The ability of climate models to reproduce the weakening of the annual air temperature cycle over the central part of the Russian Plain

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Abstract. Natural variability plays a large role in local climate that makes it difficult to specify the causes of the weakening of the annual cycle of surface air temperature in the central part of the Russian Plain. This study is to check whether this could be caused by the global warming by using the outputs of climate models. For this purpose, the changes in monthly surface air temperature simulated for the period from 1950 to 2010 were used to calculate the coefficients of correlation between the annual mean of the air temperature and the amplitude of its annual cycle. The negative correlation demonstrated by some models allows us to attribute, at least with a low confidence, the weakening of the annual temperature cycle in the central part of the Russian Plain to the global warming. The model disagreement on the sign of the correlation calls for the study of model ability to reproduce the changes in zonal and meridional atmospheric circulation over the eastern part of the European continent.

1. Background
The global warming manifests itself not only in the growth of annual means of the surface air temperature (MAT) but also in changes of its annual cycle. Therefore, considering the amplitude-phase characteristics of the surface temperature annual cycle [1] is essential for climate change detection and verification of climate models. The amplitude of annual temperature cycle (AAT) is one of these characteristics.

The tendency to AAT decrease is observed in the Northern Hemisphere since 1950 [2]. It reflects the seasonal asymmetry of global warming: winter-time air temperature grows faster than summer-time air temperature. The negative correlation of the AAT and MAT changes is widespread in the Northern Hemisphere and has a theoretical explanation [3].

However, extrapolation of this tendency to the future is valid only under the assumption that the conditions governing the negative sign of the correlation of AAT and MAT changes [3] will be maintained. Since there is no solid theoretical ground for such assumption, one cannot exclude that the sign of the correlation may change to positive under some climate change scenarios.

Moreover, it is not completely clear so far whether the current combination of the conditions causing AAT decrease can be considered as typical. Thus, for example, the large part of the AAT downward
tendency could be explained by the natural variability of the atmospheric circulation over the North Atlantic and Europe [4]. Due to this reason, the ability of climate models to reproduce the regional AAT trends is essential for predicting the global warming impact on the annual cycle of the surface air temperature.

This study is to evaluate the ability of the modern climate models [5] listed in Table 1 to reproduce the negative correlation of the AAT and MAT changes in the central part of the Russian Plain.

2. Methods
The outputs of climate models listed in the Table 1 were processed as follows. The monthly air temperature simulated by a model for the period 1950-2010 over the nodes of the model grid were used to calculate the MAT and AAT values. These values were used to calculate the times series of MAT and AAT 30-year moving averages (MAT$_{30}$ and AAT$_{30}$) and the coefficient of correlation between them (CMA) at each node of the model grid.

Table 1. The list of climate models, the outputs of which were processed to evaluate the ability of climate models to reproduce the weakening of the annual cycle of surface air temperature over the central part of the Russian Plain.

| Model name          | Institute                                         | Reference |
|---------------------|---------------------------------------------------|-----------|
| BCC-ESM1            | Beijing Climate Center                            | [6]       |
| CanESM5             | Canadian Centre for Climate Modelling and Analysis| [7]       |
| CESM2               | National Center for Atmospheric Research (USA)    | [8]       |
| GFDL-ESM4           | Geophysical Fluid Dynamics Laboratory (USA)       | [9]       |
| HadGEM3-GC31-LL     | Hadley Centre for Climate Prediction and Research (UK)| [10] |
| INM-CM5-0           | Institute of Numerical Mathematics (Russia)       | [11]      |
| IPSL-CM6A-LR        | Institut Pierre-Simon Laplace (France)            | [12]      |
| MIROC6              | Japanese climate modeling community               | [13]      |
| MPI-ESM1-2-LR      | Max Planck Institute for Meteorology (Germany)    | [14]      |
| MRI-ESM2-0          | Meteorological Research Institute (Japan)         | [15]      |

The data of GSWP3 re-analysis [16-17] on the monthly air temperature were processed in the same way to obtain the observation-based estimates of CMA.

