Supplement of Weather Clim. Dynam., 3, 377–389, 2022
https://doi.org/10.5194/wcd-3-377-2022-supplement

Supplement of

Impact of climate change on wintertime European atmospheric blocking

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Supplementary material

Computation of blocking area

In this work, two different methods are applied in order to define and quantify the blocking size: the WTD method and the DG method. A new algorithm is used to compute the area within the contour lines determined by one or the other method. Both methods and the algorithm are described below.

WTD method

We developed this method to compute the blocking area of the events defined via the WTD, thus, the WTD method is applied on the composites of the WTD-blocking events. It consists in the following steps.

1. The centers of the WTD-blocking events are detected between 30°W and 50°E (they are defined as the maximum positive anomaly of the composite within this longitude interval, see subsection 3.4).
2. The blocking size is defined by the contour line equal to a certain threshold. Such threshold cannot be higher than the minimum ΔZ500 value identified among the centers of all events in each period (HIST, SSP2, and SSP5) among all models (see Table S3). In this work, the threshold is 75 m considering $\Delta Z500_{\mathrm{HIST}}$, $\Delta Z500_{\mathrm{SSP2}}$, and $\Delta Z500_{\mathrm{SSP5}}$.
3. The algorithm to compute the area limited by the contour line defined in Step 2 is applied. As a result, the area of the WTD-blocking events ($A_{e,\mathrm{WTD}}$) is obtained for each period and all models.

DG method

This method computes the blocking area of the events identified via the DG index, following Nabizadeh et al. (2019). It is applied on daily ΔZ500 (not on the composites of the blocking events), where $\Delta Z500 = \Delta Z500(t, \phi, \lambda)$ with ϕ = latitude, λ = longitude, and t = time in days. Below, we report how blocking is identified via the DG index and describe the DG method.

DG-blocking events are defined as follows.

- The daily anomalies are scaled by a factor $\alpha(\phi) = \frac{\sin(45°)}{\sin(\phi)}$; the scaled anomalies $\tilde{\Delta}(t, \phi, \lambda) = \alpha(\phi)\Delta(t, \phi, \lambda)$ are so obtained.
- The standard deviation (over time) of the scaled anomalies is computed ($\tilde{\sigma}(\phi, \lambda)$).
- The maximum of the zonal-mean of $\tilde{\sigma}$ between latitudes 40N-60N ($\tilde{\sigma}_{max}$) is defined.
- $\tilde{\sigma}_{max}$ is used to normalize the scaled anomalies and to compute the DG index (for each day t and grid box (ϕ, λ)):

$$DG(t, \phi, \lambda) = \frac{\tilde{\Delta}(t, \phi, \lambda)}{\tilde{\sigma}_{max}}.$$

- The grid boxes where $DG > 1.5$ for at least five consecutive days are called *DG-grid boxes* and identify the DG-blocking events.
  In this study, we apply this condition in a smaller domain than the European-Atlantic sector defined for the WTD: like for the WTD method, we consider the domain between 30°W and 50°E.

The DG method consists in the following steps.

1. The daily size of blocking is defined by the contour line $\tilde{\Delta}(t, \phi, \lambda) = \tilde{\sigma}_{max}$, i.e. $DG = 1$.
   Like in Step 2 of the WTD method, in order to compare blocking areas among different models and in different periods, the same threshold must be used. In analogy with the WTD method, we use the minimum value found for $\tilde{\sigma}_{max}$: 112 m considering $\Delta Z500_{\mathrm{HIST}}$, $\Delta Z500_{\mathrm{SSP2}}$, and $\Delta Z500_{\mathrm{SSP5}}$.

2. The algorithm to compute the blocking area is applied to obtain daily blocking area ($A_{d,\mathrm{DG}}$). We remind that, in this work, we only consider those DG-blocking days that belong to the WTD-blocking events.

3. Finally, the area of the DG-blocking events ($A_{e,\mathrm{DG}}$) is computed as temporal mean of $A_{d,\mathrm{DG}} > 0$ (in fact, it can happen that $A_{d,\mathrm{DG}} = 0$ in some days which belong to the WTD-blocking events).

Algorithm to compute the blocking area

We developed an algorithm that computes the area delimited by a contour line of any shape. The contour lines are the ones computed via the WTD method and the DG method. This algorithm has the advantage of computing exactly the area of interest without any approximation or assumption about the shape of the blocking size; the disadvantage is its dependency on a threshold.

