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Changes in atmospheric blocking characteristics within Euro-Atlantic region and Northern Hemisphere as a whole in the 21st century from model simulations using RCP anthropogenic scenarios

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ABSTRACT

An analysis of simulations using the IPSL-CM5 climate model of general circulation shows the ability of this model to reproduce the current climate of the main blocking characteristics obtained from reanalysis data, including number of blocking events and their duration, intensity and frequency. Possible changes of blocking characteristics in the Euro-Atlantic region (EA) and for the Northern Hemisphere (NH) as a whole are estimated from model simulations with the RCP2.6 and RCP8.5 scenarios for the 21st century. Results of the model simulations show a general increase in the blocking frequency for the EA in winter, summer and for the entire year during the 21st century for both analyzed RCP scenarios, while changes of the opposite sign are characteristic for NH as a whole. It is also noted that there is a tendency for an increase in the blocking intensity in the EA during the winter from model simulations with both analyzed RCP scenarios for the 21st century. A significant increase is obtained in the EA for the likelihood of extreme winter with the total blocking duration longer than seven weeks. Also, a similar tendency is characteristic for the EA summer.

1. Introduction

In the midst of global climate change, the impact of climate extremes may have significant ecological and social consequences with a major role in human activities, including agriculture and economics (Field et al., 2012). Mature regional weather and climate anomalies are connected with long-lived atmospheric blocking anticyclones, which lead to the occurrence of heat waves with fires in summer and heavy frosts in winter (Rex, 1950; Charney and De Vore, 1979; Lejenas and Okland, 1983; Obukhov et al., 1984; Agayan and Mokhov, 1989; Lupo et al., 1997, 2012; Mokhov and Petukhov, 1997; Wiedenmann et al., 2002; Barriopedro et al., 2006; Mokhov, 2006, 2011; Bardin, 2007; Kreienkamp et al., 2010; Sillmann et al., 2011; Semenov et al., 2012; Masato et al., 2013; Mokhov et al., 2013). Long-term (about 2 months) blocking of zonal circulation in the Northern Hemisphere (NH) mid-latitude troposphere initiated the anomalous heat for the European part of Russia in 2010 (Mokhov, 2011; Lupo et al., 2012). According to Mokhov et al. (2013), modern climate models are able to reproduce such modes of blocking in the atmosphere. Using data produced by the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM) (Lupo et al., 1997) demonstrated that under the conditions of global warming caused by the doubling of atmospheric CO_2 concentration, the intensification of extreme effects, connected with winter blockings and leading to extreme frosts, is expected (see also (Mokhov, 2006)). Similarly, the connection of winter blocking events with Arctic basin sea-ice modes is significant (Semenov et al., 2012). In spite of the recent increases in global temperatures, cold winters have occurred during the last five years across the Northern Hemisphere, in particular, within the European (Sillmann et al., 2011; Semenov et al., 2012) and North American (in 2014) regions.

In this study, estimates of blocking characteristic tendencies are demonstrated for the Euro-Atlantic (EA) region and for NH in general. These estimates are based on simulations of climate using an atmospheric global circulation model for the 20th–21st centuries (with anthropogenic forcing) using the blocking definitions and characteristics described in Lupo et al. (1997), Wiedenmann et al. (2002) and Mokhov et al. (2013). This study using the methods described in Section 2 is unique to the published literature, and will update the results of Lupo et al. (1997) using a more advanced modeling system. The results comparing the observations to the model are described in Section 3, and the model projections for the 21st century are given in Section 4.

2. Data and methods

Simulations were constructed using the IPSL-CM5A-MR (Institute Pierre-Simone Laplace Climate Model 5 with Medium Resolution)

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general circulation model (GCM) (Dufresne et al., 2013) with a grid resolution of 1.15° × 2.5° latitude/longitude. These were used to create three scenarios: historical (data for the 30-year period 1976–2005), and two anthropogenic projections (data for the 30-year period 2071–2100); a) the RCP2.6 (weaker anthropogenic forcing), and b) RCP8.5 (stronger anthropogenic forcing).

