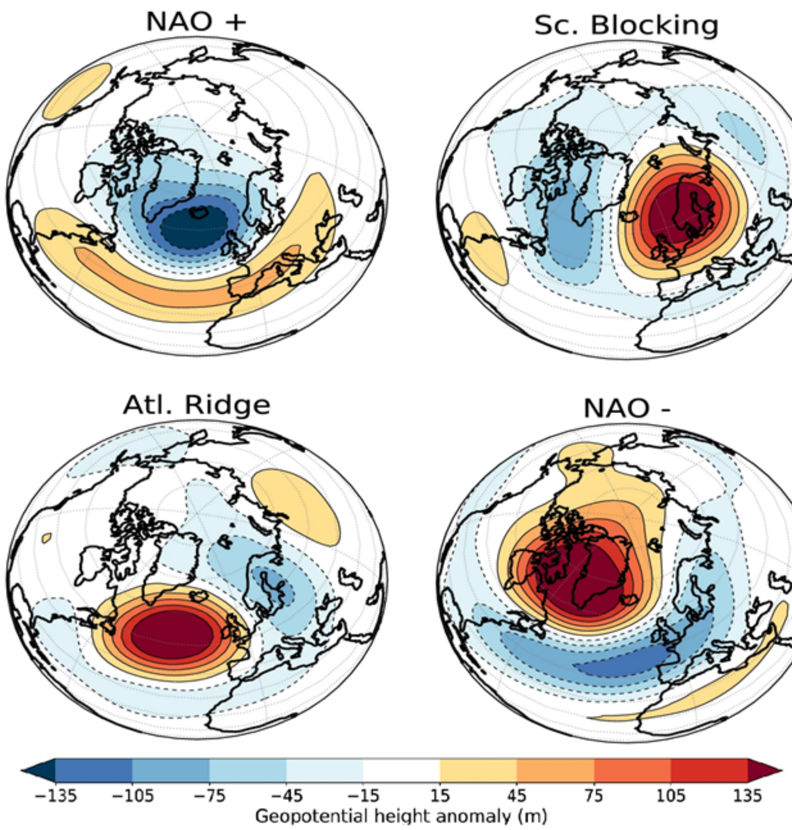
Atmospheric circulation regimes in Euro-Atlantics by CMIP6 models' and reanalysis data



An example of EAT weather regimes by Fabiano, 2020

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- Weather regimes (WR) approach is a common way to describe large-scale low-frequency atmospheric dynamics by dividing a large set of ever changing atmospheric fields into a limited number of stable and recurring patterns called weather regimes.
- WR are mostly used for studying atmospheric dynamics in Northern Hemisphere, particularly Euro-Atlantic and North Pacific sectors
- There are different approaches to define weather regimes. Usually, WRs are defined through cluster analysis of daily sea level pressure or geopotential height fields (at the 500 hPa level). «K-means» is the most common cluster analysis method used for defining WRs.
- Weather Regimes approach can be used to check climate models ability to reproduce large-scale atmospheric dynamics and for assessing its future long-term changes.
- In our study, we use CMIP6 climate models (including INM-CM5-0) to check how classical Weather Regimes in Euro-Atlantics are reproduced in the historical experiments by these models.

