



# Enhanced Stratosphere/Troposphere Coupling During Extreme Warm Stratospheric Events with Strong Polar-Night Jet Oscillation

Dieter H. W. Peters <sup>1,\*</sup>, Andrea Schneidereit <sup>1</sup> and Alexey Y. Karpechko <sup>2</sup>

<sup>1</sup> Leibniz-Institute for Atmospheric Physics, University of Rostock, Ostseebad Kühlungsborn, D-18225 Mecklenburg, Germany; schneidereit@iap-kborn.de

<sup>2</sup> Finnish Meteorological Institute, Arctic Research, PL 503, 00101 Helsinki, Finland; Alexey.Karpechko@fmi.fi

\* Correspondence: peters@iap-kborn.de; Tel.: +49-38293-68284

Received: 31 August 2018; Accepted: 26 November 2018; Published: date

**Table ST1.** ERA-Interim, period 1979-2017, event numbers of NAM, CD and PJO diagnose.

| N ERAI | Winter | MSSW       | CD(NAM)  | Str.-PJO | Non-PJO | Int.-PJO |
|--------|--------|------------|----------|----------|---------|----------|
| 1      | 78-79  | exclude    |          |          |         |          |
| 2      | 79-80  | 1          | 01.03.80 |          | 1       |          |
| 3      | 81-82  | 2          | 25.01.82 |          | 2       |          |
| 4      | 83-84  | 3          | 25.02.84 |          |         | 1        |
| 5      | 84-85  | 4          | 31.12.84 | 1        |         |          |
| 6      | 86-87  | 5          | 23.01.87 | 2        |         |          |
| 7      | 87-88  | 6          | 07.12.87 | 3        |         |          |
| 8      | 88-89  | 7          | 19.02.89 | 4        |         |          |
| 9      | 91-92  | 8          | 18.01.92 |          | 3       |          |
| 10     | 94-95  | 9          | 04.02.95 |          | 4       |          |
| 11     | 97-98  | 10         | 07.01.98 |          |         | 2        |
| 12     | 98-99  | 11         | 16.12.98 | 5        |         |          |
| 13     | 98-99  | 12         | 26.02.99 |          |         | 3        |
| 14     | 00-01  | 13         | 07.02.01 |          |         | 4        |
| 15     | 01-02  | 14         | 28.12.01 |          | 5       |          |
| 16     | 02-03  | 15         | 18.01.03 |          | 6       |          |
| 17     | 03-04  | 16         | 04.01.04 | 6        |         |          |
| 18     | 04-05  | exclude    |          |          |         |          |
| 19     | 05-06  | 17         | 21.01.06 | 7        |         |          |
| 20     | 07-08  | 18         | 22.02.08 |          | 7       |          |
| 21     | 08-09  | 19         | 23.01.09 | 8        |         |          |
| 22     | 09-10  | 20         | 28.01.10 |          | 8       |          |
| 23     | 10-11  | exclude    |          |          |         |          |
| 24     | 12-13  | 21         | 07.01.13 | 9        |         |          |
| sum    | 24     | 21         | 21       | 9        | 8       | 4        |
| 25     | 15-16  | no include | 06.03.16 |          | 9       |          |
| 26     | 16-17  | no include | 29.01.17 |          | 10      |          |
| Sum    | 26     | 21         | 22       | 9        | 10      | 4        |

