The effect of Arctic warming on Moscow climate continentality

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Abstract. The annual cycle of incoming solar radiation is the major factor that determines the amplitude of the annual cycle of the surface air temperature over the continents in the Northern Hemisphere. There are, however, other important factors that contribute to the seasonal temperature difference. The combined effect of these factors is characterized by the Gorczinski’s continentality index (GCI). The gradual decrease of Moscow GCI during the second half of the 20th century could be attributed to the combined effect of the warming due to increasing atmospheric concentration of carbon dioxide and intensification of the zonal atmospheric circulation. However, these factors cannot explain the increase of Moscow GCI during the 1920-1950 period. Taking into account the Arctic temperature variations with pronounced multi-decadal variability helped us to fill this gap in the explanation of the historical changes in Moscow climate continentality.

1. Background
Over the last 50 years, the amplitude of the annual cycle of the surface air temperature (ASAT) had a tendency to decrease across most mid- to high-latitude land areas in the Northern Hemisphere [1-3]. However, the factors responsible for this trend remain uncertain, particularly at a regional scale [4].

In general, the annual cycle of the surface air temperature (SAT) over the Northern Eurasia is at large extent a result of the annual cycle of incoming solar radiation. The other factors, such as westerly circulation strength that is linked to heat advection from the North Atlantic, also play an important role in shaping SAT seasonal cycle. The combined effect of these factors could be characterized by the Gorczinski’s continentality index (GCI) that was originally proposed to quantify the spatial changes in the annual cycle of SAT resulted from heat exchange between the land and ocean [5]. Dividing ASAT by the sinus of latitude reduced the effect of the annual cycle of incoming radiation and highlighted the effect of other factors. Moreover, GCI was linearly calibrated to be equal to 100% at Verkhoyansk and used to categorize climatic conditions as maritime (GCI≤0%), transitional maritime (0%<GCI≤33%), continental (33%<GCI≤66%), and extremely continental (GCI>66%).
The Moscow GCI progressively decreased during the second half of the 20th century [6]. In the middle of the 20th century, Moscow GCI varied in the range of 37-39%, which corresponds to continental climate, and gradually declined to 33% by the end of the century. The shift toward transitional maritime climate can be explained by the combined effect of the warming due to increasing atmospheric concentration of carbon dioxide and intensification of the zonal heat transport from the North Atlantic Ocean and Europe [7]. However, these factors cannot explain the increase of Moscow GCI during the 1920-1950 period.

The growth of Moscow GCI during that period indicates that there must have been a third driver of the changes of the Moscow climate continentality, and so we hypothesize that the additional variations of heat transport not related to zonal circulation strength is a suitable candidate for this role. Such variations could be related to intensity of meridional heat transport or to heat advected with the zonal flow.

2. Methods
Rapid warming in the Arctic [8] reduces the poleward temperature gradient and thus affects the intensity of the meridional heat exchange in the Northern Hemisphere [9]. Due to this reason, the mean annual temperature anomalies over the Arctic (north of 60°N) (ATA) may serve as an indicator of the meridional heat exchange intensity. ATA is also highly correlated with Atlantic Multidecadal Oscillation (AMO) linked to ocean surface temperature variations in the North Atlantic.

The ATA time series was transformed into ATA 30-year moving average time series (ATA30) and added to the right part of the equation attributing the historical changes in GCI to the annual North Atlantic Oscillation (NAO) that characterizes the strength of zonal circulation in winter time, and the mean annual temperature in Moscow (MAT) [7]:

\[
\text{GCI}_{30} - \text{GCI}_{av} = a(\text{MAT}_{30} - \text{MAT}_{av}) + b(\text{NAO}_{30} - \text{NAO}_{av}) + c(\text{ATA}_{30} - \text{ATA}_{av}) + \varepsilon
\]

(1)

where NAO30 is 30-year moving average of NAO, MAT30 is 30-year moving average of MAT, GCI30 is the time series of GCI calculated from time series of 30-year moving average of monthly temperature in Moscow taken from the GHCN [10] (WMO code: 27612), and \( \varepsilon \) is the unexplained part of GCI30 time series.

The coefficients \( a, b, \) and \( c \) quantify the contributions of changes in MAT, NAO, and ATA, respectively. They were set at the values providing the best least squares approximation of the GCI30 time series.

3. Results
The best approximation of the GCI30 time series (Fig. 1) suggests that ATA effect is of opposite sign to the effects of MAT and NAO (\( a=-3.66, b=-3.32, c=3.62 \)) and that GCI increases by 3.62% with ATA increase by 1°C. In other words, Arctic warming decelerates the shift to the transitional maritime climate caused by the warming associated with the greenhouse effect of carbon dioxide and intensification of the

![Figure 1. The accuracy of GCI30 approximation by the linear function of MAT30, NAO30, and ATA30 (Eq.1), \( R^2=0.87 \).](image)
zonal flow associated with heat exchange between the Atlantic Ocean and European continent in winter time.

Figure 2. Historical changes in the Gorczyński continentality index calculated from (1) the monthly air temperature in Moscow, (2) by the equation (1) where \(a=3.6, b=-3.3, c=3.6\), (3) by equation \(\text{GCI}_{30} = GCI_{av} - 3.1(\text{MAT}_{30} - \text{MAT}_{av}) - 2.7(\text{NAO}_{30} - \text{NAO}_{av})\), [7].

Taking into account that ATA possibly associated with meridional heat transport intensity helped us to fill the gap in the earlier explanation [7] of the historical changes in Moscow climate continentality. The linear function of \(\text{MAT}_{30}, \text{NAO}_{30}\), and \(\text{ATA}_{30}\) given by Eq.1 approximates well the GC30 time series calculated from the time series of 30-year moving average of monthly temperature during the period of 1920-1950, and, in contrast to linear function of \(\text{MAT}_{30}\) and \(\text{NAO}_{30}\) [7], explains the high GCI during this period (Fig.2) by the short period of Arctic warming (Fig.3).

Figure 3. Historical changes of \(\text{NAO}_{30}\) (1) and \(\text{ATA}_{30}\) (2) during the 20th century.
4. Discussion and conclusions

During the period of 1920-1950, the progressive rise of ATA30 was accompanied by the NAO30 decline (Fig. 3), and so both the effect of ATA30 and the effect of NAO30 were positive – that is, making Moscow climate more continental. The positive effect of ATA30 and NAO30 was counterbalanced by the negative effect of increasing MAT30, and due to this reason, GCI30 did not show neither upward nor downward trend during this period (Fig. 2).

In contrast to the Zhang et al. [11] assumption that westerly jet strengthening suggests meridional heat exchange weakening, the period of 1920-1950 was the period of negative correlation between ATA30 and NAO30. In the beginning and in the end of the 20th century, they were both rising (Fig. 3), but it does not seem impossible that during the next 30 years the further increase in ATA30 will be accompanied by decrease in NAO30. This may stop or even reverse the shift toward the transitional maritime climate.

The sixth Coupled Model Intercomparison Project (CMIP6) [12] may shed some light on the continentality of the future climate in the Moscow region. This paper reports a strong statistical relationship between the changes of Moscow climate continentality, Arctic warming, NAO, and local mean air temperature and poses the question if a similar statistical relationship could be found in the CMIP6 simulations. We suggest that Arctic temperature may reflect a strength of meridional heat transport in Moscow region. However, the role of AMO as a modulator of heat transported to Europe with zonal atmospheric circulation can be another factor that should be further analyzed.

Acknowledgments

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