Reanalysis used in the study – ERA5

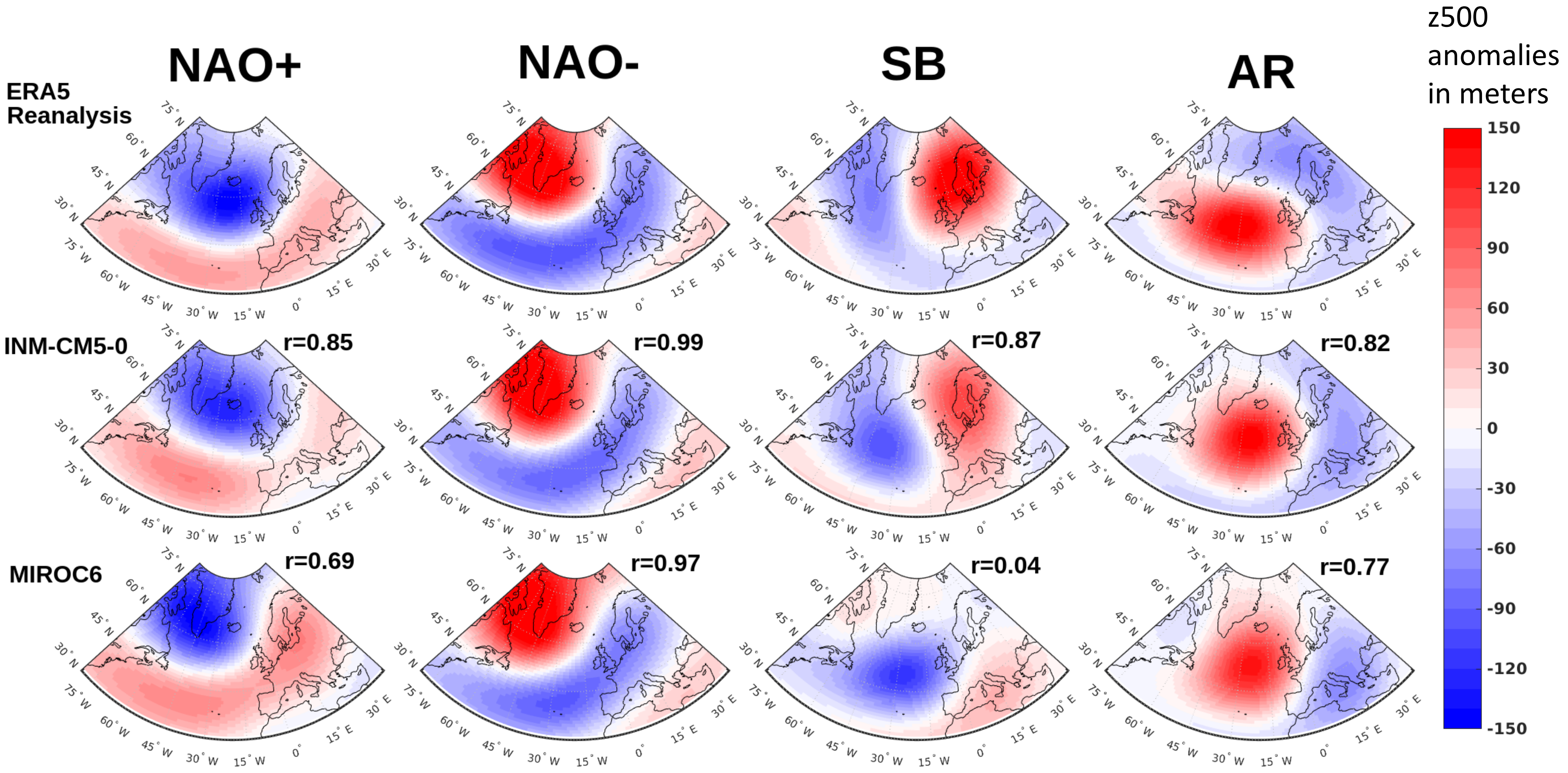
List of models used in the study (historical experiments r1i1p1f1 members)

- 1) INM-CM5-0 (Russia)
- 2) CESM2 (USA)
- 3) GFDL-CM4 (USA)
- 4) EC-Earth3 (Europe)
- 5) MIROC6 (Japan)
- 6) NorESM2-LM (Norway)
- 7) CanESM5 (Canada)
- 8) ACCESS-CM2 (Australia)