Step A. Storing the coordinates of the grid boxes that belong to the positive anomaly including blocking center/DG-grid box. Starting from one corner of the domain, the ΔZ500 field is scanned. The coordinates of those grid boxes with positive anomalies higher than the threshold are stored (we call "blob" the ensamble of these grid boxes). As shown in Figure S1, more blobs can be present at the same time, thus, only the one that contains the blocking center (for the WTD method) or at least one DG-grid box (for the DG method) is retained.

Step B. Computing the grid-box area. The area of each grid box forming the selected blob is computed taking into account the curvature of the Earth (assumed to be spherical). We recall below the formula for an infinitesimal element of surface area over a sphere (dA). Being $\delta = 90° - \phi$ the colatitude, where $0 \leq \lambda < 2\pi$, $-\pi/2 \leq \phi \leq -\pi/2$, and $0 \leq \delta \leq \pi$:

$$dA = r^2 \sin\delta \; d\lambda d\delta = r^2 \cos\phi \; d\lambda d\phi.$$

In the discrete case of a regular mesh-grid over a sphere, like in the GCMs, the area of one grid box is $\Delta A_i = r^2 \cos\phi_i \; \Delta\lambda\Delta\phi$, where $r = 6371$ km is the Earth radius. In this work, the size of the grid boxes is 1.0°x1.0° by construction, so $\Delta\lambda\Delta\phi \simeq (0.017453)^2$.

Step C. Computing the blocking area. The areas of the grid boxes are summed up in order to get the area of one blocking event (A_e) in the case of the WTD method and one blocking day (A_d)

in the case of the DG method. In both cases, the blocking area (in km^2) is:

$$A = \sum_i \Delta A_i = (r^2 \Delta\lambda \Delta\phi) \sum_i \cos\phi_i$$

where i =1...N and N is the total number of grid boxes of the selected blob.

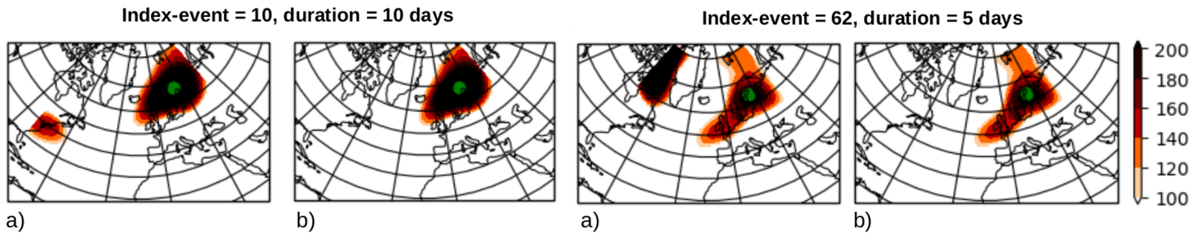

Figure S1: Examples of "blobs" detected in Step A before *a*) and after *b*) the selection of the blob containing the blocking center. In this example, the Z500 anomalies are composites of WTD-blocking events identified with ERA5 reanalysis.

Figures and Tables

	ERA5	MPI	BCC	MRI	GFDL	MIROC	CanESM	IPSL	INM	FGOALS	MM
$\Delta Z500_{\text{HIST}}$											
HIST [%]	26.8	26.2	28.9	27.7	23.2	27.6	26.6	28.4	23.2	22.9	25.4
$\Delta Z500_{\text{SSP2}}$ and $\Delta Z500_{\text{SSP5}}$											
SSP2 [%]	/	25.1	20.8	25.5	24.5	/	/	/	26.8	27.0	25.0
SSP5 [%]	/	24.5	24.3	26.1	26.4	/	/	/	26.7	24.2	25.4
$\Delta Z500_{\text{SSP2-HIST}}$ and $\Delta Z500_{\text{SSP5-HIST}}$											
SSP2 [%]	/	26.1	23.0	24.1	21.8	/	/	/	26.9	26.5	24.7
SSP5 [%]	/	24.3	25.8	24.9	25.0	/	/	/	26.6	24.2	25.1

Table S1: Occurrence of the blocking weather type. We report the k-mean results (instead of the occurrence of the blocking events as defined in subsection 3.2) to allow a direct comparison with previous studies that apply the WTD.