Representative concentration pathway (RCP) scenarios concern plausible pathway towards reaching each target radiative forcing trajectory, e.g., Moss et al. (2010). The RCP8.5 scenario provides for the increase of greenhouse gas (GHG) concentration during the 21st century to 1370 ppm (CO_2 equivalent) by 2100 (and reaching an effective anthropogenic radiative forcing at 8.5 W m^{-2}). The RCP2.6 scenario provides for reaching the GHG peak concentration of 490 ppm (CO_2 equivalent) by mid-century (anthropogenic radiative forcing at around 3.1 W m^{-2}) and then the decline of this forcing thereafter (anthropogenic radiative forcing at 2.6 W m^{-2} in 2100) (Moss et al., 2010). To obtain a blocking climatology for a comparison with the historical simulation, we used the NCEP/NCAR reanalysis data (NNR) (Kistler et al., 2001).

When considering blocking events in Euro-Atlantic (EA) region (60 W–60E) during the summers of 2003 and 2010, it is important to examine the ability of GCMs to reproduce blocking characteristics in this sector, and also these parameters' tendencies for change. In our previous study (Mokhov et al., 2013) dedicated to this problem, the IPSL-CM3 (Institute Pierre-Simone Laplace Climate Model) GCM was used. It was shown, that this model reproduced not only common features of blocking characteristics such as distribution in EA and NH, but also duration of the blocking episode of 2010 was sufficiently reproduced. Additionally, the current version of this model (IPSL-CM5A) was used, and it was included in CMIP5 project, e.g., Dufresne et al. (2013).

Blocking anticyclones were detected using a modified version of the Lejenas-Okland (LO) criterion described in Lupo et al. (1997) and Wiedenmann et al. (2002). The Lejenas-Okland (LO) criterion (Lejenas and Okland, 1983) is defined as the difference between the 500 hPa geopotential height at 40 N and 60 N. We choose these two latitudes similar to those in Wiedenmann et al. (2002). Thus, the LO index is given by:

$$LO = Z_{42.5^\circ} - Z_{62.5^\circ}. \quad (1)$$

These latitudes were chosen since they are the values output by IPSL-CM5A-MR that are closest to the original formulation of the LO index. In Lejenas and Okland (1983), blocking is specified to occur when the LO index is negative over a sufficient longitudinal width. In order to meet this requirement, the next relationship that must be fulfilled is:

$$\left(LO(l-10^\circ) + LO(l) + LO(l+10^\circ)\right)/3 < 0, \quad (2)$$

where l is the longitude.

Block intensity (I) is determined by normalizing the geopotential height value at the anticyclone center (Z_m) through the use of the height contour that best represents the blocking anticyclone (C_r). Therefore, I is given by:

$$I = 100.0 * [(Z_m/C_r) - 1.0], \quad (3)$$

where 100.0 and 1.0 are constants chosen such that I varies between 1 and 10 on any given day. In order to minimize subjectivity, C_r was determined in the following manner: (a) C_r must represent the full wavelength between the trough lines of the upstream and downstream troughs, (b) C_r may not be a closed contour, and (c) C_r is the middle contour of contours meeting the first two criteria. (If two contours satisfy (a) and (b), then the contour with the higher value is chosen.) Z_m represents the grid point with the maximum 500 hPa geopotential height value in the closed blocking anticyclone region or on the ridge line associated with the block. Therefore, I is a measure of the average maximum height of the block over its lifetime normalized to adjust for daily and regional anomalies.

Table 1
Blocking characteristics, obtained from historical simulations (historical) and NCEP/NCAR reanalysis (NNR) for 30-year period (1976–2005).

