Supplementary material

Computation of blocking area

In this work, two different methods are applied in order to define and quantify the blocking extension: the center 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.

Center method

We developed this method to compute the blocking area of the events defined via the WTD, thus, the center 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 3.3).

2. The blocking extension 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 100 m (in agreement with Carrera et al. 2004) considering $\Delta Z500_{\mathrm{HIST}}$ and 75 m considering $\Delta Z500_{\mathrm{SSP}}$.

3. The algorithm to compute the area limited by the contour line defined in Step 2 is applied. As a result, the area of WTD-blocking events ($A_{e,\mathrm{WTD}}$) is obtained for each period and all models.

DG method

This method, which follows Nabizadeh et al. (2019), is applied on the 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. The DG method follows the steps below.

1. The 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.

2. The standard deviation (over time) of the scaled anomalies is computed ($\tilde{\sigma}(\phi, \lambda)$).

3. The maximum of the zonal-mean of $\tilde{\sigma}$ between latitudes 40N-60N ($\tilde{\sigma}_{max}$) is defined.

4. $\tilde{\sigma}_{max}$ is used to normalize the scaled anomalies and to compute the DG index (for each day t and grid box (ϕ, λ)):

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

5. The grid boxes where $DG > 1.5$ for at least five consecutive days are identified as 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 center method, we consider the domain between 30°W and 50°E.

6. The daily extension 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 center method, in order to compare blocking areas among different models and in different periods, the same threshold must be used. In analogy with the center method, we use the minimum value found for $\tilde{\sigma}_{max}$: 116 m for $\Delta Z500_{\mathrm{HIST}}$ and 112 m for $\Delta Z500_{\mathrm{SSP}}$.

7. 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.

8. Finally, the area of 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 center 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 extension; the disadvantage is its dependency on a threshold.

Step A. Storing the coordinates of the grid boxes that belong to the positive anomaly including the blocking center. Starting from one corner of the domain, the $\Delta Z500$ 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 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 center 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.

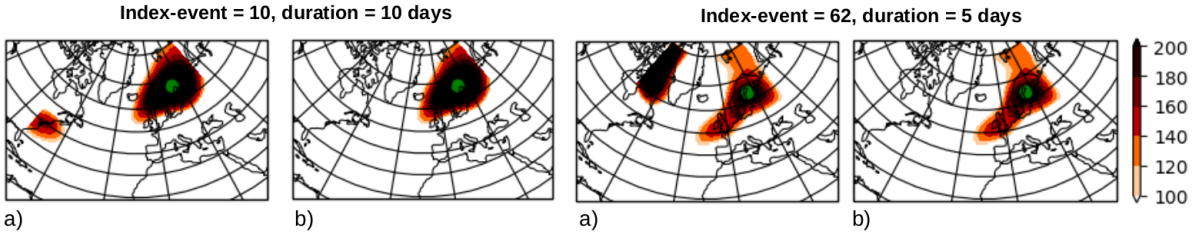

Figure S1: Examples of "blobs" detected in Step A before *(a)* and after *(b)* the selection of the blob containing the center. In this example, the Z500 anomalies are composites of WTD-blocking events identified with ERA5 reanalysis.

Figures and Tables

	ERA5	MPI	BCC	MRI	GFDL	MIROC	CanESM	IPSL	INM	FGOALS	MM
HIST [%]	26.8	26.2	28.9	27.7	23.2	27.6	26.6	28.4	23.2	22.9	25.4
$\Delta Z500_{HIST}$											
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
$\Delta Z500_{SSP}$											
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

Table S1: Occurrence of the blocking weather type obtained with $\Delta Z500_{HIST}$ and $\Delta Z500_{SSP}$. 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.

