Projections of temperature-dependent mortality in Russian subarctic under climate change scenarios: a longitudinal study across several climate zones

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Abstract. The magnitude of climate change in Arctic is greater than in other regions. Climate projections confirmed the ongoing warming in the circumpolar areas. The study goal was to estimate the fraction of mortality attributable to the exposition to non-optimal ambient temperatures during the 21st Century under the selected IPCC Representative Concentration Pathways RCP4.5 and RCP8.5. Three study areas were chosen to represent the different types of subarctic climate: from marine-type to transitional to extremely continental. Our dataset comprised 160363 deaths occurred between 1999 and 2016 in the cities of Murmansk, Archangelsk and Yakutsk. Non-linear distributed lag model was used to estimate the relationship between daily air temperatures and mortality rates. Daily temperature anomalies projected by the decades 2050-2059 and 2090-2099 were derived from the ensemble modelling with the regional climate model developed in the Voeikov Main Geophysical Observatory. The study showed positive net health impacts in all locations, and indicated uneven distribution of the benefits of climate change. Under the RCP8.5 scenario, mortality from all natural causes in the age group over 30 years will decrease by 4.5% (95% CI 1.1%; 7.9%) in Murmansk, 3.1% (1.1%; 5.1%) in Archangelsk and 3.6% (0.3%; 7.0%) in Yakutsk between the decades 1990-99 and 2090-99.

1. Introduction

Intergovernmental Panel on Climate Change (IPCC) emphasized that anthropogenic emissions of greenhouse gases (carbon dioxide, methane and nitrous oxide) together with other anthropogenic drivers are extremely likely to have been the dominant cause of the observed warming since the mid-20th century [1]. The projections of future climate should be based on the specific assumptions about the current and future trajectories of greenhouse gas emissions, concentrations and land-use. Since its Fifth Assessment Report issued in 2014, these trajectories have been formulated by IPCC in terms of “representative concentration pathways”. Among the four RCPs which have been developed for the climate modeling community as a basis for long-term modeling experiments [2], the current research considers an intermediate scenario RCP4.5 which leads to a mild warming, and a high-emissions scenario RCP8.5. The latter is an energy-intensive scenario, a result of faster population growth, lower incomes in developing countries and a lower rate of technology development which leads to the greatest warming in the absence of greenhouse gas emission reduction policies.
The researchers study various direct and indirect links between climate change and health. For such studies, the territories with the greatest monthly temperature anomalies, as compared to global averages, could be especially important. The Russian Federation is an example, because it experiences greater temperature rise than the global average. The mean annual temperature increment in the Russian Federation between 1976 and 2018 was 0.47°C per decade compared to the global average of 0.17°C per decade [3]. Regional differences in climate projections reflect the differences in the types of climate among Russian regions. The relationships between climate and mortality may in turn vary from one region to another. For example, the number of additional climate-induced deaths in Brasilia grew as the local climate changed from moderate to equatorial [4].

Russian Arctic and Subarctic territories will experience relatively faster warming than the global and national averages. The comparison of annual temperature anomalies between 2000-2009 as compared to 1951-1980 showed so-called polar amplification: the anomaly in Arctic reached 2.0°C whereas the global average anomaly for the same period was 0.6°C [5]. The reasons for this phenomenon include the physics of jet streams and the changes in albedo of polar caps due to melting of ice-sheets [6].

The territories with subarctic climate include North Scandinavia, greater parts of Alaska and Canada to the north of 50°N. Russian legislation established the list of “Far North territories” located mainly north of the Arctic Circle and identified by the adverse climatic factors, most importantly, low air temperatures. Above 8 million Russians live on these territories, or 5.8% of Russian population. The largest cities there are Murmansk, Archangelsk and Yakutsk. Global warming will likely bring about certain benefits for this population, including milder winters, an increase in agricultural productivity due to longer vegetation period and greater heat availability [7].

The study goal was evaluation of health consequences of increasing anomalies in daily temperatures due to global warming in Russian Subarctic. The authors obtained a direct epidemiological evidence of impacts of varying daily temperatures on daily mortality. This could be done by analyzing daily mortality counts among a sufficiently large population, above 100,000 people, during several years’ observation period [8].