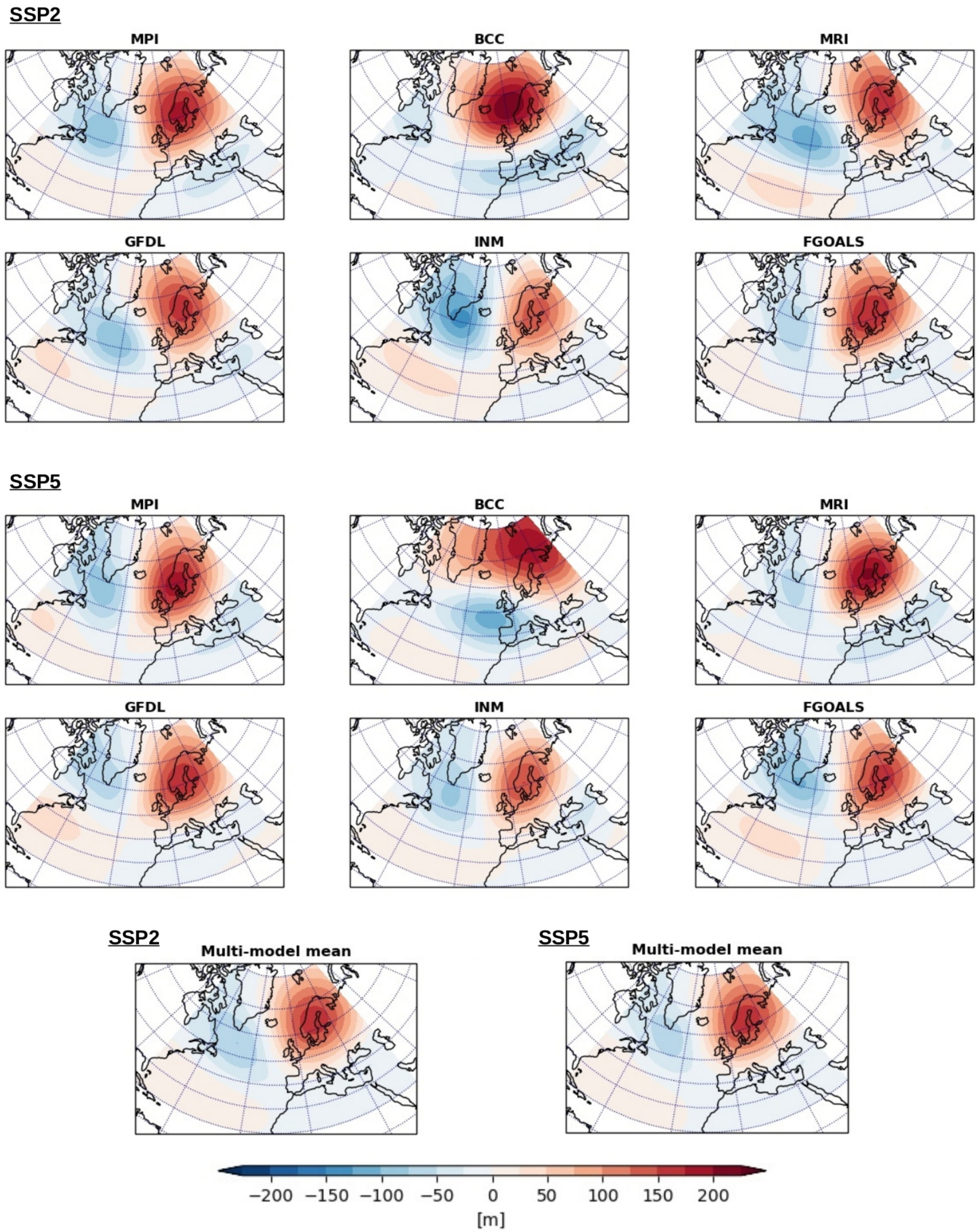

Figure S2: $\Delta Z500_{SSP2}$ and $\Delta Z500_{SSP5}$ composites averaged over all blocking events for the six selected GCMs during SSP2 and SSP5; in the last row, the multi-model mean is computed over all blocking events of the six selected GCMs.