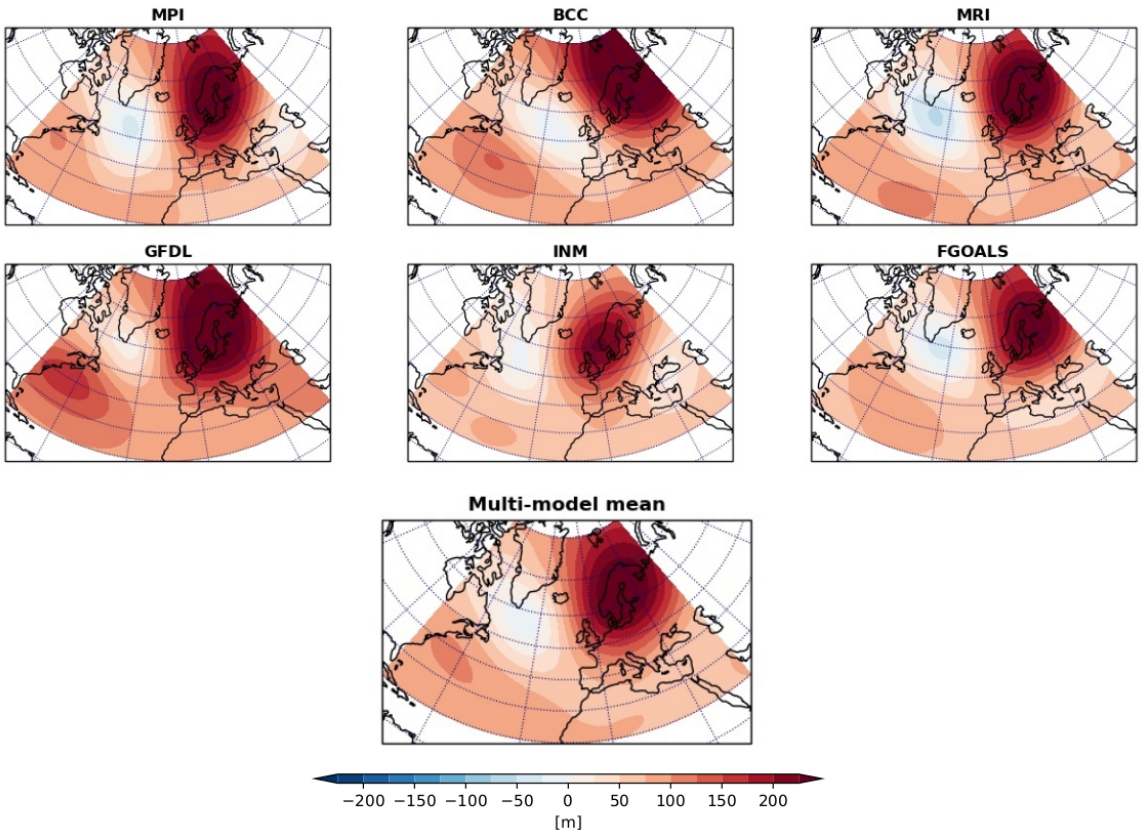

Figure S2: $\Delta Z500_{HIST}$ composites averaged over all blocking events for the six selected GCMs during the winter SSP5 period (2070-2099); in the last row, the multi-model mean is computed over all blocking events of the six selected GCMs.