**Table ST2.** CMIP5-ESM, period 1950-2005, LR-1 run, event numbers of NAM, CD and PJO diagnose.

| N LR-1 | Winter | MSSW | CD(NAM)  | Str.-PJO | No-PJO | Int.-PJO |
|--------|--------|------|----------|----------|--------|----------|
| 1      | 50-51  | 1    | 18.12.50 |          | 1      |          |
| 2      | 50-51  | 2    | 21.02.51 | 1        |        |          |
| 3      | 54-55  | 3    | 21.12.54 |          | 2      |          |
| 4      | 56-57  | 4    | 24.12.56 |          | 3      |          |
| 5      | 56-57  | 5    | 11.02.57 |          | 4      |          |
| 6      | 57-58  | 6    | 12.01.58 | 2        |        |          |
| 7      | 59-60  | 7    | 10.02.60 |          | 5      |          |
| 8      | 63-64  | 8    | 21.12.63 |          | 6      |          |
| 9      | 64-65  | 9    | 30.01.64 |          |        | 1        |
| 10     | 65-66  | 10   | 06.12.65 |          |        | 2        |
| 11     | 69-70  | 11   | 11.02.70 |          | 7      |          |
| 12     | 70-71  | 12   | 13.12.70 |          | 8      |          |
| 13     | 73-74  | 13   | 21.01.74 |          |        | 3        |
| 14     | 74-75  | 14   | 05.02.75 |          | 9      |          |
| 15     | 78-79  | 15   | 05.01.79 |          | 10     |          |
| 16     | 82-83  | 16   | 25.01.83 |          |        | 4        |
| 17     | 83-84  | 17   | 13.12.83 |          |        | 5        |
| 18     | 84-85  | 18   | 05.01.85 | 3        |        |          |
| 19     | 85-86  | 19   | 31.12.85 |          | 11     |          |
| 20     | 86-87  | 20   | 07.02.87 |          |        | 6        |
| 21     | 87-88  | 21   | 10.01.88 | 4        |        |          |
| 22     | 89-90  | 22   | 06.12.89 | 5        |        |          |
| 23     | 92-93  | 23   | 15.12.92 | 6        |        |          |
| 24     | 93-94  | 24   | 13.01.94 |          |        | 7        |
| 25     | 95-96  | 25   | 26.12.95 | 7        |        |          |
| 26     | 97-98  | 26   | 10.12.97 |          | 12     |          |
| 27     | 97-98  | 27   | 02.02.98 |          | 13     |          |
| 28     | 98-99  | 28   | 22.02.02 |          | 14     |          |
| 29     | 01-02  | 29   | 19.01.02 | 8        |        |          |
| 30     | 04-05  | 30   | 04.03.05 |          | 15     |          |
| Sum    | 30     | 30   | 30       | 8        | 15     | 7        |

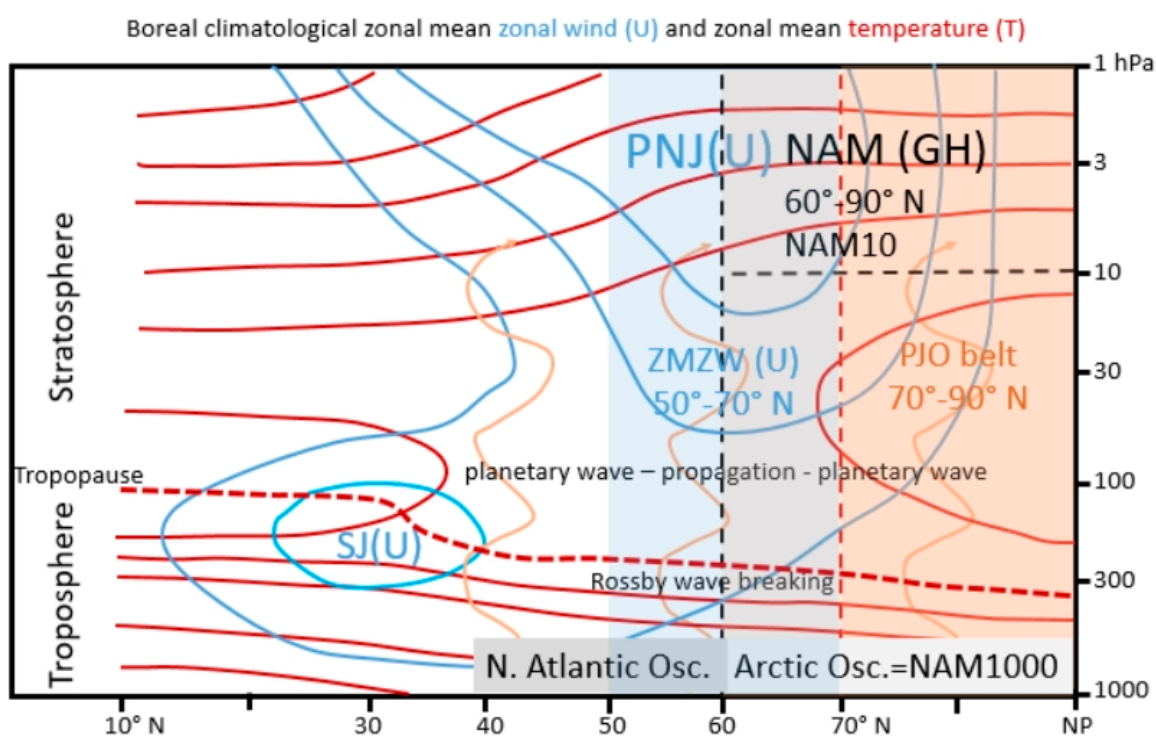
**Table ST3.** CMIP5-ESM, period 1950-2005, LR-2 run, event numbers of NAM, CD and PJO diagnose.

