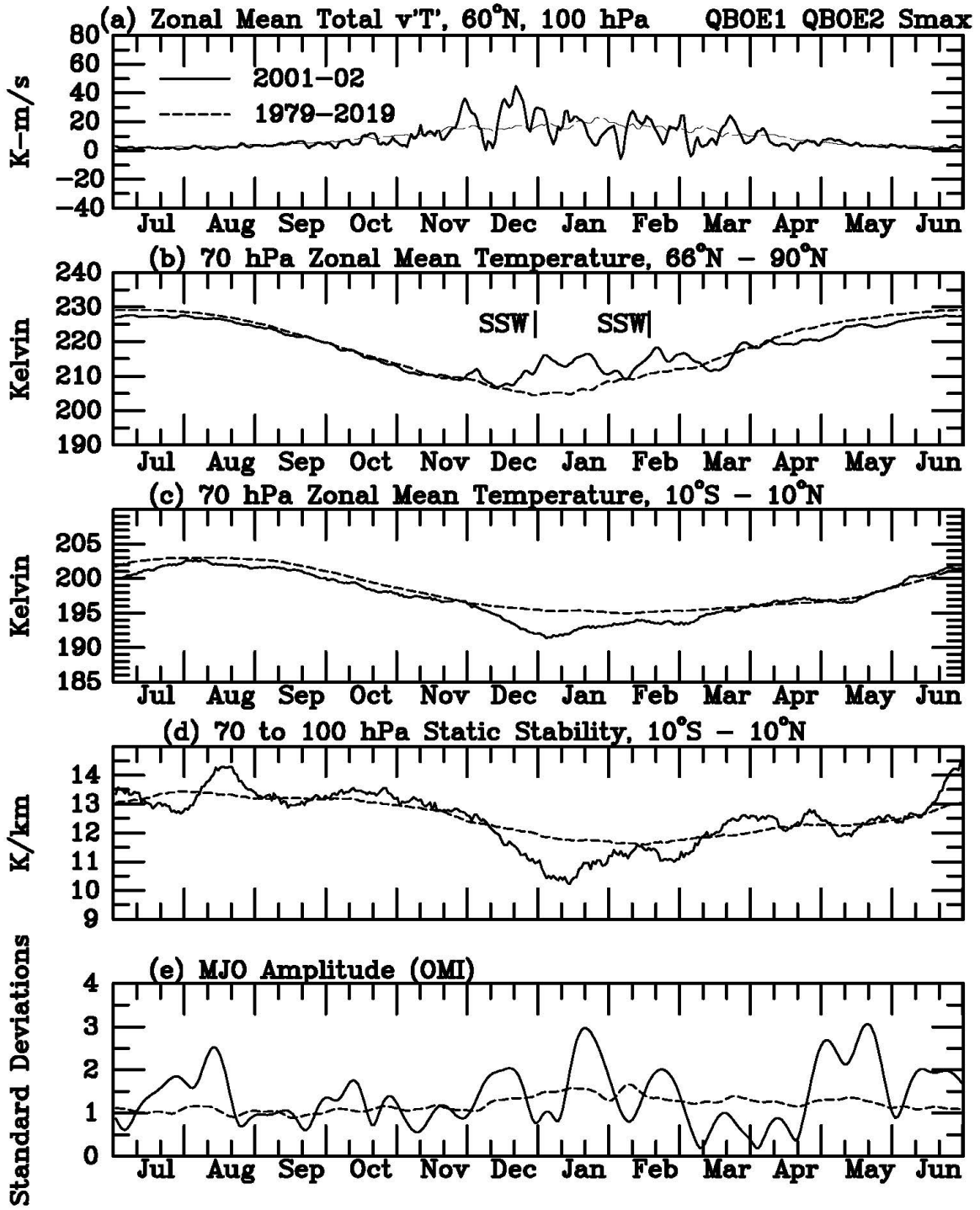


Figure S10. As in Figure S6 but for the 2001-2002 winter.

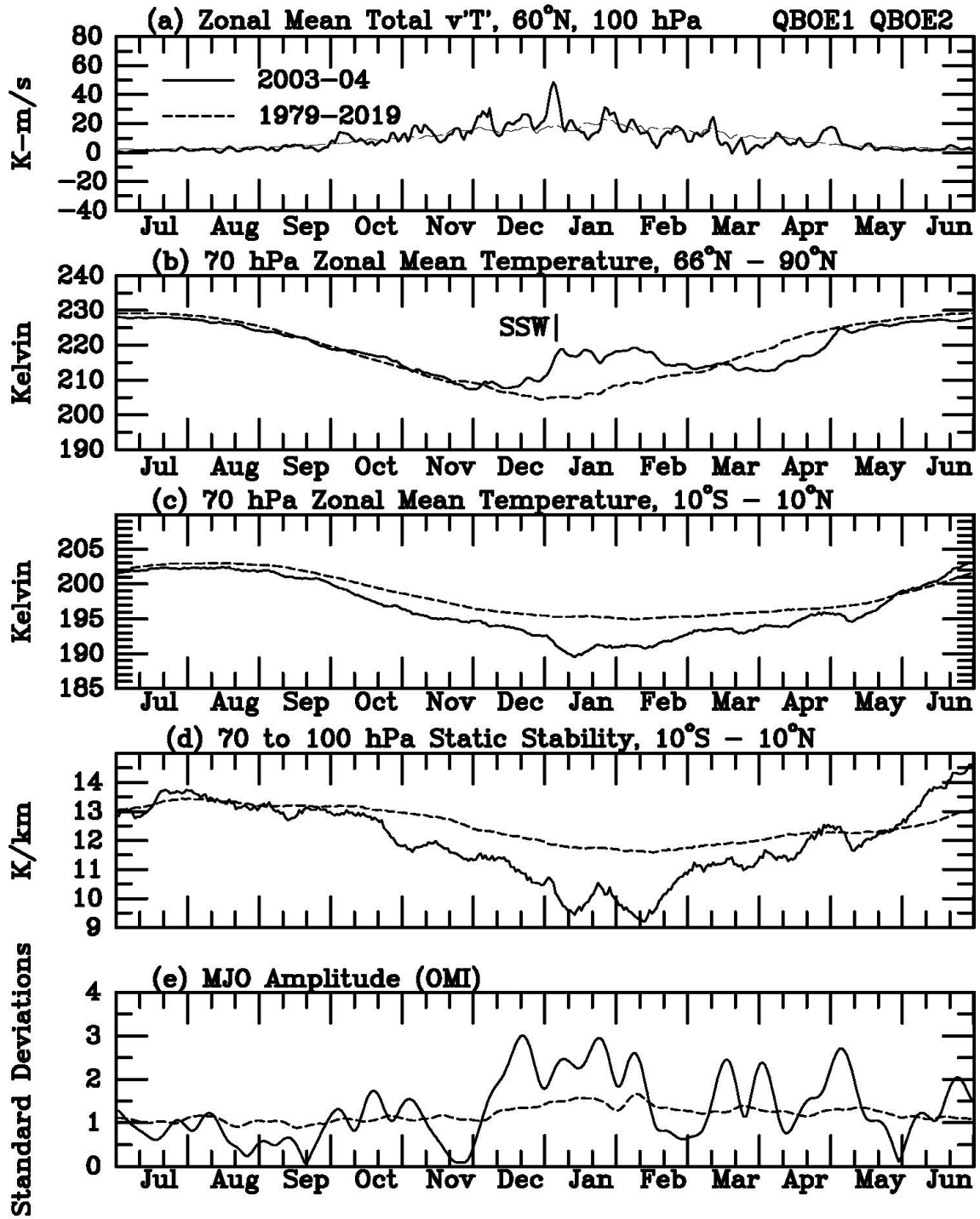


Figure S11. As in Figure S6 but for the 2003-2004 winter.