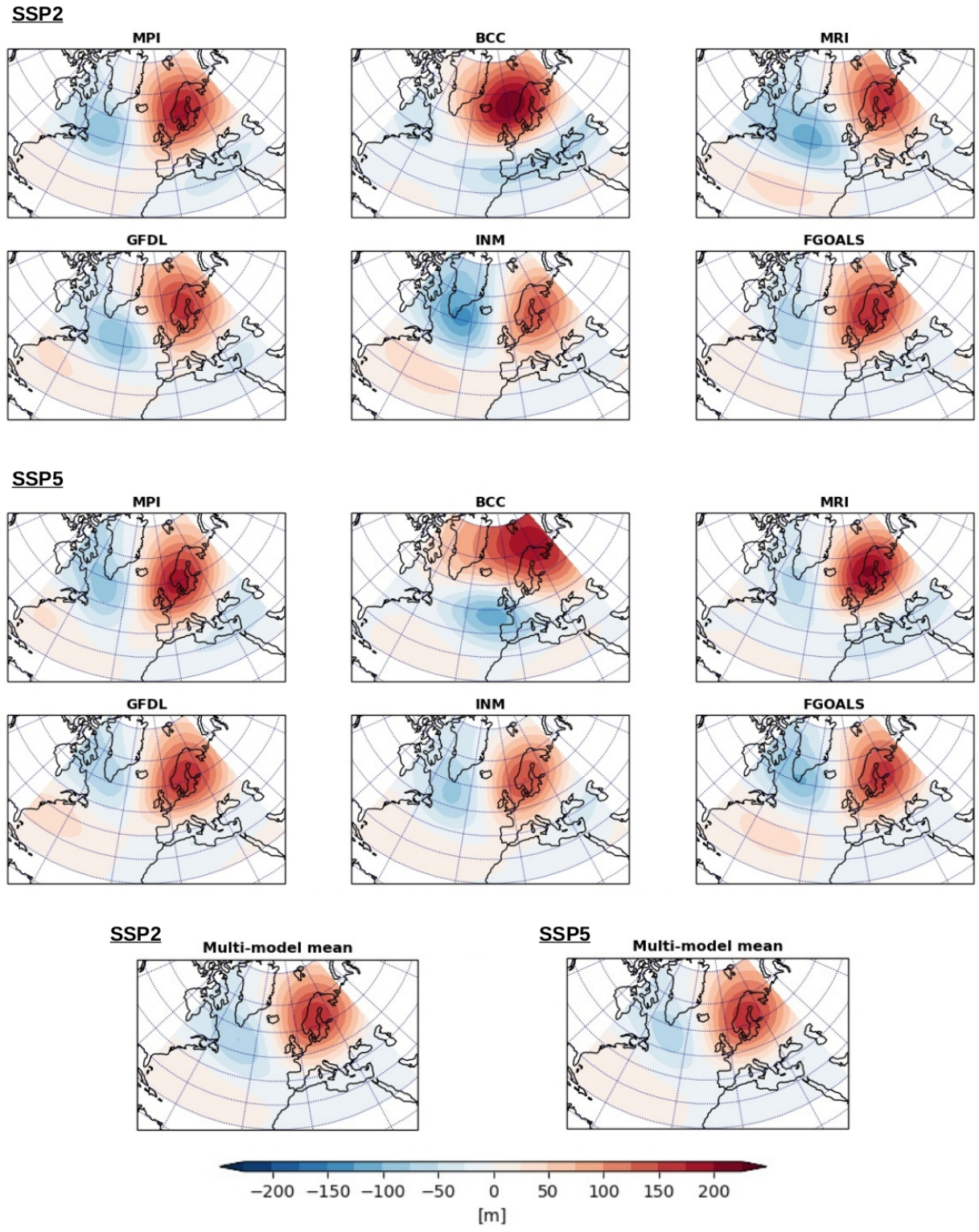

Figure S3: $\Delta Z500_{SSP2}$ and $\Delta Z500_{SSP5}$ composites averaged over all blocking events for the six selected GCMs during SSP2 and SSP5; in the last row, the multi-model mean is computed over all blocking events of the six selected GCMs.

		tot #days	**tot #events**	**#days/winter**	**#events/winter**	**mean duration**
ERA5	HIST	979	96	32.63±14.41	3.2±1.19	10.20±5.33
MPI	HIST	926	97	30.83±15.2	3.23±1.31	9.54±4.87
	SSP2	901	97	30.03±15.48	3.23±1.28	9.29±5.44
	SSP5	830	91	27.67±13.96	3.03±1.17	9.12±4.84
BCC	HIST	1149	103	38.3±16.39	3.43±1.41	11.16±6.32
	SSP2	804	92	26.8±11.68	3.07±1.5	8.74±4.02
	SSP5	936	88	31.2±16.62	2.93±1.46	10.64±5.14
MRI	HIST	994	107	33.13±14.93	3.57±1.38	9.29±4.72
	SSP2	865	88	28.83±13.27	2.93±1.06	9.83±6.17
	SSP5	835	99	27.83±16.46	3.3±1.66	8.43±3.72
GFDL	HIST	794	88	26.47±13.47	2.93±1.31	9.02±4.4
	SSP2	762	85	25.4±16.86	2.83±1.83	8.96±4.5
	SSP5	895	95	29.83±15.89	3.17±1.46	9.42±4.97
INM	HIST	771	84	25.7±12.38	2.8±1.42	9.18±4.91
	SSP2	1007	94	33.57±15.57	3.13±1.36	10.71±5.79
	SSP5	965	104	32.17±16.66	3.47±1.59	9.28±4.66
FGOALS	HIST	864	77	28.8±13.12	2.57±1.12	11.22±6.33
	SSP2	980	102	32.67±15.99	3.4±1.47	9.61±4.99
	SSP5	853	97	28.43±14.44	3.23±1.52	8.79±4.22
MM	HIST	916.3±140.7	92.8±11.7	30.5±4.3	3.1±0.4	9.9±0.9
	SSP2	886.5±96.2	93.0±6.1	29.6±2.9	3.1±02	9.5±0.6
	SSP5	885.6±55.9	95.6±5.7	29.5±1.7	3.2±0.2	9.3±0.7

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 $\Delta Z500_{\mathrm{HIST}}$. The multi-model (MM) mean is computed by averaging the values of the six GCMs.