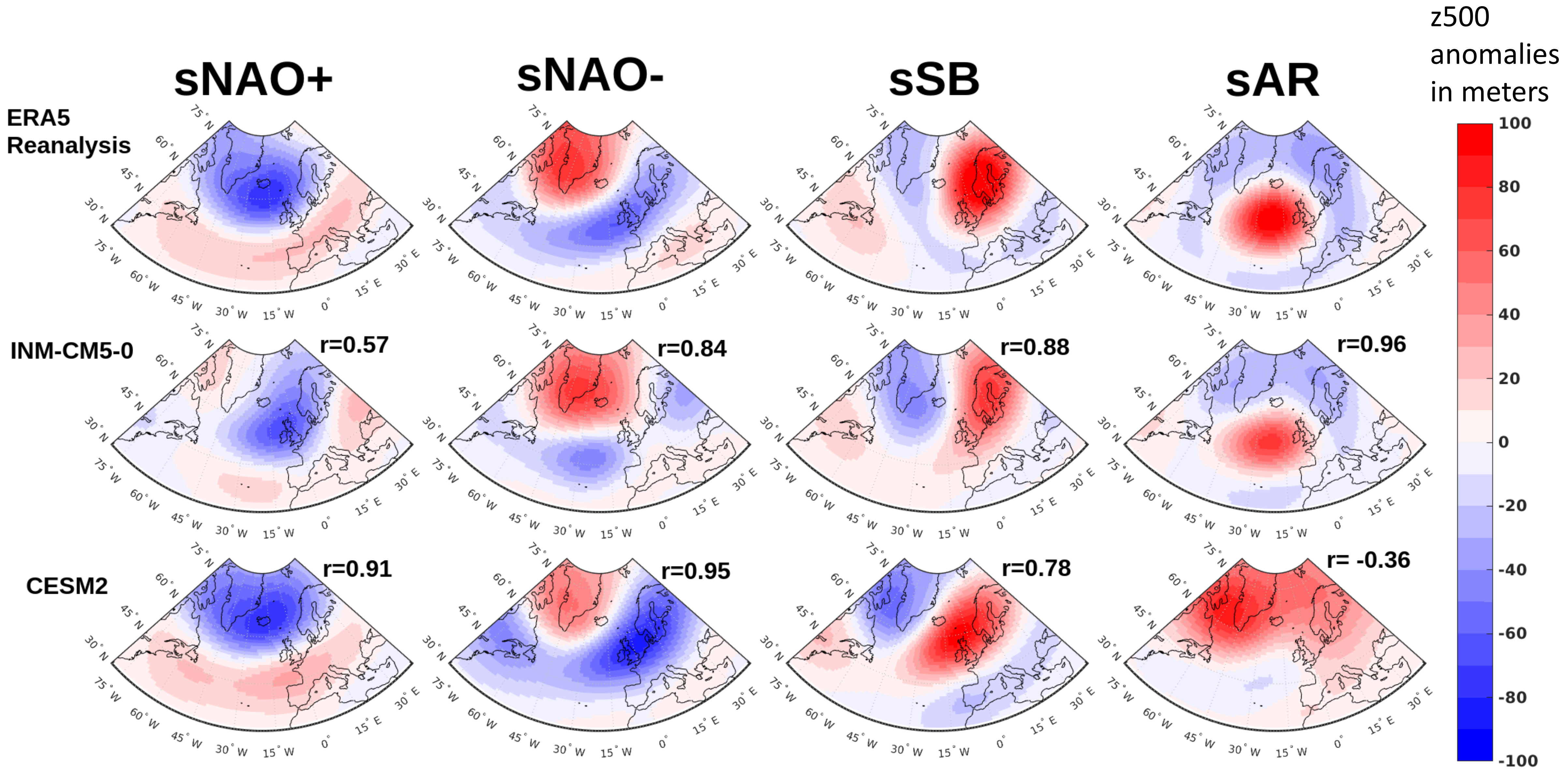
Data and preprocessing:

- Variable – daily geopotential heights at the 500 hPa level (z500);
- Area – Euro-Atlantics, 80W-40E; 30N-80N (the most common for this sector);
- Time period – 1950 to 2014;
- Seasons – winter (DJF, without February 29th) and summer (JJA);
- Preprocessing:
  - 1) z500 model and reanalysis fields are interpolated to 1x1 degree field.
  - 2) Getting anomalous fields by removing seasonal cycle by subtracting mean fields of each calendar day smoothed by 5-day running mean from each daily field
  - 3) Removing synoptic-scale variability by applying 10-day low-pass filtering using Butterworth filter
  - 4) EOF-decomposition of area-weighted filtered anomalous fields using 10 first EOFs explaining ~90% of winter and ~80% of summer z500 variability
- Cluster analysis is applied to time series of Principal Components (PC) of first 10 EOF of filtered daily anomalous z500 fields. For the reanalysis and each climate model «k-means» with implemented simulated annealing modification is run 1000 times, the best solution is kept.