Blocking days	Winter		Summer		Year	
	NNR	historical/NNR	NNR	historical/NNR	NNR	historical/NNR
NH	67.7	0.94	41.3	0.96	210.4	0.96
EA	39.1	0.92	18.6	0.84	112.4	0.96

Mean duration	Winter		Summer		Year	
	NNR	historical/NNR	NNR	historical/NNR	NNR	historical/NNR
NH	7.5	1.05	8.2	0.93	9.7	0.95
EA	7.4	1.03	8.1	1.01	8.8	0.98

Mean number of events	Winter		Summer		Year	
	NNR	historical/NNR	NNR	historical/NNR	NNR	historical/NNR
NH	9.0	0.89	5.0	1.04	21.7	1.01
EA	5.3	0.89	2.3	0.83	12.8	0.99

Mean intensity	Winter		Summer		Year	
	NNR	historical/NNR	NNR	historical/NNR	NNR	historical/NNR
NH	4.4	0.95	2.4	0.96	3.5	0.97
EA	4.7	0.94	2.0	1.05	4.2	0.93

3. Comparative analysis of blocking characteristics from model simulations and reanalysis data

3.1. Northern Hemisphere as a whole

In Table 1, the blocking characteristics, obtained from the historical simulation and NCEP/NCAR reanalysis data for 30-year period (1976–2005), are compared. For the entire year in NH as a whole we get sufficient agreement for all analyzed blocking characteristics. Differences between mean blocking parameters from model simulations and reanalysis data do not exceed five percent. The correspondence of the model and observed blocking shown in Table 1 is an improvement over the model simulations to observations found in Lupo et al. (1997), especially for block intensity an duration.

A comparison of the different seasons in Table 1 provides evidence for better reproduction by the model for blocking characteristics in NH during summer rather than in winter, except mean blocking duration. For the summer, the model slightly overestimates the blocking events' mean number with a slight underestimation of blocking intensity and frequency (number of blocking days) (4%). The largest underestimate for the mean blocking duration does not exceed 7%. In the winter, the mean intensity (5%) and blocking day number (6%) are slightly underestimated, while the mean duration is slightly overestimated (5%). The most remarkable model characteristic underestimated was noted for blocking occurrences (11%). Thus, these results show that the IPSL GCM improves the annual variability of blocking parameters from the earlier publication, but as in Lupo et al. (1997) the summer blocking occurrences were largely overestimated, while winter frequencies were vastly underestimated. Additionally, across the entire NH, Lupo et al. (1997) showed that block intensity was underestimated by 15–25% in all seasons. The IPSL GCM block intensities (Table 1) are much closer to the ones observed.

In Fig. 1 the cumulative distributions for the NH blocking occurrences (ordinate) versus duration (abscissa) for summer and winter are shown. The distributions for individual block durations, obtained from NCEP/NCAR reanalysis (NNR) and from the historical simulation are close to each other for summer but display a greater difference during the winter season.

3.2. Euro-Atlantic region

According to Table 1, in the EA the annual mean number of blockings and their mean duration are reproduced very well by the model. The blocking frequency (blocking days) is also faithfully reproduced from model simulations. The most remarkable underestimate of blocking character by the model is associated with the mean intensity (7%).