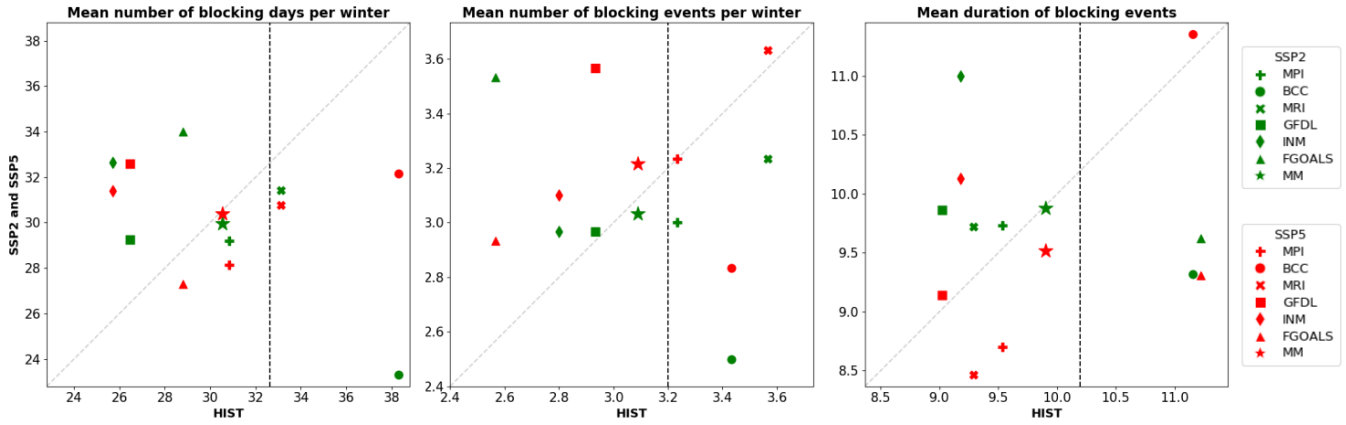

Figure S4: Number of blocking days (*left*) and blocking events (*center*) averaged over all winters of the 30-year periods, and mean duration (in days) of blocking events occurred in 30 winters (*right*) for recent-past climate and future scenarios (SSP2-4.5 and SSP5-8.5) considering $\Delta Z500_{SSP}$. The black dashed line is the ERA5 mean. (The values are taken from Table S2.)