Mean z500 fields of winter EAT regimes



Mean z500 fields of summer EAT regimes



Comparison of model regimes' **mean fields** against reanalysis regimes' mean fields (worst values for each regime highlighted with bold font in tables)

WINTER REGIMES

Weighted field correlations	NAO+	NAO-	SB	AR	Score (mean r)
INM-CM5-0	0.85	0.99	0.87	0.82	0.88 (#5 of 8)
CESM2	0.97	0.96	0.91	0.95	0.95
GFDL-CM4	0.93	0.98	0.86	0.95	0.93
EC-Earth3	0.94	0.97	0.95	0.96	0.95
MIROC6	0.69	0.97	**0.04**	0.77	**0.62**
NorESM2-LM	0.87	0.98	0.90	0.90	0.91
CanESM5	0.69	**0.80**	0.81	0.92	0.80
ACCESS-CM2	**0.68**	0.91	0.87	**0.68**	0.78
Model Mean	0.83	0.95	0.78	0.87	0.85

Weighted field sum of differences, m^2	NAO+	NAO-	SB	AR	Score (mean sqrsum)
INM-CM5-0	762	148	831	926	667 (#5 of 8)
CESM2	240	445	650	283	404
GFDL-CM4	358	208	843	352	440
EC-Earth3	438	444	343	247	368
MIROC6	**2010**	386	**4800**	1160	**2090**
NorESM2-LM	646	351	650	642	572
CanESM5	1530	**2400**	1160	443	1380
ACCESS-CM2	1910	1030	889	**2480**	1580
Model Mean	987	677	1270	817	938

SUMMER REGIMES

Weighted field correlations	sNAO+	sNAO-	sSB	sAR	Score (mean r)
INM-CM5-0	**0.57**	**0.84**	0.88	0.96	0.81 (#5 of 8)
CESM2	0.91	0.95	0.78	**-0.36**	**0.57**
GFDL-CM4	0.85	0.93	0.88	0.81	0.87
EC-Earth3	0.94	0.96	0.96	0.67	0.88
MIROC6	0.84	0.88	**0.53**	0.65	0.73
NorESM2-LM	0.83	0.96	0.82	0.57	0.80
CanESM5	0.90	0.92	0.79	0.69	0.82
ACCESS-CM2	0.95	0.91	0.93	0.78	0.90
Model Mean	0.85	0.92	0.82	0.60	0.80

Weighted field sum of differences, m^2	sNAO+	sNAO-	sSB	sAR	Score (mean sqrsum)
INM-CM5-0	**432**	**295**	232	90	262 (#4 of 8)
CESM2	125	291	423	**2420**	**815**
GFDL-CM4	169	136	211	318	208
EC-Earth3	147	114	86	513	215
MIROC6	187	220	**675**	542	406
NorESM2-LM	225	134	321	982	416
CanESM5	134	156	371	539	300
ACCESS-CM2	56	206	135	337	183
Model Mean	184	194	307	718	351

Conclusions: 1) most climate models reproduce mean z500 fields of WRs well except for winter SB regime in MIROC6 and summer sAR regime in CESM2.
2) winter regimes are generally better reproduced then summer regimes. Summer regimes are less pronounced in terms of z500 anomalies.
3) INM-CM5-0 model performance in reproducing reanalysis weather regimes is average compared to other studied climate models.

Relative occurrence of models' WRs against reanalysis WRs

Values in tables are absolute differences between model occurrence and reanalysis occurrence in % points;
Values in (…) brackets are relative regime occurrences in % points.