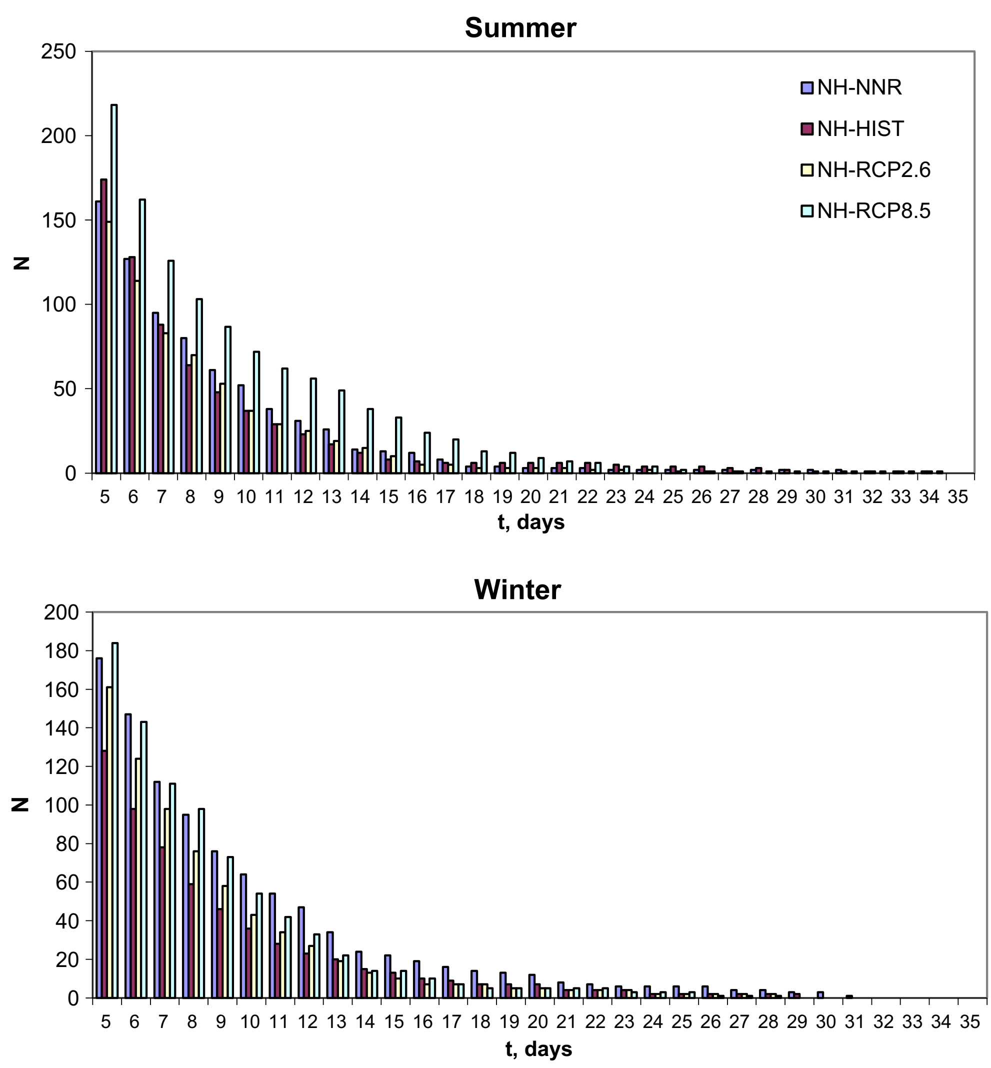

Fig. 1. Cumulative distributions for the blocking number in dependence of its duration for summer and winter in the NH for current climate from NCEP/NCAR reanalysis (NH-NNR) and historical simulations (NH-HIST) for the period 1976–2005 and for the last 30 years of the 21st century (from model simulations with anthropogenic forcing scenarios RCP2.6 (NH-RCP2.6) and RCP8.5 (NH-RCP8.5).

In the winter and summer seasons within the EA, the mean blockings' duration is the characteristic best reproduced by the model (the difference was only 1–3%). The mean blockings' intensity is slightly overestimated by the model during the summer and winter seasons (by 5% and 6%, respectively). The blockings' frequency in days (underestimated by 8% in winter and 16% in summer) and the number of blocking events (underestimated by 11% in winter and 17% in summer) are reproduced less well.

It should be noted that in the EA both IPSL-CM5 simulations and CCM model results from Lupo et al. (1997) demonstrate general underestimation for blocking frequency (blocking days) and mean number of block occurrences, as well as for mean intensities during the winter (and for the entire year). However, there was little overestimation of the total mean blocking duration for both the summer and winter seasons in EA by the model (Table 1).