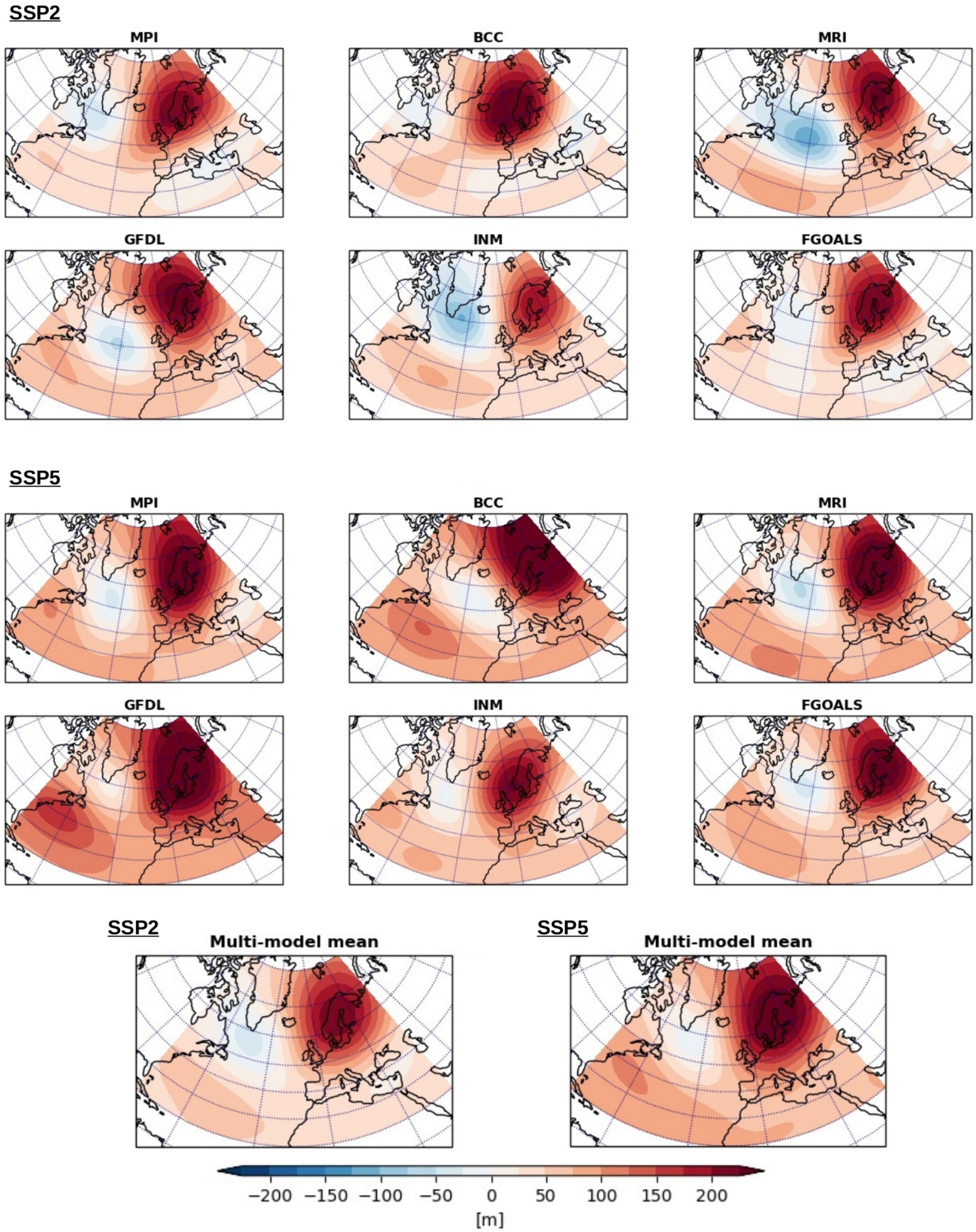

Figure S3: $\Delta Z500_{\text{SSP2-HIST}}$ and $\Delta Z500_{\text{SSP5-HIST}}$ composites averaged over all blocking events for the six selected GCMs during SSP2 and SSP5; in the last row, the multi-model mean is computed over all blocking events of the six selected GCMs.