2. Methods and materials

2.1. Study sites
The selection of the study sites was guided by mortality data availability, population sizes, and our intent to include various types of climates one finds in Russian subarctic: from a cold marine-type near Norwegian border to extremely continental in East Siberia. In order to obtain reliable temperature-mortality relationships, only the compact populations living in the largest Arctic and Subarctic cities could be studied. The city of Murmansk (population 295,000 in 2018) belongs to Atlantic-Arctic zone of moderate climate. It is the world’s largest city beyond the Polar Circle. The weather there is influenced by Gulf Stream and Barents Sea. The city of Yakutsk in East Siberia (population 312,000) has extremely continental climate. It is the world’s largest city constructed on permafrost, while its weather is characterized by the greatest seasonal variations of daily temperatures. As an example of the transitional type of climate between marine and continental, the moderately-cold city of Archangelsk (population 350,000) was chosen. The climate of Archangelsk is influenced by the northern seas. Thus, the results obtained in these locations could potentially reflect the differences between “marine”, “transitional” and “continental” climates of Russian Subarctic. The most important characteristics of these climates (mean temperatures of the coldest and the hottest months) are reported in Table 1.

2.2. Climate projections and temporal slices
Scenario-based projections of daily temperature anomalies in the 21st century were obtained in the three study locations from the Voeikov Main Geophysical Observatory regional climate model [9]. Compared to global climate models, the regional model has a higher spatial resolution (25 km) and better describes mesoscale climate variability and its contribution to the uncertainty of regional climate projections. The decade of 1990-1999 was chosen as the baseline period, and the projections were made for the decades of 2050-59 and 2090-99 to reflect the temporal dynamics of the changes in
mortality during the 21st century under the two global warming scenarios: RCP4.5 and RCP8.5. The climate model ensemble size was 25 realizations for the former scenario and 50 realizations for the latter.

2.3. Indicators of mortality

This study analyzed climate-dependent causes of mortality. The following five groups of causes were considered: all natural causes, all respiratory causes, all circulatory causes, of which myocardial infarctions and brain strokes were identified and studied separately. To reflect the possible differences with respect to the age of death, the deaths occurred at ages 30-64 and 65+ years were studied separately, representing mortality among the able-bodied population and the senior people. Notably, the elderly populations have been found particularly vulnerable to the temperature extremes associated with climate change, and the proportion of population over 65 years of age is now included in the heat vulnerability index developed by the Lancet countdown on health and climate change [10]. Combining the two age groups with the five groups of causes, we studied ten indicators of mortality in each city.

2.4. Mortality-temperature relationship and attributable risk

Modeling of excess mortality attributable to climate change involved the establishment of the underlying temperature-mortality relationship as a dose-response function. For this, the data from the baseline period were used. The estimated minimum mortality temperature (MMT) is an important characteristic of local mortality-temperature relationship, it depends upon local climate and the characteristics of local population.

Attributable fractions of deaths (AF) and the numbers of excess deaths attributable to exposition to non-optimal temperatures (AN) were calculated for the three study sites. Attribution fractions were then used to make comparisons between the results obtained in different climates of Russian Subarctic. These measures of attributable risk were calculated against a counterfactual assumption that the temperatures on all days were equal to MMT. A general definition of the attributable fraction \( AF_T \) and number \( AN_T \) for an exposure to temperature \( T \) can be provided by:

\[
AF_T = 1 - \exp (-\beta_T) ; \quad AN_T = n \times AF_T
\]

where \( \beta_T \) is log-risk – natural logarithm of relative increase in mortality caused by non-optimal temperature; \( n \) is total mortality on the day \( i \) with the temperature \( T \). This definition can be generalized to include the lagged responses to non-optimal temperatures. The modelling showed that the acute effects of temperature can be lagged for 1-3 days for exposition to high temperatures and for 2-3 weeks for cold temperatures.