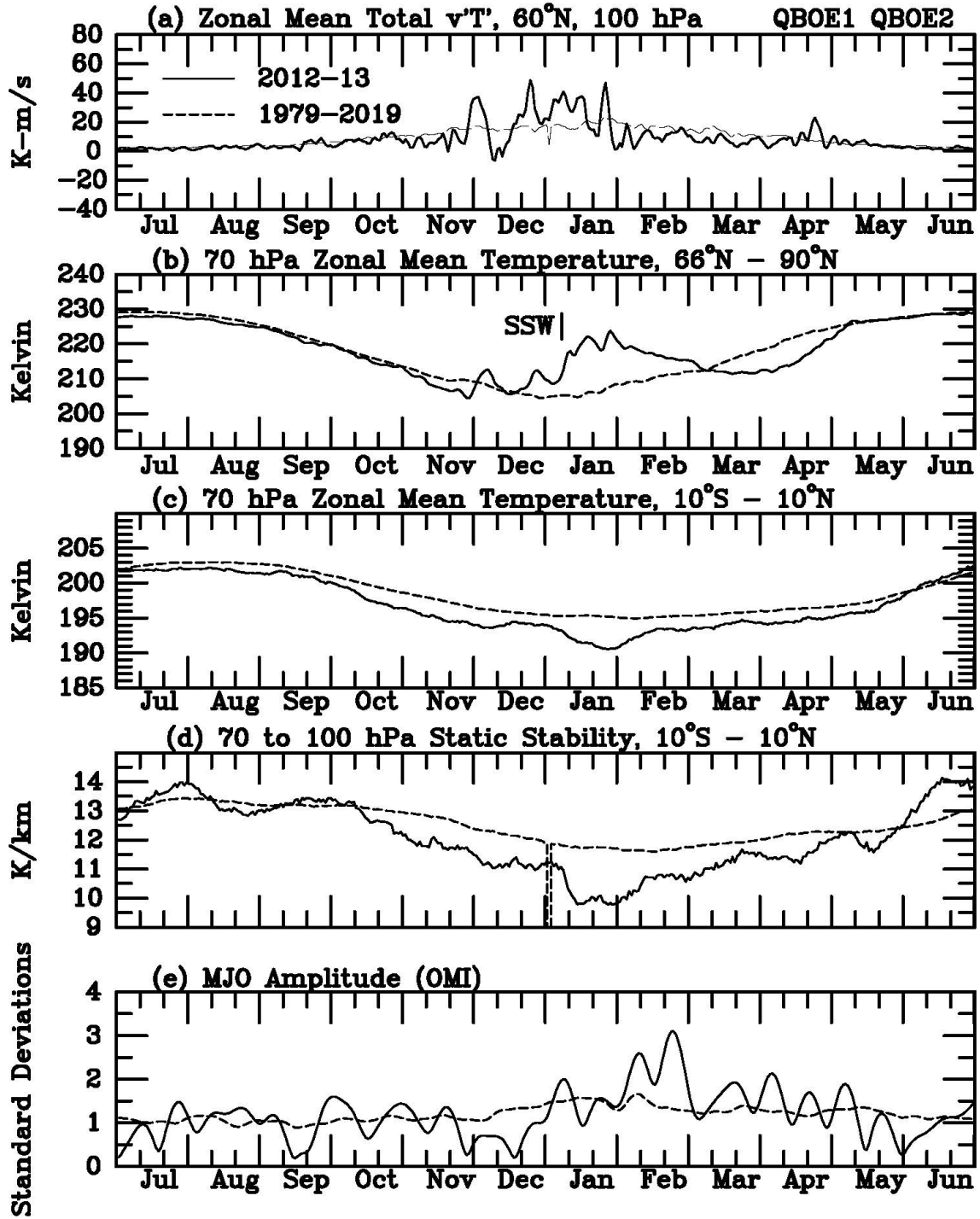


Figure S12. As in Figure S6 but for the 2013-2014 winter.

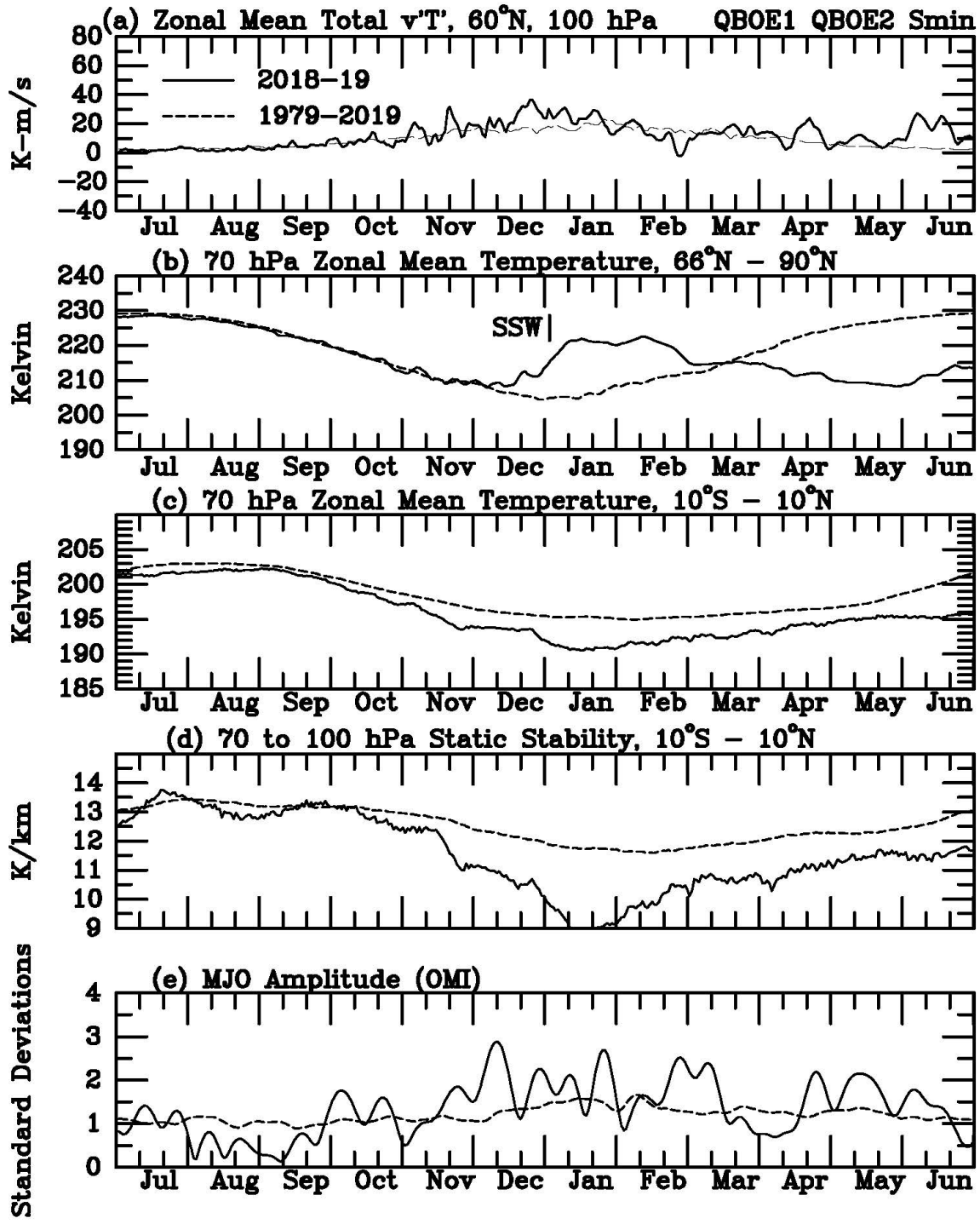


Figure S13. As in Figure S6 but for the 2018-2019 winter.