		tot #days	**tot #events**	**#days/winter**	**#events/winter**	**mean duration**
ERA5	HIST	979	96	32.6±14.4	3.2±1.2	10.2±5.3
MPI	HIST	926	97	30.8±15.2	3.2±1.3	9.5±4.9
	SSP2	876	90	29.2±15.9	3.0±1.37	9.7±5.6
	SSP5	844	97	28.1±14.3	3.2±1.4	8.7±4.6
BCC	HIST	1149	103	38.3±16.4	3.4±1.4	11.2±6.3
	SSP2	699	75	23.3±12.1	2.5±1.2	9.3±3.9
	SSP5	965	85	32.2±16.8	2.8±1.4	11.4±7.2
MRI	HIST	994	107	33.1±14.9	3.6±1.4	9.3±4.7
	SSP2	943	97	31.4±13.2	3.2±1.4	9.7±5.3
	SSP5	923	109	30.8±16.9	3.6±1.7	8.5±3.9
GFDL	HIST	794	88	26.5±13.5	2.9±1.3	9.0±4.4
	SSP2	878	89	29.3±16.2	3.0±1.6	9.9±5.7
	SSP5	978	107	32.6±16.7	3.6±1.5	9.1±5.6
INM	HIST	771	84	25.7±12.4	2.8±1.4	9.2±4.9
	SSP2	979	89	32.6±14.6	3.0±1.2	11.0±5.9
	SSP5	942	93	31.4±16.7	3.1±1.5	10.1±5.5
FGOALS	HIST	864	77	28.8±13.1	2.6±1.1	11.2±6.3
	SSP2	1020	106	34.0±16.6	3.5±1.3	9.6±5.8
	SSP5	819	88	27.3±14.9	2.9±1.2	9.3±4.5
MM	HIST	916.3±140.7	92.8±11.7	30.5±4.3	3.1±0.4	9.9±0.9
	SSP2	899.2±113.1	91.0±10.3	30.0±3.4	3.0±0.3	9.9±0.5
	SSP5	911.8±65.5	96.5±9.8	30.4±2.0	3.2±0.3	9.5±1.0

Table S2: Total number of blocking days and blocking events in 30 winters, means and standard deviations of number of blocking days per winter, number of blocking events per winter, and blocking duration during HIST, SSP2, and SSP5 considering $\Delta Z500_{\mathrm{HIST}}$, $\Delta Z500_{\mathrm{SSP2}}$, and $\Delta Z500_{\mathrm{SSP5}}$. The multi-model (MM) mean is computed by averaging the values of the six GCMs.