$$\frac{|Occurence(WR_{ERA5}) - Occurence(WR_{model})|}{Occurence(WR_{ERA5})}$$

Relative occurrence - fraction of daily fields assigned to each regime

WINTER REGIMES

	NAO+	NAO-	SB	AR	Mean
ERA5 Reanalysis	(29.6)	(22.2)	(23.7)	(24.5)	
INM-CM5-0	2.9 (30.5)	5.7 (20.9)	11.1 (26.3)	9.0 (22.3)	7.2 (#3 of 8)
CESM2	8.1 (32.1)	18.4 (18.1)	6.0 (25.1)	1.0 (24.8)	8.4
GFDL-CM4	9.4 (32.4)	0.2 (22.1)	1.8 (23.2)	9.5 (22.2)	5.2
EC-Earth3	1.7 (29.1)	6.9 (20.6)	7.5 (25.4)	1.1 (24.8)	4.3
MIROC6	4.8 (28.2)	12.7 (19.4)	-	8.6 (26.7)	8.7
NorESM2-LM	**10.0** (32.6)	9.9 (20.0)	8.5 (21.6)	5.0 (25.8)	8.4
CanESM5	4.3 (28.4)	15.0 (18.8)	2.2 (24.2)	16.6 (28.6)	9.6
ACCESS-CM2	4.8 (28.2)	**18.1** (26.2)	**15.5** (27.3)	**25.5** (18.3)	**16.0**
Model Mean	5.8 (30.2)	10.9 (20.8)	7.5 (24.7)	9.5 (24.2)	8.4

SUMMER REGIMES

	sNAO+	sNAO-	sSB	sAR	Mean
ERA5 Reanalysis	(24.5)	(28.8)	(23.3)	(23.3)	
INM-CM5-0	10.5 (27.1)	19.7 (23.1)	1.8 (23.7)	11.5 (26.0)	10.9 (#4 of 8)
CESM2	19.6 (29.4)	14.2 (24.7)	7.7 (25.1)	-	13.8
GFDL-CM4	27.1 (31.2)	16.8 (24.0)	4.3 (22.3)	3.4 (22.5)	12.9
EC-Earth3	1.8 (25.0)	13.8 (24.8)	2.6 (23.9)	12.6 (26.2)	7.7
MIROC6	2.7 (25.2)	12.0 (25.4)	**14.2** (26.6)	2.2 (22.8)	7.8
NorESM2-LM	**42.2** (34.9)	**27.1** (21.0)	4.4 (24.3)	**15.3** (19.7)	**22.2**
CanESM5	0.8 (24.7)	12.7 (25.2)	11.5 (26.0)	3.3 (24.1)	7.1
ACCESS-CM2	22.6 (30.1)	19.1 (23.3)	3.4 (24.1)	3.6 (22.5)	12.2
Model Mean	15.9 (28.5)	16.9 (23.9)	6.2 (24.5)	7.4 (23.4)	11.6

Conclusions:
1) All models reproduce the fact that NAO+ is the most frequent winter regime and NAO- is the least frequent.
2) As it is for mean fields, summer regimes' occurrences are reproduced worse than the winter ones.
All models overestimate summer sNAO+ occurrence and underestimate sNAO- occurrence.
3) INM-CM5-0 performance is average (#3 and #4 place among the 8 models).

Time series of seasonal occurrences of WRs (days of a given regime per season)

Time series correlations and trends of model's regimes seasonal occurrences against reanalysis regimes seasonal occurrences

WINTER REGIMES

	NAO+	NAO-	SB	AR
INM-CM5-0	0.16	0.15	0	-0.19
CESM2	-0.01	0.13	-0.01	-0.09
GFDL-CM4	-0.03	-0.30	0.05	-0.21
EC-Earth3	-0.06	-0.05	-0.06	0.01
MIROC6	-0.01	-0.15	-0.04	-0.14
NorESM2-LM	-0.01	-0.19	0.28	0.14
CanESM5	0.09	0.18	0.20	0.10
ACCESS-CM2	0.08	0.01	-0.06	0.01

SUMMER REGIMES

	sNAO+	sNAO-	sSB	sAR
INM-CM5-0	0.09	0.11	-0.07	0.10
CESM2	0.08	-0.09	-0.08	-0.13
GFDL-CM4	-0.03	0.06	0.05	0.25
EC-Earth3	0.12	-0.10	0	-0.21
MIROC6	-0.05	0.04	0.27	-0.20
NorESM2-LM	0.25	0.14	0.10	0
CanESM5	0.05	-0.10	013	-0.22
ACCESS-CM2	0	-0.03	0.28	0.21