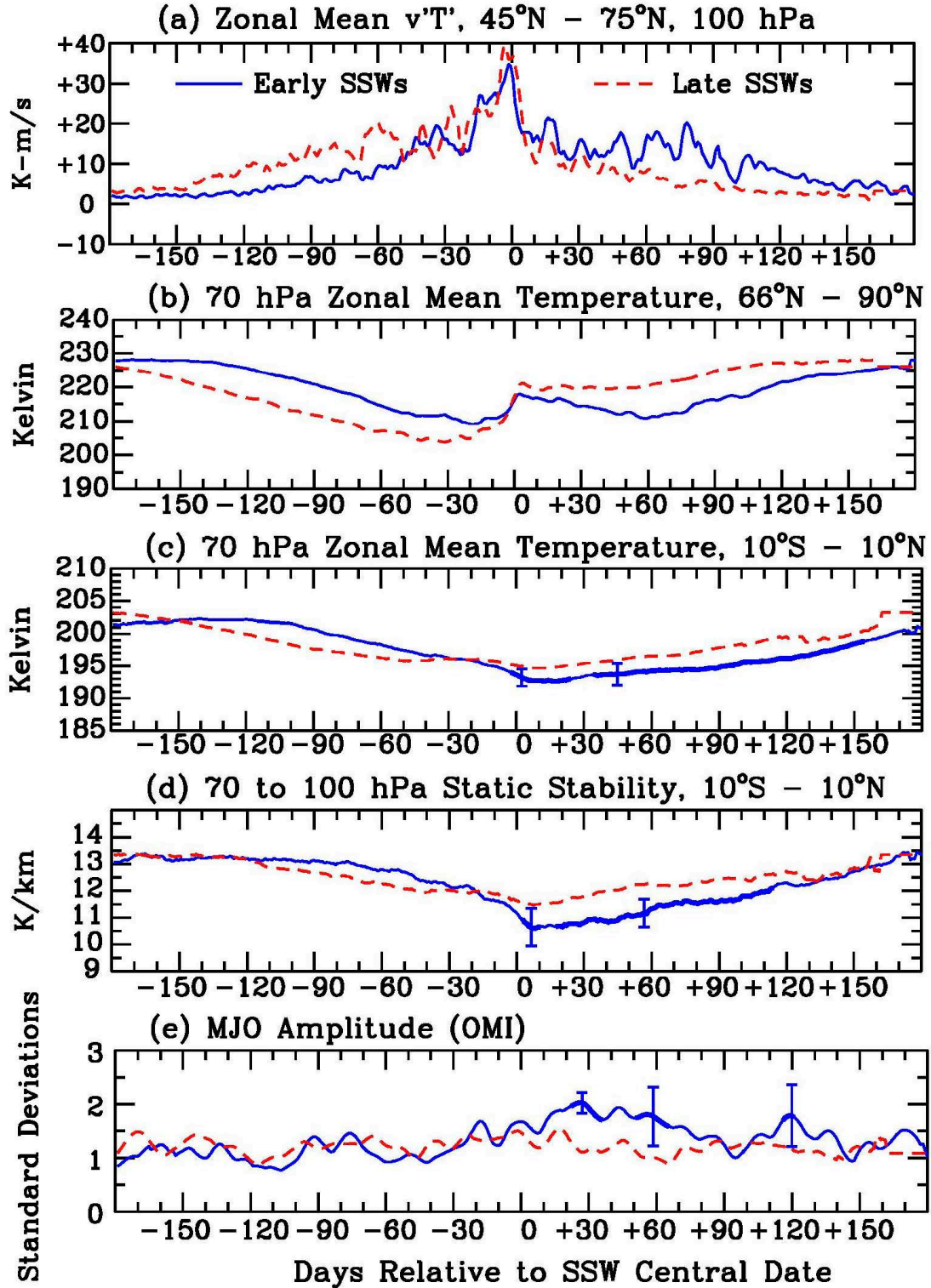


Figure S14. As in Figure 6 but the early winter SSW composite is compared to a late winter SSW composite (red dashed lines) for 15 SSWs occurring after January 15 (Table 2).

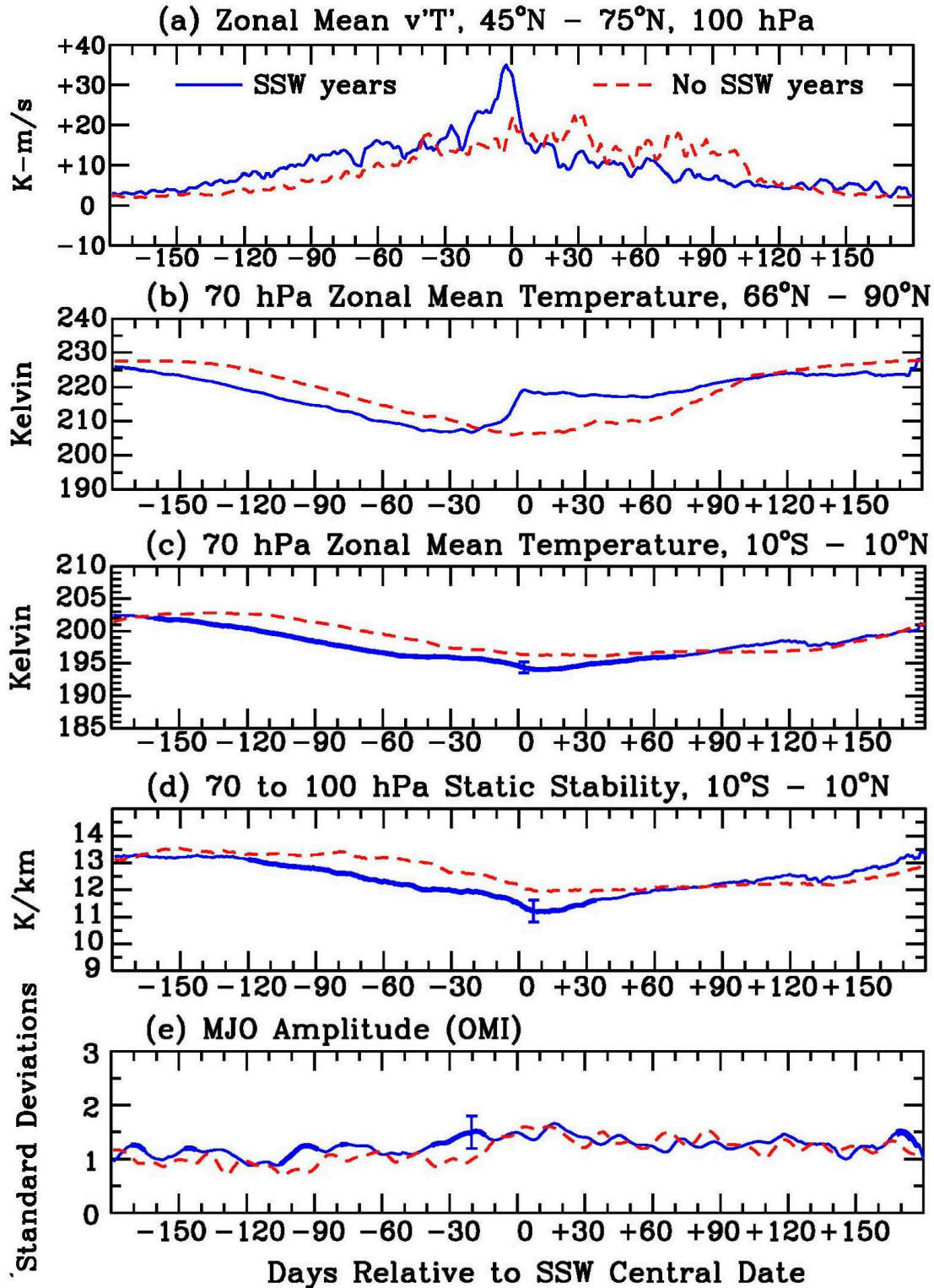


Figure S15. As in Figure 6 but composites relative to the central dates of all SSWs listed in Table 2 (blue lines) are compared to composites for winters with no SSWs (red dashed lines).