| N LR-2 | Winter | MSSW | CD(NAM)  | Str.-PJO | No-PJO | Int.-PJO |
|--------|--------|------|----------|----------|--------|----------|
| 1      | 50-51  | 1    | 1.12.50  |          |        | 1        |
| 2      | 50-51  | 2    | 06.22.52 |          | 1      |          |
| 3      | 51-52  | 3    | 03.03.55 |          | 2      |          |
| 4      | 53-54  | 4    | 15.02.56 |          | 3      |          |
| 5      | 53-54  | 5    | 06.02.58 |          | 4      |          |
| 6      | 55-56  | 6    | 29.12.58 | 1        |        |          |
| 7      | 58-59  | 7    | 25.01.61 |          |        | 2        |
| 8      | 59-60  | 8    | 17.12.64 |          | 5      |          |
| 9      | 61-62  | 9    | 13.02.66 |          | 6      |          |
| 10     | 62-63  | 10   | 18.02.71 |          | 7      |          |
| 11     | 63-64  | 11   | 13.01.72 |          |        | 3        |
| 12     | 65-66  | 12   | 06.02.73 |          |        | 4        |
| 13     | 67-68  | 13   | 27.01.74 | 2        |        |          |
| 14     | 70-71  | 14   | 05.03.75 | 3        |        |          |
| 15     | 72-73  | 15   | 19.01.80 | 4        |        |          |

|     |       |    |          |    |    |   |
|-----|-------|----|----------|----|----|---|
| 16  | 73-74 | 16 | 05.03.80 | 5  |    |   |
| 17  | 74-75 | 17 | 03.01.89 | 6  |    |   |
| 18  | 75-76 | 18 | 22.01.91 | 7  |    |   |
| 19  | 77-78 | 19 | 09.02.92 |    |    | 5 |
| 20  | 78-79 | 20 | 15.12.99 |    | 8  |   |
| 21  | 79-80 | 21 | 20.12.00 |    |    | 6 |
| 22  | 80-81 | 22 | 13.01.02 |    | 9  |   |
| 23  | 89-90 | 23 | 18.12.89 | 8  |    |   |
| 24  | 91-92 | 24 | 03.03.92 | 9  |    |   |
| 25  | 95-96 | 25 | 14.02.96 | 10 |    |   |
| 26  | 03-04 | 26 | 24.12.03 |    | 10 |   |
| 27  | 04-05 | 27 | 09.12.04 |    | 11 |   |
| Sum | 27    | 27 | 27       | 10 | 11 | 6 |