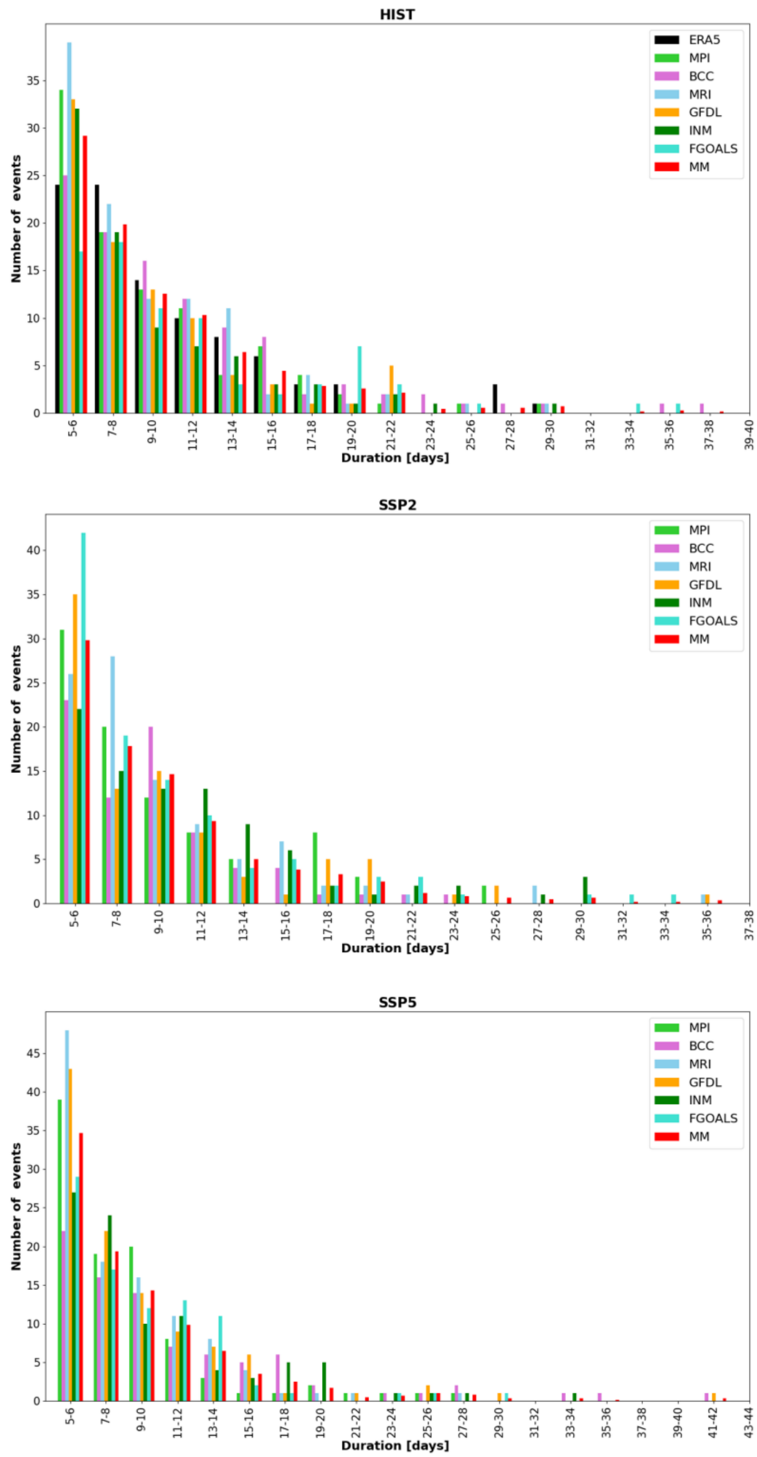

Figure S4: Occurrence of blocking events as a function of blocking duration for all models during HIST, SSP2, and SSP5 considering $\Delta Z500_{\mathrm{HIST}}$, $\Delta Z500_{\mathrm{SSP2}}$, and $\Delta Z500_{\mathrm{SSP5}}$.

Model	Mean [m]			Standart Deviation [m]			Min-Max [m]		
	HIST	SSP2	SSP5	HIST	SSP2	SSP5	HIST	SSP2	SSP5
$\Delta Z500_{HIST}$, $\Delta Z500_{SSP2}$, and $\Delta Z500_{SSP5}$									
ERA5	251	/	/	48	/	/	123-368	/	/
MPI	273	254	257	61	59	56	142-438	150-414	130-396
BCC	266	298	272	65	66	68	111-441	179-480	136-456
MRI	238	238	260	64	69	60	108-424	85-445	118-426
GFDL	240	229	240	49	47	54	141-399	130-343	118-412
INM	219	198	203	50	54	52	100-362	79-334	101-345
FGOALS	254	249	230	55	62	66	146-373	120-444	78-421
MM *	248±18	244±30	244±23						

Table S3: Mean, standard deviation, minimum, and maximum computed with the center intensities of the WTD-blocking events.

Model	Mean [10^6 km^2]			Std Deviation [10^6 km^2]			Min-Max [10^6 km^2]		
	HIST	SSP2	SSP5	HIST	SSP2	SSP5	HIST	SSP2	SSP5
$\Delta Z500_{HIST}$, $\Delta Z500_{SSP2}$, and $\Delta Z500_{SSP5}$									
ERA5	8.9	/	/	2.7	/	/	2.9-17.6	/	/
MPI	10.2	9.9	9.7	2.8	3.3	2.9	4.4-20.8	2.8-18.0	3.3-16.4
BCC	8.9	11.1	8.1	3.5	3.4	3.6	2.4-23.2	4.9-19.9	2.4-19.4
MRI	8.3	7.6	9.3	3.5	2.9	3.5	1.0-20.7	0.4-14.7	1.9-22.7
GFDL	9.6	8.6	8.8	3.1	3.3	3.5	3.9-18.2	0.9-20.9	0.3-20.8
INM	7.7	6.5	7.1	2.3	3.0	2.7	1.7-13.8	1.0-18.8	1.2-14.8
FGOALS	9.9	9.3	8.2	2.9	3.8	3.7	2.8-16.9	2.0-23.4	0.1-20.7
MM *	9.1±0.9	8.8±1.5	8.5±0.9						

Table S4: Mean, standard deviation, minimum, and maximum computed with the areas of the WTD-blocking events computed with the WTD method.