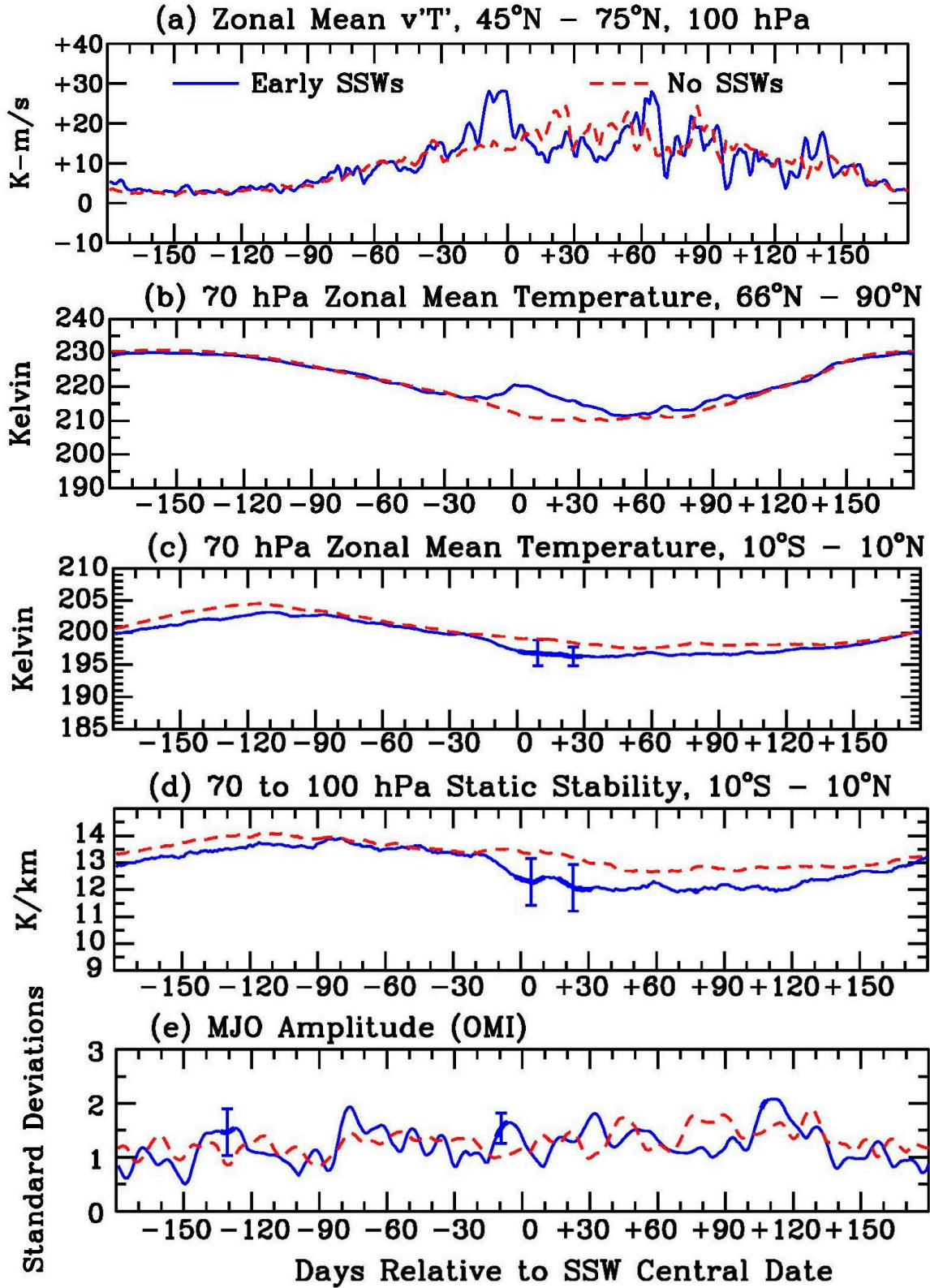


Figure S16. As in Figure 6 but comparing a composite of 5 early winter SSWs occurring in the historical MRI model simulation (blue lines; Table S1) versus a composite of 17 model winters with no SSWs (red dashed lines).

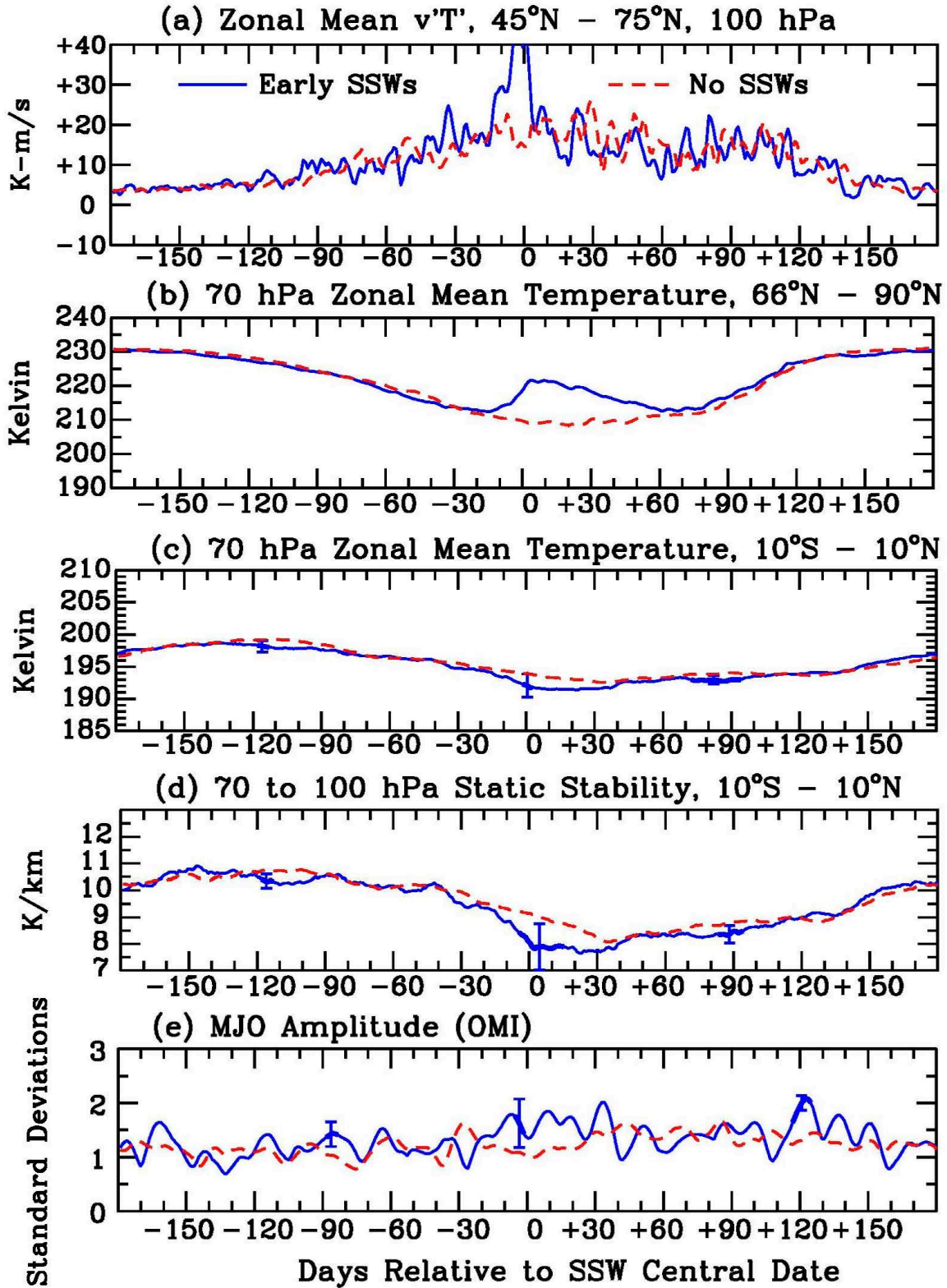


Figure S17. As in Figure 6 but comparing a composite of 5 early winter SSWs occurring in 40 winters of the r1 member of the MRI 4 \times CO $_2$ model simulation (blue lines; Table S4) versus a composite of 20 model winters with no SSWs (red dashed lines).