4. Model estimates of possible changes in blocking characteristics during the 21st century

4.1. Northern Hemisphere as a whole

Table 2 shows characteristics of blocking anticyclones, obtained from historical simulations for the modern 30-year period (1976–2005), and from the RCP2.6 and RCP8.5 simulations for the last 30 years of the 21st century.

For the entire year a general weakening of blocking activity was obtained for the NH as a whole at the end of the 21st century according to both scenarios, apart from the increase in the blockings' mean duration according to the RCP2.6. In Lupo et al. (1997), blockings are expected to be generally more persistent but weaker in a warmer climate. Similar tendencies for blockings are also noticed for NH in the summer season from the IPSL GCM simulations with the RCP2.6 scenario. The main difference in the tendencies for the winter season is connected with the total increase in the number of blocking events' number by the end of the 21st century from both scenarios. Also, the decrease in blockings' mean duration in the winter season is noticed not only for the RCP8.5, but also for the RCP2.6.

It is notable that the number of blocking event increases in the winter season, and the decreases in summer and for the entire year from both scenarios are similar to the results of Lupo et al. (1997). The tendencies for decreases in blocking intensity from both scenarios (except RCP8.5 for winter) are also in accordance with Lupo et al. (1997). The change of blocking intensity for RCP8.5 was not noticed in the winter season. For the mean blockings' duration only a decrease during the summer season in RCP8.5 and increase for the entire year in RCP2.6 are consistent with Lupo et al. (1997). For winter simulations using both the RCP2.6 and the RCP8.5 show a decrease of mean blocking duration, while it increased for the summer season in RCP2.6. The tendency for blocking days to decrease is similar to Lupo et al. (1997) only for the summer season in both scenarios. The decrease in blocking frequency during the winter in both RCP scenarios is associated with a corresponding decrease of the mean blocking duration in the NH as a whole, in spite of the increase in the number of blocking events.

4.2. Euro-Atlantic region

For the EA, changes in the character of blocking events have an essential difference from the general tendencies for the NH. In this region, the tendencies for block occurrences and number of blocking days are increasing by the end of the 21st century, and this is obtained from both scenarios (Table 2). At the same time, however, the mean values of blocking duration and intensity for the entire of year are decreasing.

The increase in the occurrence of EA blocking events and blocking days by the end of the 21st century are obtained also for the winter and summer seasons in both scenarios (except according to RCP2.6, any change in summer season blocking events is not noted). The opposite tendencies are obtained for the mean blocking intensity in the EA during the summer (decreasing) and in the winter (increasing). The mean duration of blocking events in the EA during the winter season is decreasing for both RCP scenarios with an increase in summer for the RCP2.6 scenario and without any noticeable change for the RCP8.5 scenario.

It is notable that for both RCP scenarios there was a tendency for an increase in blocking days within the EA for the entire year and for winter, and this is similar to the results of Lupo et al. (1997). In the summer

Table 2
Characteristics of blocking anticyclones, obtained from historical simulation (historical) for modern 30-year period (1976–2005), and from RCP2.6 and RCP8.5 simulations for the last 30 - years of the 21st century.

	Winter			Summer			Year		
Blocking days	XX	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5
NH	historical	57.7	54.5	39.7	37.3	36.1	202.3	198.3	192.2
EA	35.8	36.2	39.4	15.6	16.1	16.2	108.4	109.5	110.6

	Winter			Summer			Year		
Mean duration	historical	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5
NH	7.9	6.3	5.6	7.6	8.0	7.4	9.2	9.6	8.9
EA	7.6	6.5	6.6	8.2	8.4	8.2	8.6	8.3	8.5

	Winter			Summer			Year		
Mean number of events	historical	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5
NH	8.0	9.2	9.7	5.2	4.6	4.9	22.0	20.7	21.5
EA	4.7	5.6	5.9	1.9	1.9	2.0	12.6	13.2	13.0