The technical details of calculations of attributable risk measures from the non-linear distributed lag model of daily mortality are provided in [11, 12]. We employed the same method of calculation of \( AF \) and \( AN \) to make our results directly comparable to those reported in [12] for other regions of the globe. The generalized linear Poisson model specification is given by equation (2):

\[
\log[E(\tilde{M}_{\text{obs}})] = \alpha + s(\tilde{t}_{\text{obs}}; \theta) + f(i; \beta) + l(\text{dow}; \gamma)
\]

where \( \tilde{M}_{\text{obs}} \) and \( \tilde{t}_{\text{obs}} \) are the complete and ordered time series of observations of daily mortality and daily mean temperatures in each study site over the period for which mortality data were available (1999-2016); \( E \) means ‘expected’; \( s \) is a two-dimensional spline function in the spaces of temperatures and time lags defined by parameter vector \( \theta \); \( f \) is a natural cubic spline of day number \( i \) which accounts for temporal adjustments of mortality (seasonality and long-term trend); it is defined by parameter vector \( \beta \), and the last term accounts for day-of-week variations in mortality. The function \( s \) allows to calculate the independent contributions of lagged exposures to non-optimal temperatures to the expected mortality on day \( i \). Summing up these contributions across the maximum lag period of 21 days considered in the analysis, one arrives at overall effect of temperature \( T \), expressed as the cumulative risk of this temperature, and then converted to the fraction and number of deaths attributed to the exposition to this temperature.
The sum of all $AN_i$ gives the total attributable number of deaths during the baseline period $\bar{AN}_{\text{tot}}$ which can be farther subdivided in two components corresponding to all days with temperatures above optimal $\bar{AN}_{\text{heat}}$ and below optimal $\bar{AN}_{\text{cold}}$. After that, according to definitions (1), the corresponding fractions were calculated:

$$\bar{AF}_{\text{cold}} = \frac{\bar{AN}_{\text{cold}}}{M_{\text{tot}}}; \quad \bar{AF}_{\text{heat}} = \frac{\bar{AN}_{\text{heat}}}{M_{\text{tot}}} \quad (3)$$

These calculations were performed for various scenarios of future daily temperatures $\bar{T}_f$, using the daily temperature anomalies as output from the climate model. The confidence intervals around the model estimates (3) took in account both the uncertainty of climate projections and the uncertainty of the baseline estimates of $AF$ and $AN$.

3. Results

3.1. Climate projections
In all climates positive temperature anomalies were predicted during all months. These temperature anomalies increased over time in nearly linear fashion. The projected anomaly by the end of the century was approximately twice as big as the anomaly reached by the mid-century. Temperature anomalies displayed a distinct seasonality pattern. The change of climate from marine to transitional to continental corresponded to an increase in winter temperature anomalies. According to RCP8.5 scenario, by the end of the century, winter temperature anomalies will reach +8°C in Murmansk; +9°C in Archangelsk and +12°C in Yakutsk, while the summer temperature anomalies are almost equal in the marine and transitional climates (+5°C), and fall down to +3°C in extremely continental climate of Yakutsk. RCP4.5 scenario leads to moderate warming; projected daily temperature anomalies will be approximately one-half of those reported above for RCP8.5.

3.2. Baseline mortality-temperature relationships
In the marine climate (Murmansk), statistically significant estimates of $AF_{\text{cold}}$ were established for the three indicators of mortality, and one significant estimate of $AF_{\text{heat}}$ was obtained. In the transitional climate (Archangelsk) statistically significant estimates of $AF_{\text{cold}}$ were obtained for six indicators, and significant estimates of $AF_{\text{heat}}$ were obtained for two indicators. In the continental climate (Yakutsk), only one significant estimate of $AF_{\text{cold}}$ was obtained. This can be explained by relatively lower sample sizes in Yakutsk (its population in 1999 was only 195,000). The total number of deaths observed in Yakutsk was approximately one-half of those in other cities.