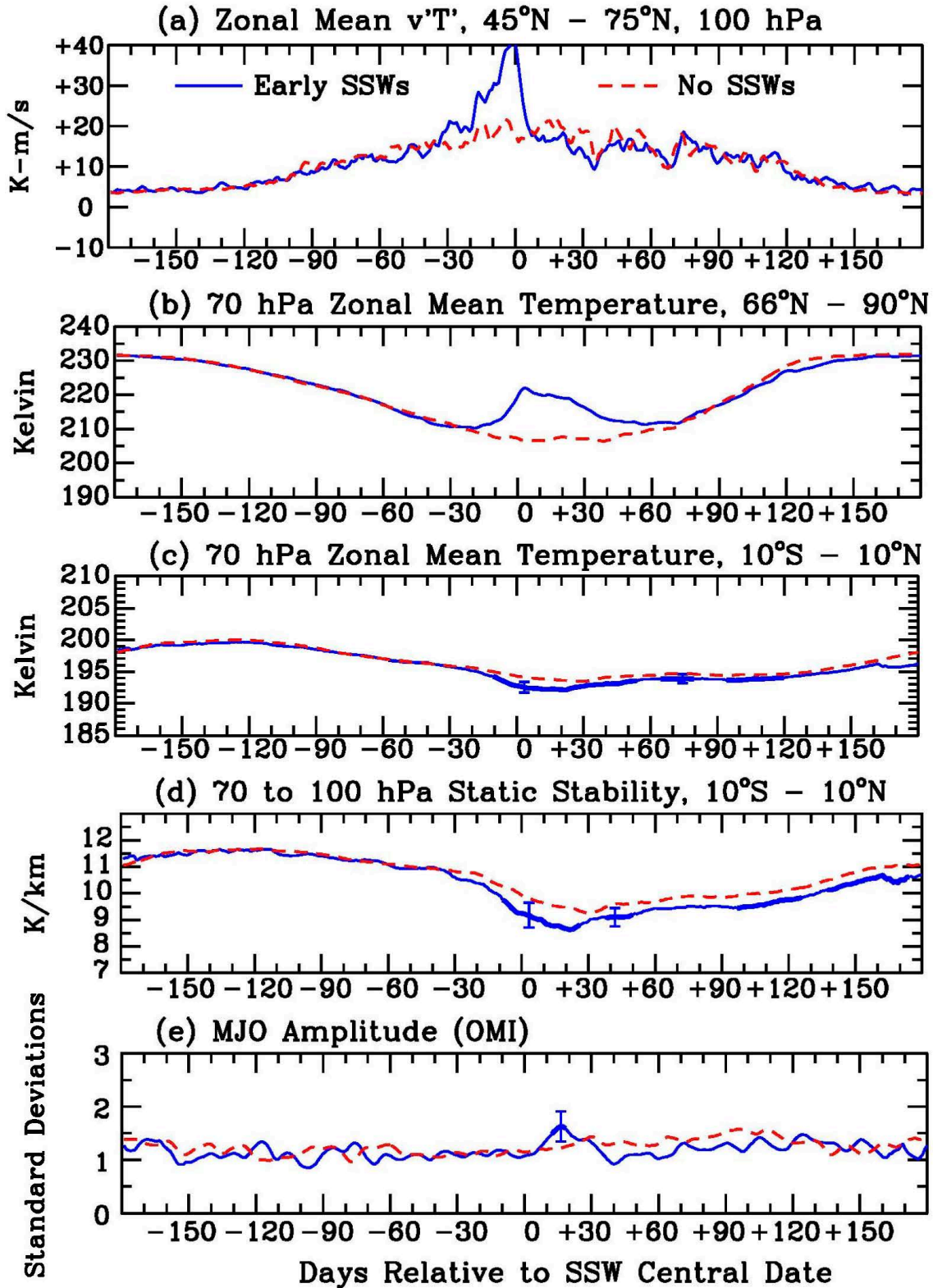


Figure S18. As in Figure 7 but comparing a composite of 24 early winter SSWs occurring in the r7 ensemble member of the MRI 4 \times CO $_2$ model simulation (blue lines) versus a composite of 60 model winters with no SSWs (red dashed lines).

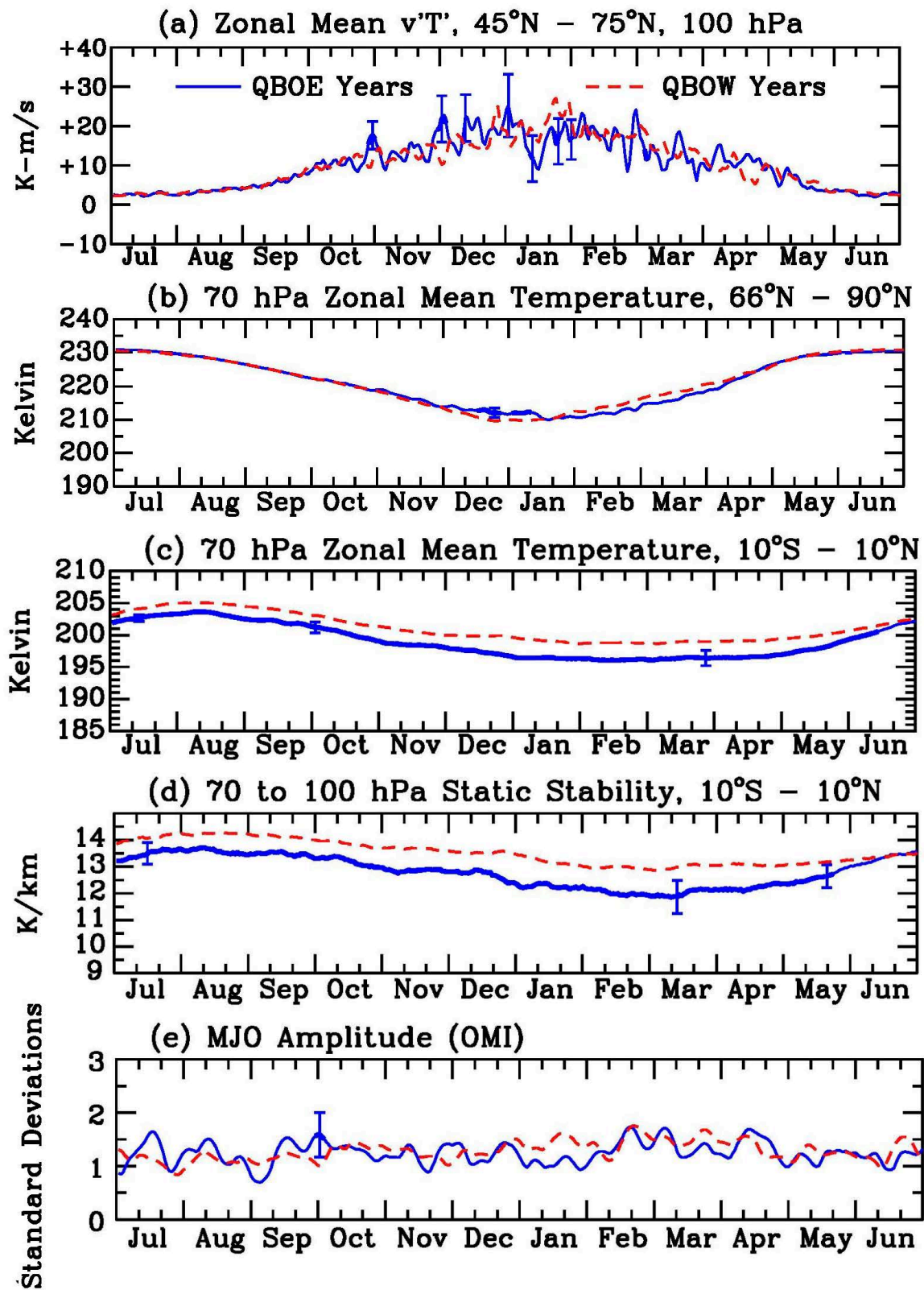


Figure S19. As in Figure 2 but calculated from MRI historical simulation model data (9 QBOE winters and 19 QBOW winters; Table S1).