3. Results
The values of CMA calculated from the data of GSWP3 re-analysis [16-17] show the negative correlation between MAT$_{30}$ and AAT$_{30}$ over the whole territory of the Russian Plain (Figure 1). The boundary between the regions of positive and negative correlation passes through the western parts of Ukraine and Poland, that is, quite far from the central part of the Russian Plain, represented by the rectangular surrounding Moscow and delineated from the east and west by 31st and 42nd meridians and from the south and north by 51st and 59th parallels.
Nevertheless, not all the climate models listed in Table 1 reproduce the negative correlation between MAT$_{30}$ and AAT$_{30}$ in the nodes of the rectangular (Figure 1) representing the central part of the Russian Plain. CESM2 and INM-CM5-0 do not reproduce it at any of such nodes: the minimal values of CMA are positive (Figure 2). CanESM2 and MIROC6 reproduce it at some nodes; GFDL-ESM4, BCC-ESM1, MPI-ESM1-2_LR and HadGEM3-GC31-LL reproduce it partly; and only MRI-ESM2-0 and IPSL-CM6A-LR reproduce it at each node: the maximal values of CMA are negative.

In summary, the weakening of annual temperature cycle over the central part of the Russian Plain is adequately reproduced by 20% the models, 60% of models reproduce it to some degree, and 20% of models do not reproduce it.

4. Discussion and conclusions
These findings raise a question about the drivers of the negative correlation between MAT$_{30}$ and AAT$_{30}$ over the Russian Plain: are they adequately represented in climate models?

Just like the diurnal asymmetry [18-19], the seasonal asymmetry of global warming can be explained by CO$_2$ radiative forcing: the higher is the surface temperature the weaker its response to radiative forcing [20]. However, CO$_2$ radiative forcing is not the only driver of the changes in the annual temperature cycle. AAT depends also on the strength of atmospheric circulation. Since AAT over the

Figure 1. The regions of positive and negative correlation between the time series of 30-year moving averages of mean annual temperature and the amplitude of annual temperature cycle (MAT$_{30}$ and AAT$_{30}$) derived from the data of GSWP3 re-analysis [16-17].
oceans is smaller than over the land, the decrease in AAT over the land could be considered as a sign of stronger ocean-to-land heat transfer [21-22].

![Figure 2](image_url)

**Figure 2.** The minimum, maximum, and mean values of the coefficients of correlation between the time series of 30-year moving averages of mean annual temperature and the amplitude of annual temperature cycle ($\text{MAT}_{30}$ and $\text{AAT}_{30}$) over the nodes of the geographic grid that falls within the rectangle delineated from the east and west by 31st and 42nd meridians and from the south and north by 51st and 59th parallels.

The strengthening of ocean-to-land heat transfer is seemingly supported by the data on North Atlantic Oscillation index (NAO), that characterizes the variability of the large-scale atmospheric circulation over the North Atlantic and Europe. The annual values of NAO show a tendency to increase during the period from 1950-2010, and therefore one may suggest that a part of AAT decrease could be attributed to the strengthening of zonal atmospheric circulation.

In contrast to CO$_2$ radiative forcing and NAO, the Arctic warming seemingly increases AAT. Suggesting that Arctic temperature anomalies may reflect a strength of meridional flow, one may suggest that the ability of a climate model to reproduce the negative correlation between $\text{MAT}_{30}$ and $\text{AAT}_{30}$ over the Russian Plain is determined by the model ability to reproduce the variations in the strength of zonal and meridional circulation [23-24].

The negative correlation between $\text{MAT}_{30}$ and $\text{AAT}_{30}$ demonstrated by some models allows us to attribute (at least with a low confidence) the weakening of the annual temperature cycle in the central part of the Russian Plain to global warming.