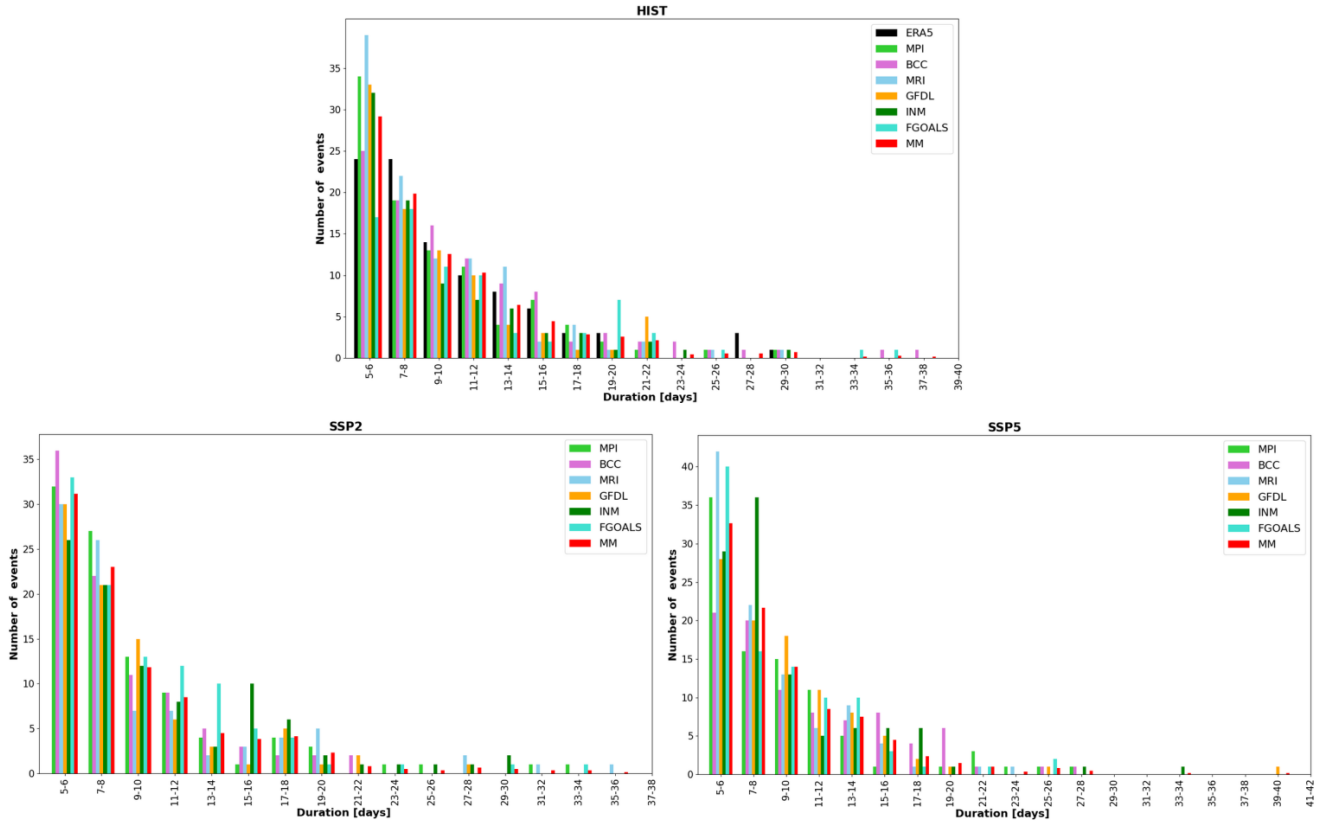

Figure S5: Occurrence of blocking events as a function of duration for all models during HIST, SSP2, and SSP5 considering $\Delta Z500_{HIST}$. The bins of the histogram merge blocking durations that differ by one day.

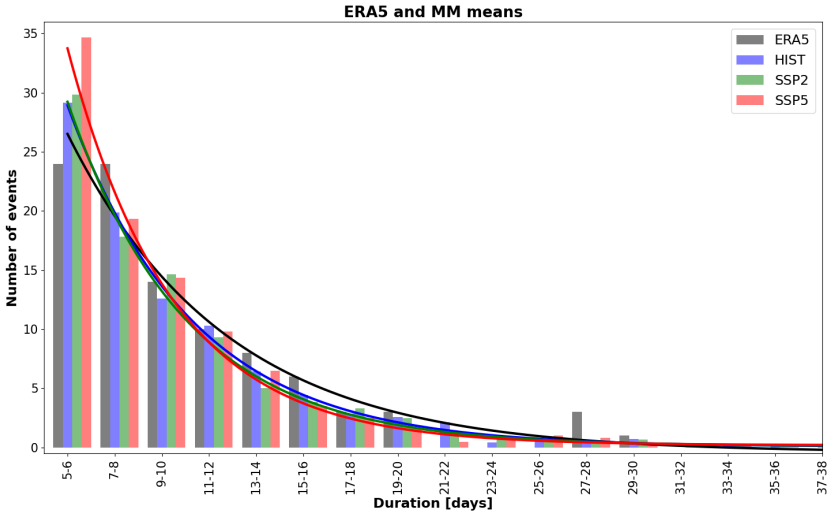

Figure S6: Occurrence of blocking events as a function of duration for ERA5 and MM means during HIST, SSP2, and SSP5 considering $\Delta Z500_{SSP}$. The bins of the histograms merge blocking durations that differ by one day. Exponential fits are drawn for ERA5 and MM means.