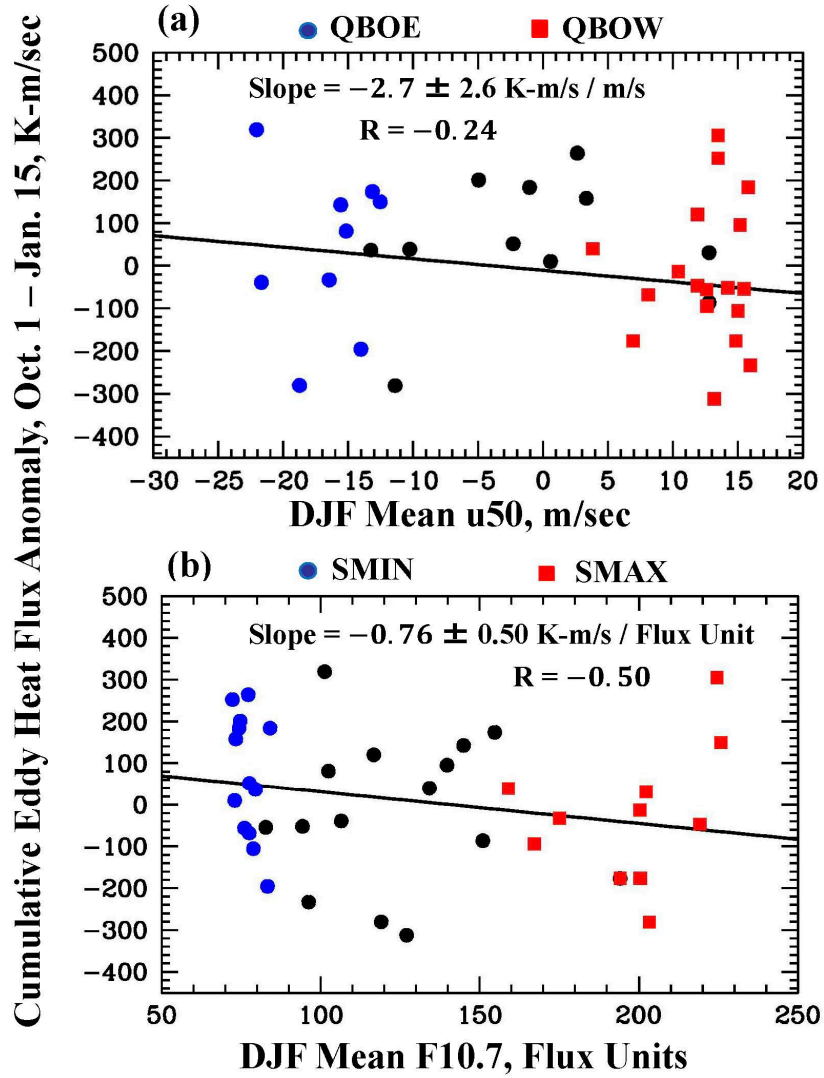


Figure S20. As in Figure 5 but using MRI historical simulation model data (Table S1).

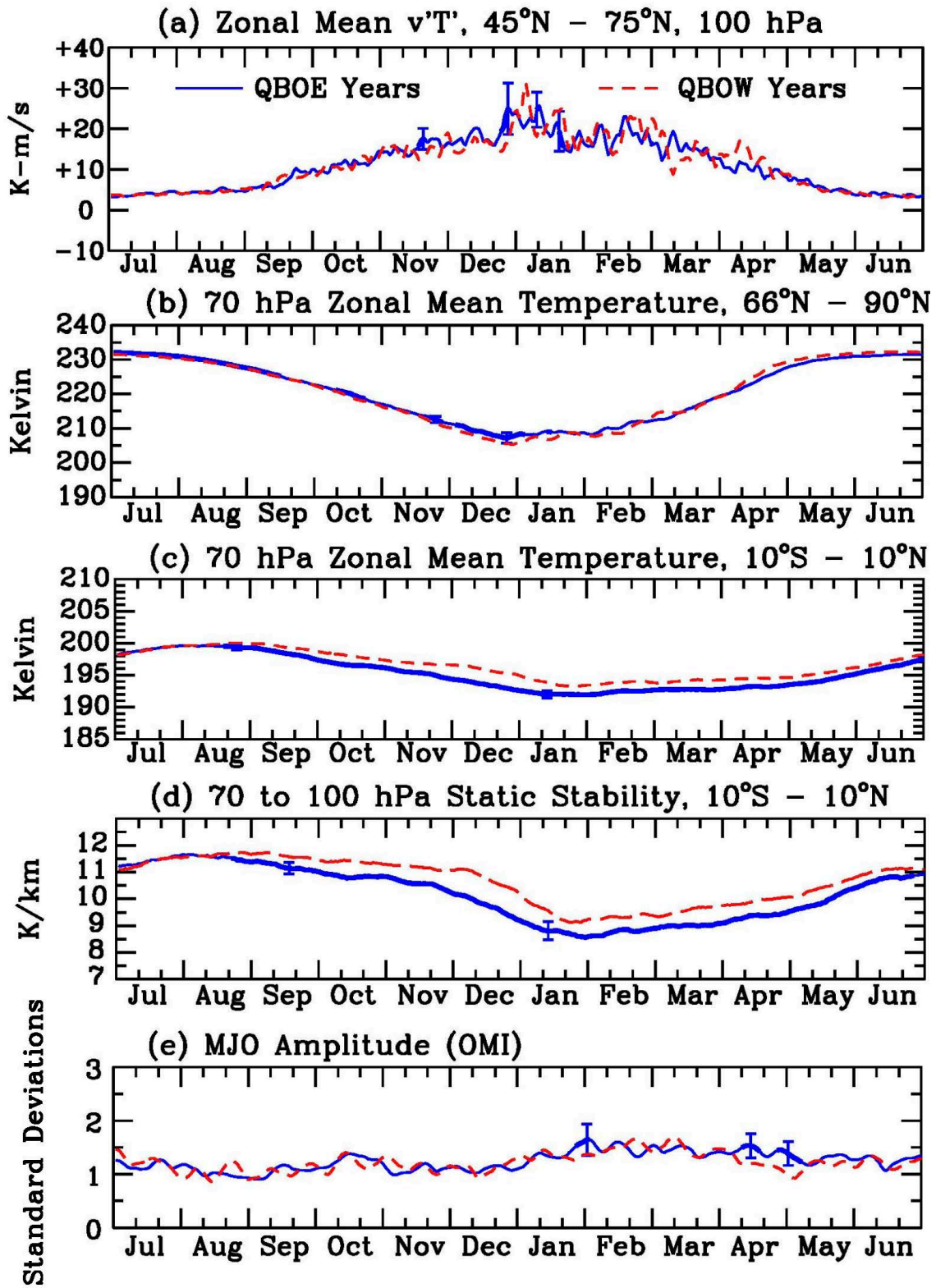


Figure S21. As in Figure 2 but calculated from MRI model data for the $4\times\text{CO}_2$ simulation (r1 ensemble member, 34 QBOE winters and 26 QBOW winters).