Trends without 95% significance market with «-»

	NAO+	NAO-	SB	AR
ERA5 Reanalysis	positive	-	-	-
INM-CM5-0	-	-	-	-
CESM2	-	-	positive	-
GFDL-CM4	negative	-	-	-
EC-Earth3	negative	-	positive	-
MIROC6	negative	-	-	-
NorESM2-LM	-	-	-	-
CanESM5	negative	-	-	-
ACCESS-CM2	-	-	-	-

	sNAO+	sNAO-	sSB	sAR
ERA5 Reanalysis	- (negative, but not significant)	-	positive	-
INM-CM5-0	negative	-	positive	-
CESM2	-	negative	-	positive
GFDL-CM4	negative	-	-	-
EC-Earth3	negative	-	positive	positive
MIROC6	negative	-	positive	-
NorESM2-LM	negative	-	positive	-
CanESM5	negative	negative	positive	-
ACCESS-CM2	negative	positive	positive	negative

Conclusions:

1) Climate models WRs do not reproduce reanalysis WRs' seasonal occurrences, their time series do not correlate (as expected).

2) Winter NAO+ positive trend isn't reproduced in any model, while summer positive sSB trend is present in 6 out of 8 models.

Mean persistence of models' WRs against reanalysis' WRs

Persistence – average number of days a given regime lasts before transitioning to another regime
Values in tables are absolute differences between models regimes mean persistence and reanalysis regimes persistence, values are in % points.
Values in (…) brackets are mean regime persistence in number of days

$$\frac{|Persistence(WR_{ERA5}) - Persistence(WR_{model})|}{Persistence(WR_{ERA5})}$$

WINTER REGIMES

	NAO+	NAO-	SB	AR	Mean
ERA5 Reanalysis	(8.6)	(9.5)	(7.4)	(7.8)	
INM-CM5-0	2.9 (8.9)	4.2 (9.9)	**8.7** (8.0)	5.4 (7.3)	5.3 (#3 of 8)
CESM2	7.1 (9.2)	3.6 (9.1)	3.8 (7.7)	6.1 (7.3)	5.1
GFDL-CM4	8.9 (9.4)	7.6 (8.7)	5.8 (7.0)	5.9 (7.3)	7.0
EC-Earth3	6.8 (8.0)	16.1 (7.9)	1.9 (7.3)	**13.0** (6.8)	9.5
MIROC6	**13.8** (9.8)	12.0 (8.3)	-	3.1 (8.0)	9.6
NorESM2-LM	10.6 (9.5)	9.3 (10.3)	5.5 (7.0)	5.6 (8.2)	7.7
CanESM5	2.4 (8.4)	3.9 (9.8)	3.9 (7.7)	0.4 (7.8)	2.6
ACCESS-CM2	9.9 (9.5)	**18.1** (11.2)	8.6 (8.0)	9.9 (7.0)	**11.6**
Model Mean	7.8 (9.1)	9.3 (9.4)	5.5 (7.5)	6.2 (7.5)	7.3

SUMMER REGIMES

	sNAO+	sNAO-	sSB	sAR	Mean
ERA5 Reanalysis	(6.9)	(9.5)	(7.1)	(6.8)	
INM-CM5-0	17.1 (8.1)	6.4 (8.9)	12.7 (8.0)	5.9 (7.2)	10.5 (#3 of 8)
CESM2	28.0 (8.8)	8.2 (8.7)	17.8 (8.3)	-	18.0
GFDL-CM4	12.3 (7.7)	9.4 (8.6)	3.6 (7.3)	12.5 (7.6)	9.4
EC-Earth3	15.3 (7.9)	11.8 (8.3)	9.8 (7.8)	13.1 (7.7)	12.5
MIROC6	18.2 (8.1)	7.9 (8.7)	8.7 (7.7)	9.5 (7.4)	11.1
NorESM2-LM	**51.4** (10.4)	6.6 (8.8)	10.0 (7.8)	**15.0** (7.8)	**20.7**
CanESM5	14.2 (7.9)	3.1 (9.2)	**19.4** (8.5)	12.0 (7.6)	12.2
ACCESS-CM2	6.6 (7.3)	**14.4** (8.1)	3.9 (7.4)	3.1 (6.6)	7.0
Model Mean	(8.3)	(8.7)	(7.8)	(7.4)	12.7