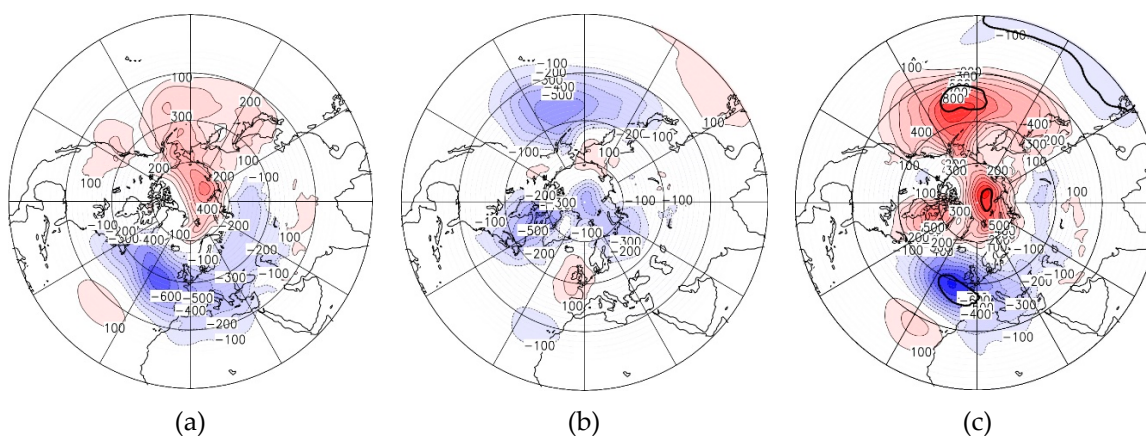
Table ST4. CMIP5-ESM, period 1950-2005, LR-3 run, event numbers of NAM, CD and PJO diagnose.

| N LR-3 | Winter | MSSW | CD(NAM)  | Str. PJO | No-PJO | Int.-PJO |
|--------|--------|------|----------|----------|--------|----------|
| 1      | 50-51  | 1    | 10.12.50 | 1        |        |          |
| 2      | 52-53  | 2    | 06.12.52 |          | 1      |          |
| 3      | 54-55  | 3    | 03.03.55 |          |        | 1        |
| 4      | 55-56  | 4    | 15.02.56 | 2        |        |          |
| 5      | 57-58  | 5    | 06.02.58 |          |        | 2        |
| 6      | 58-59  | 6    | 29.12.58 | 3        |        |          |
| 7      | 60-61  | 7    | 25.01.61 | 4        |        |          |
| 8      | 64-65  | 8    | 17.12.64 |          | 2      |          |
| 9      | 65-66  | 9    | 13.02.66 | 5        |        |          |
| 10     | 70-71  | 10   | 18.02.71 |          | 3      |          |
| 11     | 71-72  | 11   | 13.01.72 | 6        |        |          |
| 12     | 72-73  | 12   | 06.02.73 |          | 4      |          |
| 13     | 73-74  | 13   | 27.01.74 |          |        | 3        |
| 14     | 74-75  | 14   | 05.03.75 |          |        | 4        |
| 15     | 79-80  | 15   | 19.01.80 |          |        | 5        |
| 16     | 81-82  | 16   | 05.03.80 |          |        | 6        |
| 17     | 88-89  | 17   | 03.01.89 |          | 5      |          |
| 18     | 90-91  | 18   | 22.01.91 |          |        | 7        |
| 19     | 91-92  | 19   | 09.02.92 |          | 6      |          |
| 20     | 99-00  | 20   | 15.12.99 |          |        | 8        |
| 21     | 00-01  | 21   | 20.12.00 |          | 7      |          |
| 22     | 01-02  | 22   | 13.01.02 |          | 8      |          |
| Sum    | 22     | 22   | 22       | 6        | 8      | 8        |