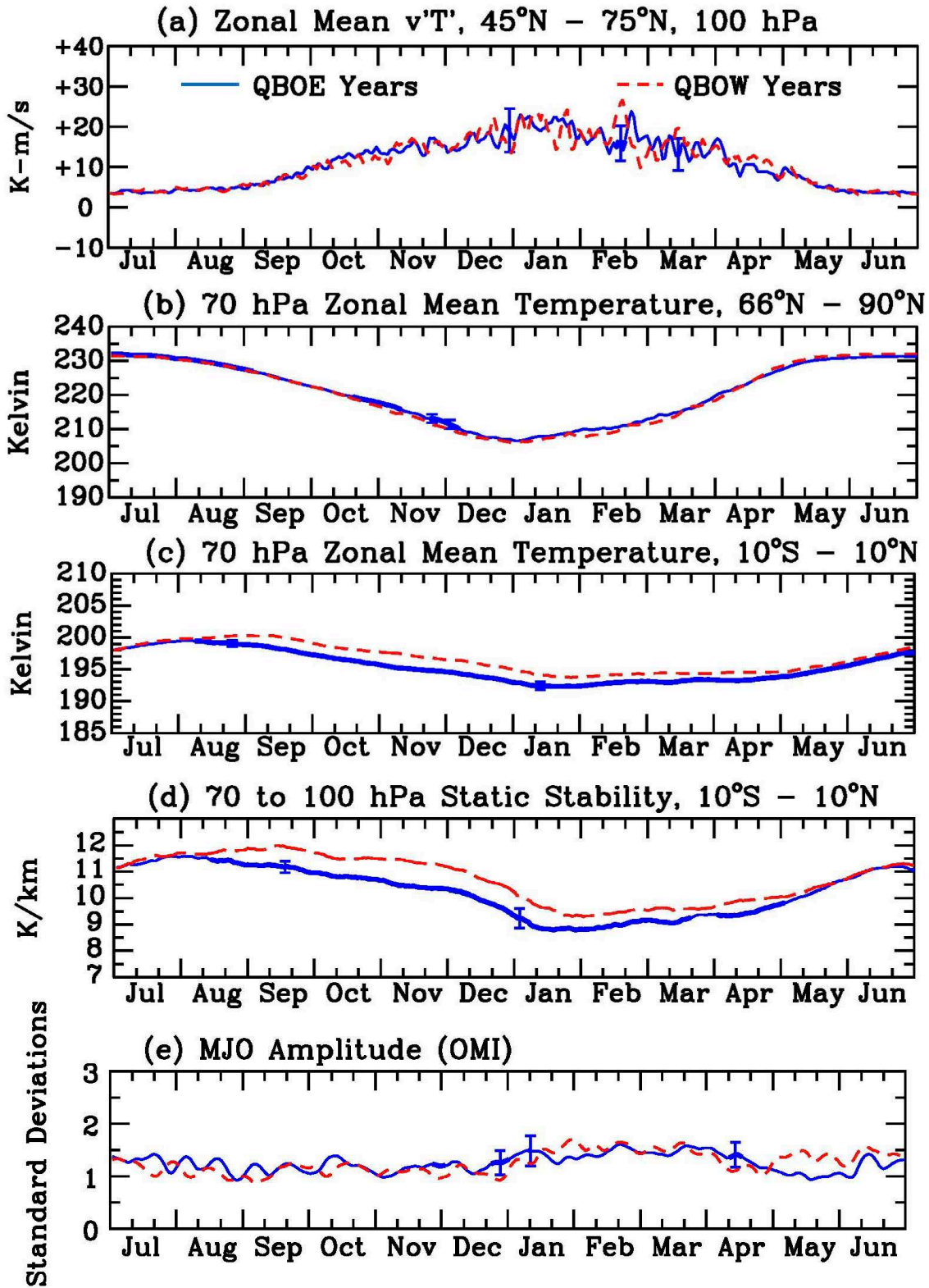


Figure S22. As in Figure 2 but calculated from MRI model data for the $4\times\text{CO}_2$ simulation (r4 ensemble member, 31 QBOE winters and 27 QBOW winters).

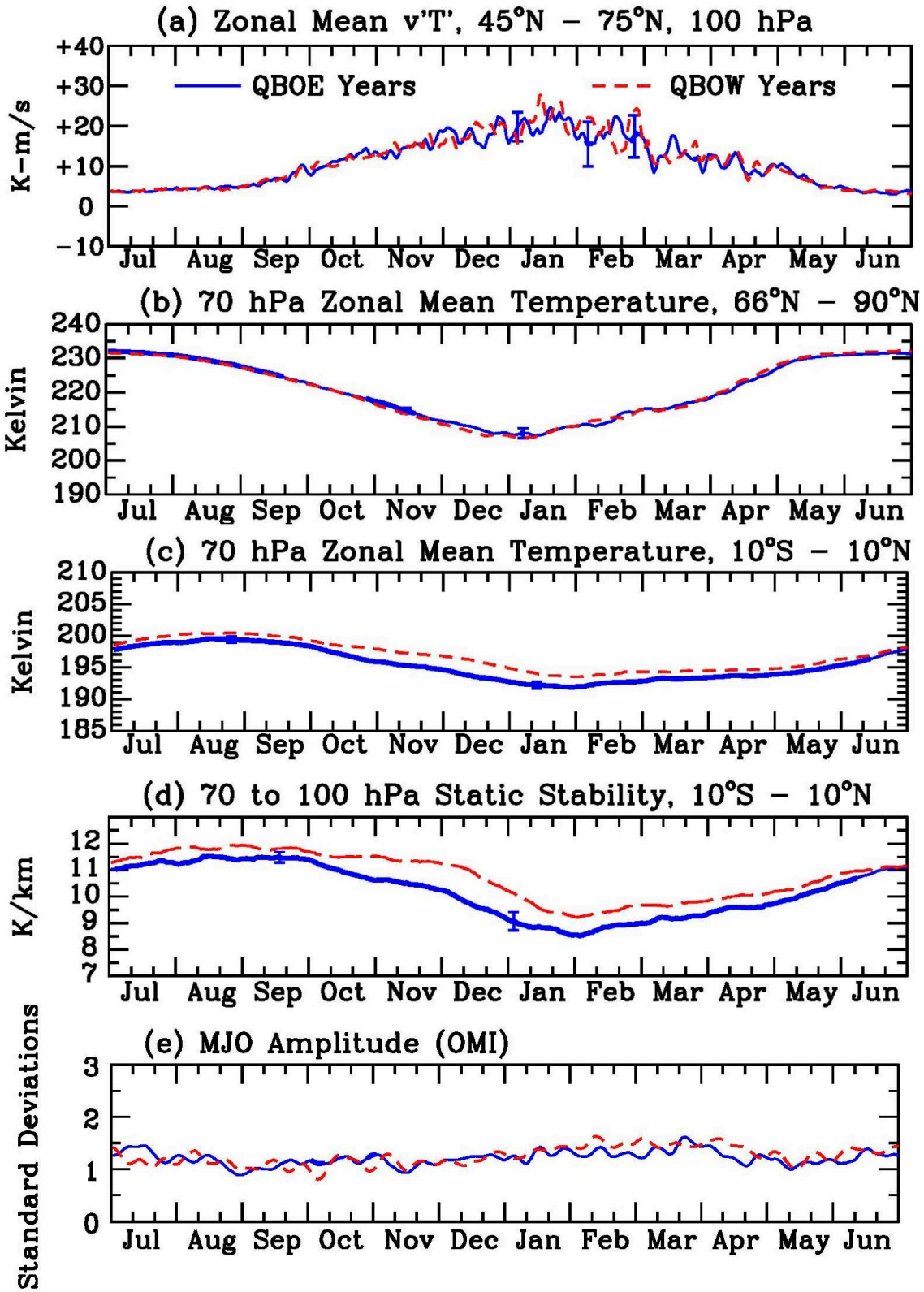


Figure S23. As in Figure 2 but calculated from MRI model data for the $4\times\text{CO}_2$ simulation (r7 ensemble member, 36 QBOE winters and 32 QBOW winters).