**References**

[1] Mokhov I I 1985 *Soviet Meteorol. Hydrol.* 5 14
[2] Stine A R, Huybers P, Fung I Y 2009 *Nature* 457 (228) 435
[3] Eliseev A V and Mokhov I I 2003 *Adv. Atmos. Sci.* 10 1
[4] Alexandrov G A, Ginzburg A S, Golitsyn G S 2019 *Izvestiya - Atmospheric and Ocean Physics* 55 (5) 407
[5] Eyring V *et al.* 2016 *Geoscientific Model Development* 9(5) 1937
[6] Wu T, Zhang F, Zhang J, Jie W, Zhang Y, Wu F, Li L, Yan J, Liu X, Lu X, and others 2020 Geoscientific Model Development 13 977
[7] Swart N C, Cole J N, Kharin V V, Lazare M, Scinocca J F, Gillett N P, Anstey J, Arora V, Christian J R, Hanna S, and others 2019 Geoscientific Model Development 12 4823
[8] Danabasoglu G, Lamarque J-F, Bacmeister J, Bailey D, DuVivier A, Edwards J, Emmons L, Fasullo J, Garcia R, Gettelman A, and others 2020 Journal of Advances in Modeling Earth Systems 12 e2019MS001916
[9] Dunne J, Horowitz L, Held I, Krasting J, John J, Malyshev S, Shevliakov E, Acroft A, Dupuis C, Ginoux P, and others 2019 Journal of Advances in Modeling Earth Systems 11 3167–211
[10] Andrews M B, Ridley J K, Wood R A, Andrews T, Blockley E W, Booth B, Burke E, Dittus A J, Florek P, Gray L J, and others 2020 Journal of Advances in Modeling Earth Systems 12 e2019MS001995
[11] Volodin E and Gritsun A 2018 Earth System Dynamics 9 1235
[12] Boucher O, Servonnat J, Albright A L, Aumont O, Balkanski Y, Bastrikov V, Bekki S, Bonnet R, Bony S, Bopp L, and others 2020 Journal of Advances in Modeling Earth Systems 12 e2019MS002010
[13] Tatebe H, Ogura T, Nitta T, Komuro Y, Ogochi K, Takemura T, Sudo K, Sekiguchi M, Abe M, Saito F, and others 2019 Geoscientific Model Development 12 2727
[14] Mauritsen T, Bader J, Becker T, Behrens J, Bittner M, Brokopf R, Brovkin V, Claussen M, Crueger T, Esch M, and others 2019 Journal of Advances in Modeling Earth Systems 11 998
[15] Yukimoto S, Kawai H, Koshiro T, Oshima N, Yoshida K, Urakawa S, Tsujino H, Deushi M, Tanaka T, Hosaka M, Yabu S, Yoshimura H, Shindo E, Mizuta R, Obata A, Adachi Y and Ishii M 2019 Journal of the Meteorological Society of Japan Ser. II 97 931
[16] Dirmeyer P A 2011 Journal of Hydrometeorology 12 729
[17] Hurk B van den, Kim H, Krinner G, Seneviratne S I, Derksen C, Oki T, Douville H, Colin J, Ducharne A and Cheruy F 2016 Geoscientific Model Development 9 2809
[18] Demchenko P F, Golitsyn G S, Ginzburg A S and Vel’tishchev N N 1994 Izvestiya, Atmospheric and Oceanic Physics 30 (5) 595
[19] Davy R, Esau I, Chernokulsky A, Outten S and Zilitinkevich S 2017 Int. J. Climatol. 37 (1) 79
[20] Alexandrov G A, Ginzburg A S and Golitsyn G S 2019 Izvestiya, Atmospheric and Oceanic Physics 55(5) 407
[21] Stine A R and Huybers P 2012 J. Clim. 25 7362
[22] McKinnon K A, Stine A R and Huybers P 2013 Journal of Climate 26 7852
[23] Shepherd T 2014 Nature Geosci 7 703
[24] Kononova N K and Lupo A R 2020 Atmosphere 11 (3) 255