Conclusions:

1) As it is for mean fields and relative occurrences, persistence of summer regimes is reproduced by the models worse than for winter regimes;

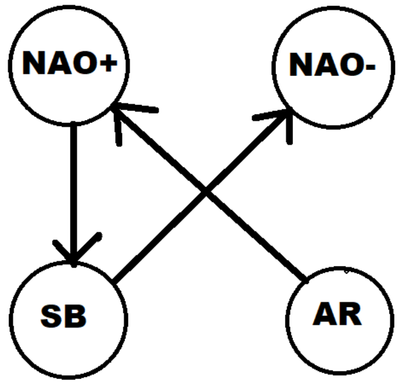
2) INM-CM5-0 performance in reproducing regimes persistence is a bit better than average (#3 place among the 8 models both for winter and summer regimes).

Transition matrixes (TM)

Statistically significant likely transitions are marked with bold font, unlikely transitions are marked with italics

Reanalysis TM in numbers	to NAO+	to NAO-	to SB	to AR
from NAO+	-	*23*	**72**	69
from NAO-	40	-	35	35
from SB	*48*	**57**	-	56
from AR	**76**	33	54	-

Reanalysis TM in probability	to NAO+	to NAO-	to SB	to AR
from NAO+	-	*0.14*	**0.44**	0.42
from NAO-	0.36	-	0.32	0.32
from SB	*0.30*	**0.35**	-	0.35
from AR	**0.47**	0.20	0.33	-



Model WRs transition matrixes are compared against the reanalysis WRs transition matrix by summation of absolute differences of each transition from every regime. So, below are sums of absolute differences of transition probabilities

Sum of absolute differences of transition probabilities	from NAO+	from NAO-	from SB	from AR	Mean
INM-CM5-0	0.06	0.47	0.35	0.17	0.26 (#6 of 8)
CESM2	0.24	0.34	0.09	0.09	0.19
GFDL-CM4	0.03	0.21	0.08	0.12	0.11
EC-Earth3	0.08	0.11	0.16	0.17	0.13
MIROC6	**0.34**	**0.80**	0.28	**0.40**	**0.46**
NorESM2-LM	0.13	0.21	0.17	0.22	0.18
CanESM5	0.16	0.22	**0.47**	0.05	0.22
ACCESS-CM2	0.27	0.56	0.31	0.38	0.38
Model Mean	0.16	0.37	0.24	0.20	0.24

Sum of absolute differences of transition probabilities	from NAO+	from NAO-	from SB	from AR	Mean
INM-CM5-0	0.37	0.10	0.14	0.23	0.21 (#4 of 8)
CESM2	***0.41***	*0.05*	*0.51*	***0.45***	**0.35**
GFDL-CM4	0.14	0.37	0.29	0.10	0.22
EC-Earth3	0.17	0.12	0.10	0.20	0.15
MIROC6	0.37	**0.45**	0.15	0.35	0.33
NorESM2-LM	0.28	0.18	**0.46**	0.36	0.32
CanESM5	0.12	0.14	0.30	0.18	0.18
ACCESS-CM2	0.15	0.14	0.39	0.15	0.21
Model Mean	0.25	0.19	0.29	0.25	0.25

Conclusions:

1) **Winter transition matrixes are better reproduced for the summer regimes than for the winter regimes**
2) **No model fully reproduced statistically significant likely/unlikely transitions as they are in reanalysis TM**

Main conclusions

- Most of studied CMIP6 models generally well reproduce reanalysis winter and summer EAT weather regimes with exceptions of MIROC6 in winter and CESM2 in summer.
- Mean fields, relative occurrences, persistence and transition matrixes are reproduced better for classical winter EAT regimes than for their summer analogues.
- INM-CM5-0 performance in reproducing reanalysis WRs is average compared to other studied model. It didn’t rank first nor last among other climate models in comparison of mean fields, relative occurrence, persistence or TMs of WRs against reanalysis data.