Table S1. QBO/Solar Phases and Related Data of 39 MRI Model Winters¹

Winter No.	Winter Years	QBO Phase Method 1	QBO Phase Method 2	Early/Late SSW?	DJF OMI	Solar Phase	Heatflux 10/1-1/15
1	1961-1962	West	West	Late	1.14	–	–233.3
2	1962-1963	–	East	–	1.35	Smin	36.9
3	1963-1964	West	West	Late	1.19	Smin	–55.7
4	1964-1965	West	West	Late	1.00	Smin	–68.0
5	1965-1966	East	East	–	1.25	Smin	–195.5
6	1966-1967	West	West	–	1.51	–	95.4
7	1967-1968	East	East	–	1.12	Smax	–33.1
8	1968-1969	West	West	Late	1.40	Smax	–470.3
9	1969-1970	–	East	Late(2)	1.36	Smax	38.9
10	1970-1971	–	West	–	1.46	–	–86.4
11	1971-1972	West	West	–	1.35	–	–312.4
12	1972-1973	East	East	–	1.17	–	319.4
13	1973-1974	West	West	–	1.57	–	–54.5
14	1974-1975	–	East	Early	1.79	Smin	51.6
15	1975-1976	–	West	Early	1.10	Smin	158.2
16	1976-1977	West	West	–	1.49	Smin	–105.4
17	1977-1978	East	East	–	1.19	–	–280.9
18	1978-1979	West	West	Late	1.65	Smax	–176.2
19	1979-1980	–	East	Late	1.09	Smax	–280.9
20	1980-1981	–	West	Late	1.05	Smax	31.1
21	1981-1982	West	West	–	1.50	Smax	–13.0
22	1982-1983	East	East	Late	1.64	–	173.9
23	1983-1984	West	West	Late	1.41	–	120.2
24	1984-1985	–	East	–	0.96	Smin	201.0
25	1985-1986	–	West	Early	1.26	Smin	264.1
26	1986-1987	West	West	Late	1.22	Smin	252.5
27	1987-1988	East	East	–	1.35	–	81.5
28	1988-1989	West	West	Late	1.35	Smax	–46.7
29	1989-1990	West	West	Late	1.47	Smax	–176.6
30	1990-1991	East	East	Early,Late	1.13	Smax	150.2
31	1991-1992	West	West	–	1.23	Smax	305.4
32	1992-1993	West	West	Late	1.24	–	40.1
33	1993-1994	East	East	–	1.23	–	–38.9
34	1994-1995	West	West	Late	1.57	Smin	184.3
35	1995-1996	–	West	Early	1.05	Smin	10.0
36	1996-1997	–	East	Late	1.30	Smin	183.7
37	1997-1998	West	West	–	1.82	–	–52.0
38	1998-1999	East	East	Late	1.00	–	142.9
39	1999-2000	West	West	–	1.45	Smax	–94.5

¹All quantities are defined as in Table 1 but are calculated from MRI model data for 39 model winters.

Table S2. Sudden Stratospheric Warmings during MRI Model Years 1961-2000¹

SSW No.	Central Date	Early / Late Winter	QBO Phase Method 1	QBO Phase Method 2	Solar Phase
1	31 March 1962	Late	West	West	—
2	28 February 1964	Late	West	West	Smin
3	28 January 1965	Late	West	West	Smin
4	25 February 1969	Late	West	West	Smax
5	28 January 1970	Late	—	East	Smax
6	22 March 1970	Late	—	East	Smax
7	3 December 1974	Early	—	East	—
8	5 November 1975	Early	—	West	Smin
9	22 February 1979	Late	West	West	—
10	16 February 1980	Late	—	East	Smax
11	2 March 1981	Late	—	West	Smax
12	29 March 1983	Late	East	East	—
13	17 February 1984	Late	West	West	—
14	9 January 1986	Early	—	West	Smin
15	27 January 1987	Late	West	West	Smin
16	9 March 1989	Late	West	West	Smax
17	22 February 1990	Late	West	West	Smax
18	5 December 1990	Early	East	East	Smax
19	26 February 1991	Late	East	East	Smax
20	26 January 1993	Late	West	West	—
21	7 February 1995	Late	West	West	Smin
22	28 November 1995	Early	—	West	Smin
23	4 February 1997	Late	—	East	Smin
24	22 March 1999	Late	East	East	—

¹All quantities are defined as in Table 2 but are determined by analyzing MRI model data for 39 winters.

Table S3. QBO/Solar Phases and Related Data of 40 MRI 4×CO₂ Model Winters¹

Winter No.	Winter Years	QBO Phase Method 1	QBO Phase Method 2	Early/Late SSW?	Solar Phase
1	1960-1961	–	West	Late	–
2	1961-1962	–	West	–	–
3	1962-1963	East	East	–	Smin
4	1963-1964	West	West	–	Smin
5	1964-1965	–	East	–	Smin
6	1965-1966	–	West	Late	Smin
7	1966-1967	West	West	–	–
8	1967-1968	East	East	–	Smax
9	1968-1969	West	West	Early	Smax
10	1969-1970	–	East	Late	Smax
11	1970-1971	–	West	–	–
12	1971-1972	–	West	Early	–
13	1972-1973	East	East	Early	–
14	1973-1974	West	West	–	–
15	1974-1975	–	East	–	Smin
16	1975-1976	–	West	Late	Smin
17	1976-1977	West	West	Late	Smin
18	1977-1978	East	East	Early	–
19	1978-1979	West	West	–	Smax
20	1979-1980	–	East	–	Smax
21	1980-1981	–	West	–	Smax
22	1981-1982	West	West	Late	Smax
23	1982-1983	East	East	–	–
24	1983-1984	West	West	Late	–
25	1984-1985	East	East	Late	Smin
26	1985-1986	–	West	–	Smin
27	1986-1987	–	East	Late	Smin
28	1987-1988	–	West	–	–
29	1988-1989	West	West	Late	Smax
30	1989-1990	East	East	–	Smax
31	1990-1991	West	West	Early, Late	Smax
32	1991-1992	–	East	–	Smax
33	1992-1993	–	West	Late	–
34	1993-1994	–	West	–	–
35	1994-1995	East	East	–	Smin
36	1995-1996	West	West	Late	Smin
37	1996-1997	East	East	–	Smin
38	1997-1998	–	West	Late	–
39	1998-1999	–	East	Late(2)	–
40	1999-2000	–	West	Late	Smax

¹All quantities are defined as in Table 1 but are determined by analyzing 4×CO₂ MRI model data for 40 winters.

Table S4. Sudden Stratospheric Warmings during 4×CO₂ MRI Years 1960-2000¹

SSW No.	Central Date	Early / Late Winter	QBO Phase Method 1	QBO Phase Method 2	Solar Phase
1	17 January 1961	Late	—	West	—
2	1 March 1966	Late	—	West	Smin
3	13 January 1969	Early	West	West	Smax
4	29 January 1970	Late	—	East	Smax
5	23 December 1971	Early	—	West	—
6	28 December 1972	Early	East	East	—
7	21 February 1976	Late	—	West	Smin
8	25 March 1977	Late	West	West	Smin
9	28 December 1977	Early	East	East	—
10	19 February 1982	Late	West	West	Smax
11	21 January 1984	Late	West	West	—
12	13 March 1985	Late	East	East	Smin
13	28 February 1987	Late	—	East	Smin
14	6 March 1989	Late	West	West	Smax
15	1 November 1990	Early	West	West	Smax
16	20 March 1991	Late	West	West	Smax
17	10 February 1993	Late	—	West	—
18	25 February 1996	Late	West	West	Smin
19	10 February 1998	Late	—	West	—
20	8 February 1999	Late	—	East	—
21	18 March 1999	Late	—	East	—
22	3 March 2000	Late	—	West	Smax

¹All quantities are defined as in Table 2 but are determined by analyzing 4×CO₂ MRI model data for 40 winters.