Model	**Mean [m]**			**Standart Deviation [m]**			**Min-Max [m]**		
	HIST	SSP2	SSP5	HIST	SSP2	SSP5	HIST	SSP2	SSP5
ERA5	251	/	/	48	/	/	123-368	/	/
$\Delta Z500_{HIST}$									
MPI	273	313	346	61	62	62	142-438	200-499	210-513
BCC	266	349	392	65	75	73	111-441	192-643	238-625
MRI	238	306	354	64	67	59	108-424	155-521	225-490
GFDL	240	309	367	49	47	51	141-399	184-422	240-494
INM	219	254	285	50	59	54	100-362	139-389	179-440
FGOALS	254	305	319	55	62	72	146-373	178-511	182-519
MM *	248±18	306±28	344±34						
$\Delta Z500_{SSP}$									
MPI	/	254	257	/	59	56	/	150-414	130-396
BCC	/	298	272	/	66	68	/	179-480	136-456
MRI	/	238	260	/	69	60	/	85-445	118-426
GFDL	/	229	240	/	47	54	/	130-343	118-412
INM	/	198	203	/	54	52	/	79-334	101-345
FGOALS	/	249	230	/	62	66	/	120-444	78-421
MM *	/	244±30	244±23						

Table S3: Statistics regarding the center intensities of all WTD-blocking events obtained with $\Delta Z500_{HIST}$ and $\Delta Z500_{HIST}$.

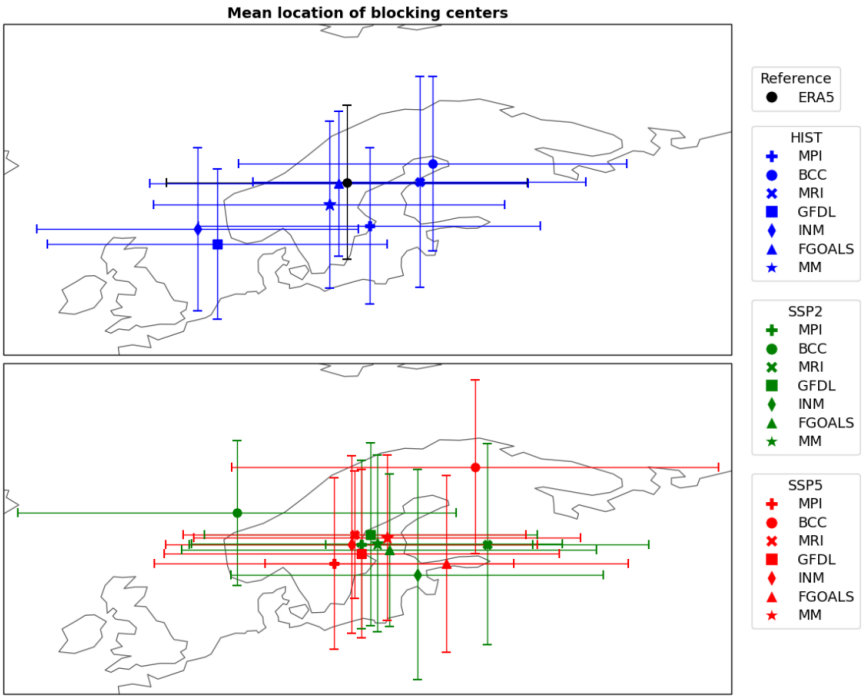

Figure S7: Locations of the blocking composite centers averaged over all blocking events for ERA5 and the GCMs during HIST (*top*), SSP2, and SSP5 (*bottom*) considering $\Delta Z500_{SSP}$. The error bars indicate the standard deviations of latitudinal and longitudinal coordinates of the blocking centers.

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
ERA5	6.9	/	/	2.3	/	/	1.6-15.9	/	/
$\Delta Z500_{HIST}$									
MPI	7.9	12.2	18.2	2.5	4.0	7.0	2.3-18.3	3.8-24.6	6.4-32.5
BCC	7.1	13.9	19.7	2.9	4.8	8.5	0.6-16.8	5.4-25.6	6.0-42.5
MRI	6.1	11.1	17.8	2.9	4.2	7.5	0.2-13.7	3.0-23.8	5.1-38.2
GFDL	7.2	14.3	29.9	2.5	4.7	10.6	2.5-15.2	5.2-30.0	7.7-47.4
INM	5.7	8.3	14.0	2.1	3.8	34.7	0-11.1	1.7-21.8	3.4-26.7
FGOALS	7.7	11.4	14.6	2.5	3.9	5.9	1.7-15.2	3.9-24.1	4.7-29.4
MM *	7.0±0.8	11.9±1.9	19.0±5.3						
$\Delta Z500_{SSP}$									
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: Statistics regarding the areas of all WTD-blocking events computed with the center method using $\Delta Z500_{HIST}$ (threshold equal to 100 m) and $\Delta Z500_{SSP}$ (threshold equal to 75 m). (See the "Computation of blocking area" section of this document for further details.)