	Winter			Summer			Year		
Mean intensity	historical	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5	historical	RCP2.6	RCP8.5
NH	4.2	4.1	4.2	2.3	2.1	2.1	3.4	3.3	3.3
EA	4.4	4.7	4.9	2.1	2.0	1.9	3.9	3.7	3.7

season, the blocking frequency (blocking days) is also increasing by the end of the 21st century according to both RCP scenarios, while in Lupo et al. (1997) it is decreasing for a warmer climate. For the number of blocking events, there is a tendency for an increase in the EA for the entire year, the winter, and summer for both RCP scenarios (but no change in summer season blocking for RCP8.5), and this is consistent with Lupo et al. (1997) for the winter and for the entire year. According to Lupo et al. (1997), the decrease for summer blocking events in the EA can be expected for a warmer climate. The obtained tendency here for a decrease in the blocking intensity during the summer season within the EA for both RCP scenarios is in accordance with Lupo et al. (1997). For the winter season, the intensification of blocking in the EA was noted for both the RCP2.6 and RCP8.5 scenarios. A similar tendency was noted in Lupo et al. (1997) for their continental regions. Changes in blocking duration found in this study differ significantly from those obtained in Lupo et al. (1997) both for the winter and summer seasons.

Fig. 2 shows the number of years with different numbers of blocking days during the winter and summer seasons in the EA for three 30-year periods: 1976–2005 and at the end of the 21st century for the RCP2.6 and RCP8.5 scenarios. It is noted here that in winter and summer, there are more years with a greater number of blocking days at the end of the 21st century from simulations using both RCP scenarios. This could result in some regions having anomalously cold winters and anomalously warm summers in a globally warmer climate.

According to the results found here, a significant increase in the likelihood of extreme winter and summer conditions might be found in the EA by the end of the 21st century associated with long lived blocking events (7 weeks or more). This increase is larger than 20% for the RCP2.6 and larger than 40% for the RCP8.5 in winter. In summer this increase is larger than 10% for RCP2.6 and about 30% for RCP8.5.

The noted increase in frequency of long-lived blocking seasons in the 21st century both in winter and summer is accompanied by a corresponding decrease in frequency of short-lived blockings. Longer lived blocking events were also found in the results of Lupo et al. (1997).

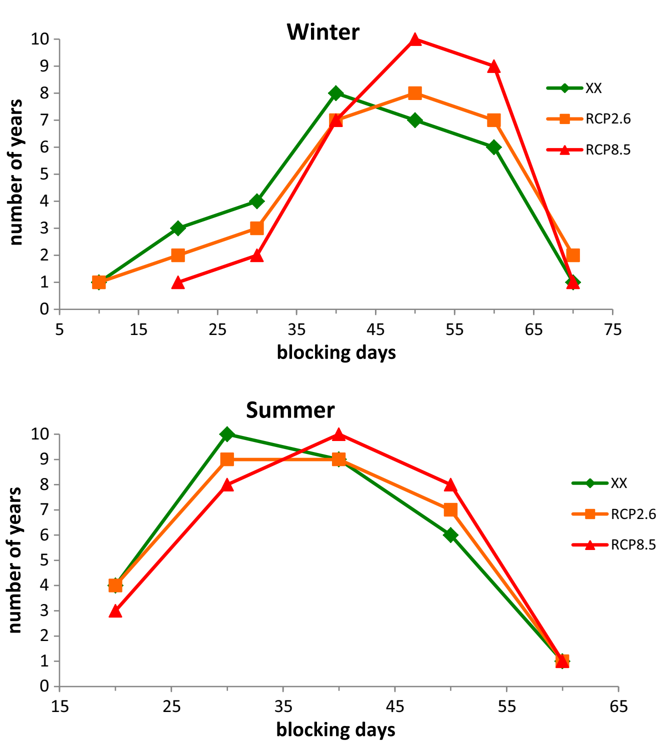

Fig. 2. The number of years in the EA with different total blocking duration (blocking days' number) in winter and in summer from model simulations for different 30-year periods: 1976–2005 (XX) and at the end of the 21st century for the RCP2.6 and RCP8.5 scenarios.