Numerical comparisons of $AF_{\text{cold}}$ vs $AF_{\text{heat}}$ were made only for the pairs in which both estimates were statistically significant. This was possible for the two indicators of mortality in the transitional climate. These pairs were $AF_{\text{cold}}=24.0\%; \quad AF_{\text{heat}}=1.0\%$ for brain strokes in age group 65+, and $AF_{\text{cold}}=23.6\%; \quad AF_{\text{heat}}=0.7\%$ for all circulatory diseases in the same age group. Such differences in the relative magnitudes of the effects of cold and heat indicated that the future changes in the absolute values of $\Delta AF_{\text{cold}}$ would also be greater than those for $\Delta AF_{\text{heat}}$. The differences in the magnitudes of these two effects can be explained by the differences in pathogenic mechanisms leading to death on cold and hot days, seen in the overall shape of mortality-temperature relationship, where MMT corresponds approximately to the 90th percentile of the long-term distribution of daily temperatures (Table 1). As climate changes from marine to continental, the absolute values of MMT increase, while the MMT values expressed as percentiles decrease from 93% in Murmansk to 88% in Yakutsk.

| Table 1. The temperatures of the coldest and hottest months for the decade 2009-2018 and MMT values (°C and the percentiles of the mean daily temperature distributions) during the same period. |
|---------------------------------|-----------|-----------|-----------|
| climate type study site         | marine Murmansk | transitional Archangelsk | continental Yakutsk |
| $T_{\text{jan}}, \degree\text{C}$ | -10.8     | -12.4     | -36.5     |
3.3. Projected changes in temperature-dependent mortality

These changes in age group 65+ are shown on figure 1. The error bars show 95% confidence intervals around the estimated changes in total attributable fractions between the baseline and future periods. The results are shown for those causes of death for which the estimates of AF<sub>cold</sub> and AF<sub>heat</sub> were obtained in all three study sites. These leave out “deaths from brain strokes” because the mortality-temperature relationships were not established in Murmansk and Yakutsk. Let us consider mortality from myocardial infarctions in age group 65+. The baseline value of AF<sub>heat</sub> increases as climate changes from marine to continental: from AF<sub>heat</sub><sup>cold</sup> = 0.2% in marine climate to 0.4% in transitional climate to 1.9% in continental climate. For example, under the RCP8.5 scenario in continental climate, AF<sub>heat</sub> will increase from 1.9% to 4.3% by the end of this century, which amounts to a 2.4% increase. Concurrently, AF<sub>cold</sub> will decrease from 33.6% to 26.3%, or by 7.3%. The net change is therefore ΔAF<sub>tot</sub>=-4.9%. Similarly, AF<sub>tot</sub> decreased for the other indicators, study sites and emission pathways.

Figure 1 shows that the effect of warming on mortality in the marine climate is approximately twice as large in the absolute value than that in the transitional or continental climates, where the effects are comparable. The effect size in the continental climate tends to be slightly larger that that in the transitional climate, with the exception of myocardial infarctions.

3.4. Scenario-based differences in health effects

For both scenarios RCP4.5 and RCP8.5, the values of AF<sub>tot</sub> decrease steadily (almost linearly) during the 21st century, with one exception: AF<sub>tot</sub> for mortality from all natural causes in age 30-64 attributable to exposition to non-optimal temperatures under RCP8.5 scenario in the marine climate decreases from 16.3% (95% CI -7.4; 32.1) in 1990-99 to 15.4% (-7.3; 26.2) by 2050-59 and then increases to 15.8% (-4.7; 23.5) by 2090-99. For this indicator, ∆AF<sub>tot</sub>=0.9% (-4.1%; 3.3%) by the middle of the century and ∆AF<sub>tot</sub>=0.5% (-7.0%; 8.0%) by the end of the century. However, these estimates have very low statistical significance, nearly linear fashion with time.

Let us consider scenario-based differences in the attributable numbers of annual temperature-related deaths AN<sub>tot</sub>. Table 2 reports these for all non-accidental causes of death among the studied urban populations. The attributable numbers of deaths decrease linearly with time during the 21st century. The rate of the decrease under RCP8.5 scenario almost doubles as compared to that under RCP4.5 scenario. The attributable numbers for the two age groups can be summed up to produce the total health costs (or benefits). For example, under RCP8.5 scenario in Archangelsk, 51+71=122 deaths (or 3.1% of total mortality) can be avoided annually by the end of the century. This estimate does not include the age group under 30 years, but the number of deaths in this age group is negligible.