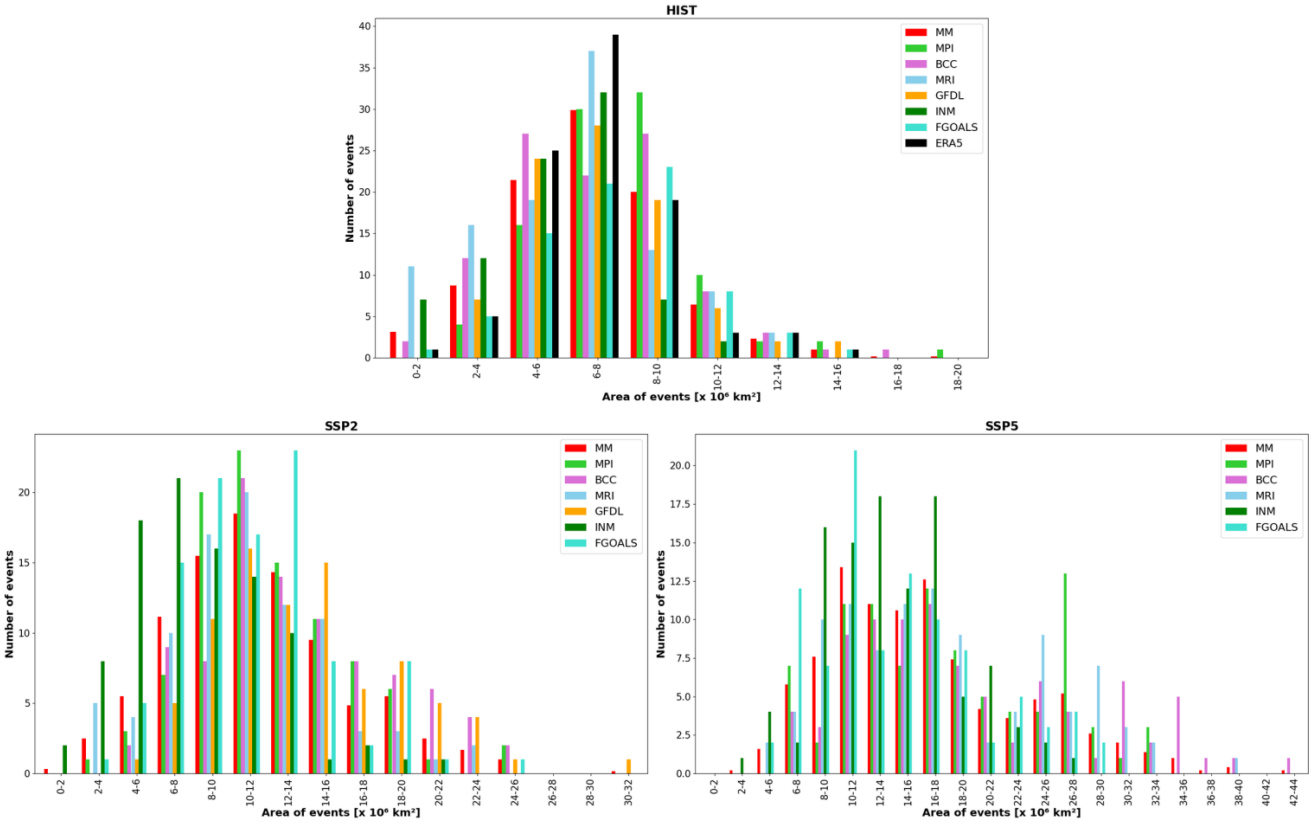

Figure S8: Occurrence of blocking events as a function of area for all models during HIST, SSP2, and SSP5 (excluding GFDL) considering $\Delta Z500_{\mathrm{HIST}}$. The bins of the histogram merge blocking events which differ by $2 \cdot 10^6$ km^2.