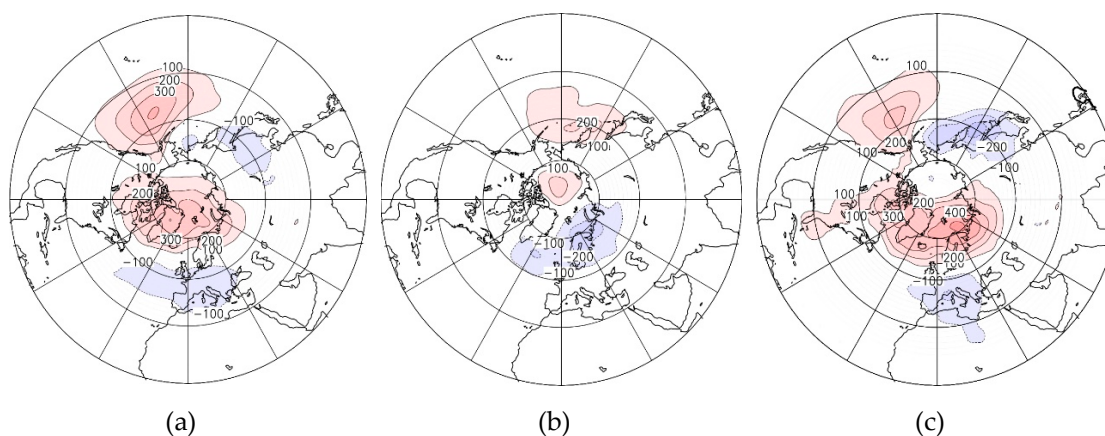


**Figure S1.** The scheme shows the main subjects of this study, the cross-section of the climatological zonal mean zonal wind (ZMW, blue contours) with the polar-night jet (m/s; PNJ(U)) and subtropical jet (m/s; SJ(U)), and the mean zonal mean temperature (K; T, red contours) for boreal winters. The PNJ is linked with the emergence of the polar vortex caused by enhanced radiative cooling in the polar stratosphere in winter.

Strong oscillations of PNJ have been observed during major sudden stratospheric warming events (MSSWs) [2]. Planetary waves are mainly responsible for the high variability of PNJ including its break down due to an enhanced upward wave activity propagation. The Northern annular mode (NAM) is defined as the normalized mean polar cap ( $60^{\circ}$ – $90^{\circ}$  N) geopotential height anomaly [35]. The NAM index is a quantitative measure of the polar vortex strength at each level. Near the surface NAM1000 is referred to as Arctic oscillation (AO) [45]. Seesaw of the surface pressure between polar- and mid-latitudes in the Euro-Atlantic region is referred to as North Atlantic Oscillation and it is strongly linked to AO. MSSW events are defined when NAM index at 10hPa drops below the threshold of  $-2.3$ . The first day when the threshold is exceeded is referred to as central day (CD) of a MSSW event, similar to [27]. The so-called polar-night jet oscillation (PJO) is defined as the polar cap integrated ( $70^{\circ}$ – $90^{\circ}$  N) temperature anomaly [14]. It is a specific measure of the mean vertical gradient of geopotential height anomaly and it is linked to ZMW by the thermal wind relationship within the quasi-geostrophic approximation, [2]. Coupling between the stratosphere and the troposphere changes the propagation of the ultra-long planetary waves [22], which influences the breaking of the synoptic-scale Rossby wave in the upper troposphere [9]. The effect of the stratosphere-troposphere coupling on the surface climate is examined by pattern changes of AO or NAO and by changes in meteorological quantities following MSSW events.



**Figure S2.** Mean composites of surface pressure anomaly (Pa) for strong-PJO (a), non-PJO (b), and difference of strong-PJO minus non-PJO (c) for ERA-Interim during 1–15 days after CD. Thick black (green) line in (c) includes area of significant differences with student t-test of 80% (90%) confidence.



**Figure S3.** Same as Figure S2 for mean composites of geopotential height anomaly (m) at 1000 hPa during 16–75 days after CD.