5. Summary and conclusions

An analysis of simulations using the IPSL-CM5 GCM shows the model's ability to reproduce the main blocking characteristics for the current climate. The most remarkable differences between blocking characteristics obtained from model simulations and the reanalysis data for the NH as a whole were obtained for the winter season with an underestimation of the total blocking numbers from model simulations by 11%. A remarkable underestimation from model simulations was noted also for the number of blockings in the EA during the summer and winter seasons, but, as a whole, the results obtained from the IPSL GCM simulations display a significant improvement in the ability to reproduce the climatological characteristics of blocking events in comparison to earlier less comprehensive model simulations, e.g., Lupo et al. (1997).

The results of the analyzed model simulations show a general increase during the 21st century in the number of blocking days for the EA region in the winter, summer and for the entire year for both analyzed RCP scenarios, while changes of the opposite sign are characteristic for the NH as a whole. The obtained tendencies showing an increase in the blocking frequency within the EA are related to an appropriate increase in the number of blocking events (except for RCP2.6 in summer). The general decrease in the blocking frequency for the NH as a whole is accompanied by changes of opposite sign in the number and duration of blocking events, but with a dominating tendency of decrease (for number of blocks not for their duration). A significant increase in likelihood of extreme winter and summer conditions is noted in the EA (with the total blocking duration longer than 7 weeks, in particular).

For the entire year, all analyzed characteristics of blocking activity in the NH as a whole display general tendency for decrease at the end of the 21st century (except for the mean blocking duration in the RCP2.6). For blocking intensity, such a tendency for decrease was obtained as well for the summer and winter seasons (except in winter for the RCP8.5 there were no remarkable changes). Similar tendencies were noted in the EA for the entire year and in the summer season. A different tendency, an increase in blocking intensity by the end of the 21st century was detected from the model simulations in the EA during the winter for both of the analyzed RCP scenarios.

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References

Agayan, G.M., Mokhov, I.I., 1989. Quasi-stationary autumn regimes in the atmosphere of the Northern Hemisphere in FGGE. Izv. Atmos. Oceanic Phys. 25, 1150–1156.

Bardin, M.Y., 2007. Anticyclonic quasi-stationary circulation and its influence on anomalies and extrema of air temperature in western regions of Russia. Meteorol. Hydrol. 2, 5–18.

Barriopedro, D., García-Herrera, R., Lupo, A.R., Hernández, E., 2006. A climatology of Northern Hemisphere blocking. J. Clim. 19, 1042–1063.

Charney, J.G., De Vore, J.G., 1979. Multiple flow equilibria in the atmosphere and blocking. J. Atmos. Sci. 36, 1205–1216.

Dufresne, J.L., Foujols, M.-A., Denvil, S., Caubel, A., Marti, O., Aumont, O., Balkanski, Y., Bekki, S., Bellenger, H., Benshila, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., de Noblet, N., Duvel, J.-P., Ethé, C., Fairhead, L., Fichefet, T., Flavoni, S., Friedlingstein, P., Grandpeix, J.-Y., Guez, L., Guilyardi, E., Hauglustaine, D., Hourdin, F., Idelkadi, A., Ghattas, A., Joussaume, S., Kageyama, M., Krinner, G., Labetoulle, S., Lahellec, A., Lefebvre, M.-P., Lefevre, F., Levy, C., Li, Z.X., Lloyd, J., Lott, F., Madec, G., Mancip, M., Marchand, M., Masson, S., Meurdesoif, Y., Mignot, J., Musat, I., Parouty, S., Polcher, J., Rio, C., Schulz, M., Swingedouw, D., Szopa, S., Talandier, C., Terray, P., Viovy, N., Vuichard, N., 2013. Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Clim. Dyn. 40 (9-10), 2123–2165.

Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), 2012. IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change, Cambridge.

Kistler, R., Collins, W., Saha, S., White, G., Woollen, J., Kalnay, E., Chelliah, M., Ebisuzaki, W., Kanamitsu, M., Kousky, V., van den Dool, H., Jenne, R., Fiorino, M., 2001. The NCEP-

NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bull. Am. Meteorol. Soc. 82 (2), 247–267.

Kreienkamp, F., Spekat, A., Enke, W., 2010. Stationarity of atmospheric waves and blocking over Europe — based on a reanalysis dataset and two climate scenarios. Theor. Appl. Climatol. 102, 205–212.

Lejenas, H., Okland, H., 1983. Characteristics of Northern Hemisphere blocking as determined from a long time series of observational data. Tellus 35A, 350–362.

Lupo, A.R., Oglesby, R.J., Mokhov, I.I., 1997. Climatological features of blocking anticyclones: a study of Northern Hemisphere CCM1 model blocking events in present-day and double CO2 concentration atmospheres. Clim. Dyn. 13, 181–195.

Lupo, A.R., Mokhov, I.I., Akperov, M.G., Chernokulsky, A.V., Athar, H., 2012. A dynamic analysis of the role of the planetary- and synoptic-scale in the summer of 2010 blocking episodes over the European part of Russia. Adv. Meteorol. 2012, 11.

Masato, G., Hoskins, B.J., Woollings, T., 2013. Winter and summer Northern Hemisphere blocking in CMIP5 models. J. Clim. 26 (18), 7044–7059.

Mokhov, I.I., 2006. Action as an integral characteristic of climatic structures: estimates for atmospheric blockings. Dokl. Earth Sci. 409A (6), 925–928.

Mokhov, I.I., 2011. Specific features of the 2010 summer heat formation in the European territory of Russia in the context of general climate changes and climate anomalies. Izv. Atmos. Oceanic Phys. 47 (6), 653–660.

Mokhov, I.I., Petukhov, V.K., 1997. Blockings and tendencies of their change. Dokl. Earth Sci. 357A (8), 1485–1488.

Mokhov, I.I., Akperov, M.G., Prokofyeva, M.A., Timazhev, A.V., Lupo, A.R., Le Treut, H., 2013. Blockings in the Northern Hemisphere and Euro-Atlantic region: estimates of changes from reanalysis data and model simulations. Dokl. Earth Sci. 449 (2), 430–433.

Moss, R.H., et al., 2010. The next generation of scenarios for climate change research and assessment. Nature 463 (7282), 747–756.

Obukhov, A.M., Kurgansky, M.V., Tatarskaya, M.S., 1984. Dynamic conditions of occurrence of drought and other large-scale weather anomalies. Meteorol. Hydrol. 10, 5–13.

Rex, D.F., 1950. Blocking action in the middle troposphere and its effect on regional climate. The climatology of blocking action. Tellus 2, 275–301.

Semenov, V.A., Mokhov, I.I., Latif, H., 2012. Influence of the ocean surface temperature and sea ice concentration on regional climate changes in Eurasia in recent decades. Izv. Atmos. Oceanic Phys. 48 (4), 355–372.

Sillmann, J., Croci-Maspoli, M., Kallache, M., Katz, R.W., 2011. Extreme cold weather temperatures in Europe under the influence of North Atlantic atmospheric blocking. J. Clim. 24 (22), 5899–5913.

Wiedenmann, J.M., Lupo, A.R., Mokhov, I.I., Tikhonova, E.A., 2002. The climatology of blocking anticyclones for the Northern and Southern Hemispheres: block intensity as a diagnostic. J. Clim. 15 (23), 3459–3473.