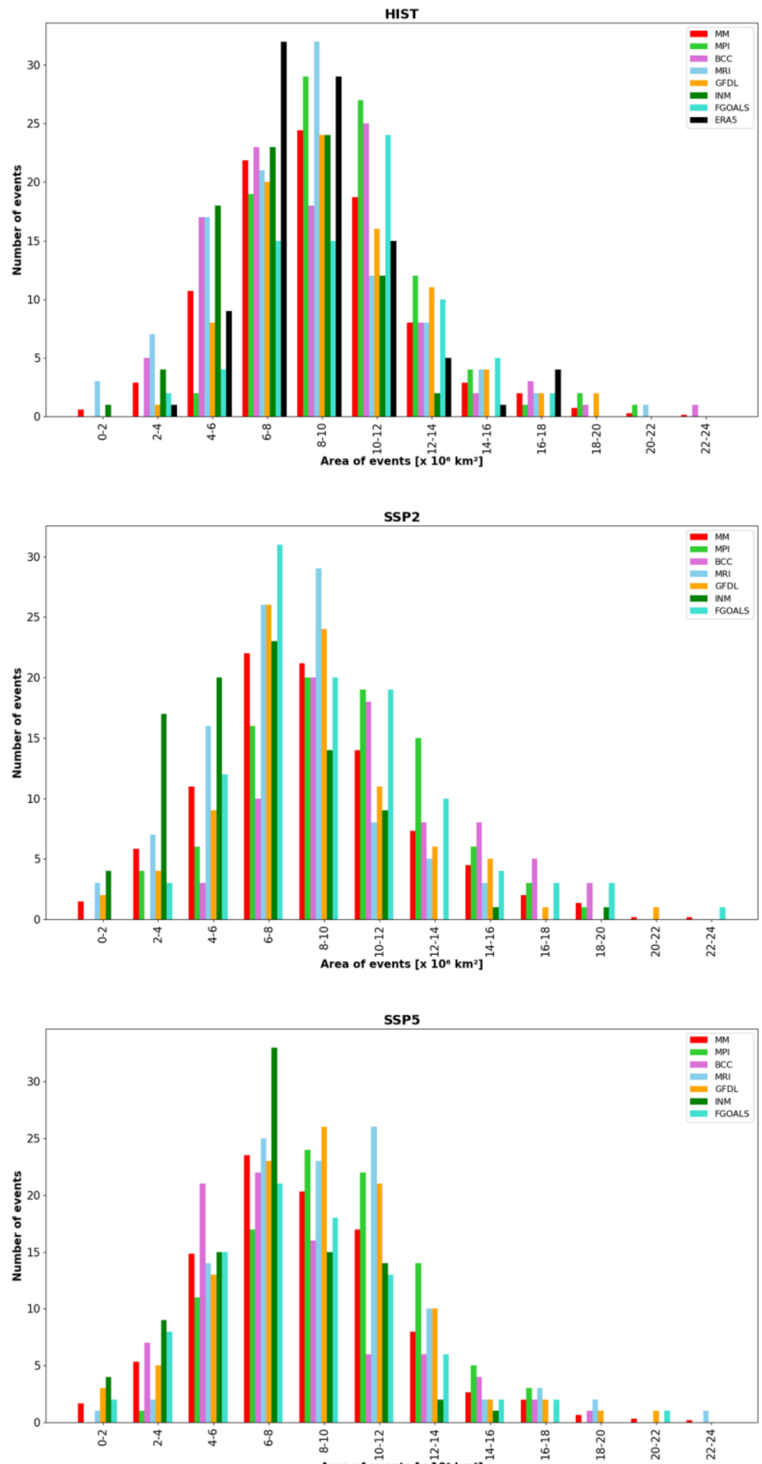

Figure S5: Occurrence of blocking events as a function of blocking area for all models during HIST, SSP2, and SSP5 considering $\Delta Z500_{\mathrm{HIST}}$, $\Delta Z500_{\mathrm{SSP2}}$, and $\Delta Z500_{\mathrm{SSP5}}$.

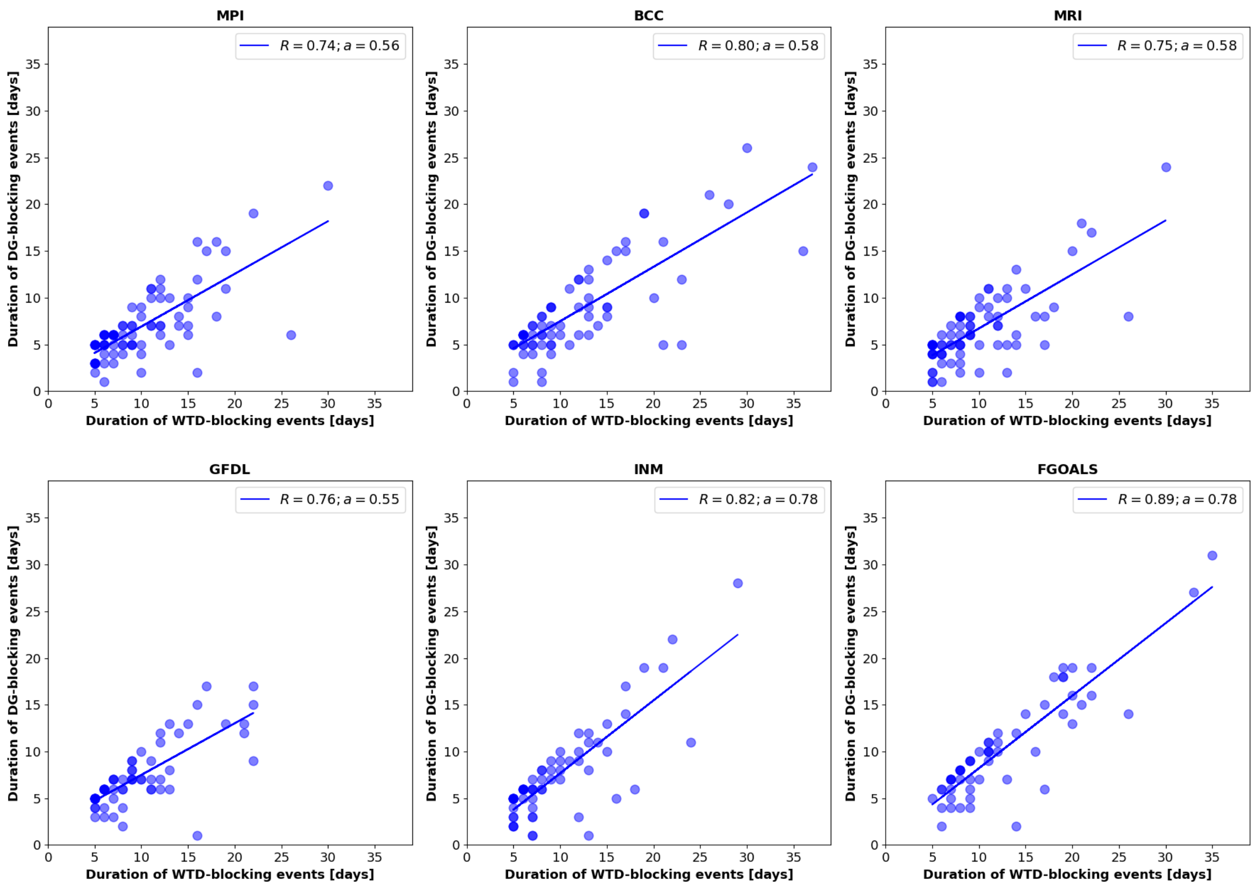

Figure S6: Correlation between duration of WTD-blocking events and DG-blocking events during the HIST period. R is the correlation; a is the slope of the linear regression.
70%-85% of the total blocking events identified via the WTD are shown; the remaining part is not displayed as it corresponds to those events that are not identified via the DG method (i.e. those WTD-blocking events for which the duration of DG-blocking events is null). The plots show a quite high correlation ($R > 0.74$). The underestimation of the DG-blocking duration is due to the fact they are identified within the WTD-blocking events (as written in subsection 3.4).