Table 2 also shows that the AN estimates were statistically significant for both age groups only in Archangelsk. The estimates in Murmansk were significant for age group 65+, and the estimates in Yakutsk were significant for age group 30-64.

3.5. The differences of health effects between the age groups

These differences can be seen in greater numbers of cause-specific estimates obtained for the senior age group. Summing up across the three study sites, the effects of warming were established for 8 out of 15 indicators of mortality in age group 30-64, and for 13 out of 15 indicators in age group 65+. The effect sizes also tended to be greater in the senior are group. This finding confirmed greater vulnerability of the senior age group.
Figure 1. Scenario-based net changes in excess mortality (%) in different climates, during the 21st century, compared to 1990-99, with empirical 95% CIs. RCP=representative concentration pathway.
Table 2. Scenario-based annual attributable numbers of temperature-related deaths from all non-accidental causes (95% CI)

| City            | age group | baseline 1990-99 | RCP4.5 2050-55 | RCP4.5 2090-95 | RCP8.5 2050-55 | RCP8.5 2090-95 |
|-----------------|-----------|------------------|-----------------|----------------|----------------|----------------|
| Murmansk (marine) | 30-64     | (-98; 424)       | (-80; 408)      | (-49; 408)     | (-41; 403)     | (-22; 392)     |
|                 | 65+       | (53; 680)        | (11; 642)       | (21; 578)      | (25; 590)      | (4; 501)       |
| Archangelsk (transitional) | 30-64     | (71; 423)        | (56; 387)       | (64; 382)      | (62; 370)      | (73; 343)      |
|                 | 65+       | (104; 582)       | (93; 555)       | (76; 528)      | (77; 524)      | (87; 481)      |
| Yakutsk (continental) | 30-64     | (29; 494)        | (19; 475)       | (0; 476)       | (0; 478)       | (8; 460)       |
|                 | 65+       | (-74; 348)       | (-97; 346)      | (-79; 335)     | (-113; 331)    | (-113; 305)    |

*Significant at \( p<0.05 \) level estimate

4. Discussion

The projections of future changes in temperature-dependent mortality assumed that the underlying mortality-temperature relationships would remain exactly the same as they were during the baseline period. These projections imply no demographical changes, no acclimatization and no adaptation to climate change. This assumption was also used in international climate and mortality study [12], meaning a simplified vision of the future. It was argued that clear assumptions facilitate the proper and more focused interpretation of the results, as the impact due to global warming can be disentangled from the contribution of numerous other factors. Our estimates should be interpreted as the projections of hypothetical health impacts based on current socio-economic conditions, stable populations, population structure and level of vulnerability.

Further refining of such estimates was suggested by other authors who have speculated that adaptation would likely lead to a gradual increase in the MMT with time. A study of historically long time series of daily mortality in Stockholm showed that both the absolute and the relative MMT values increased there during the 20th century [13]. The authors reported that the absolute value of MMT increased from \( 11\,^\circ C \) to \( 20\,^\circ C \), while the relative value of MMT increased from the 70th to the 93rd percentile. At the same time, mean annual temperatures increased by only \( 1.4\,^\circ C \) during the same period, which suggested autonomous adaptation within the context of the large epidemiological, demographical, and societal changes, climate warming not being the main driver of such adaptation. A gradual increase in MMT since 1968 was also observed in France [14].

These findings suggest an important area for further research in the diverse climates of Russian Federation. Unfortunately, the use of long time series of daily mortality counts in this country is limited, because the data are available in digital format only since 1999.

The numerical estimates of health impacts of climate change presented here for Russian subarctic are unique, because international studies have been limited to more moderate and milder climates. The quantitative estimates obtained in this study can be compared to those obtained in [12] for other climates and regions of the globe, because we used the same methodology, RCP scenarios and projection periods. Summing up the weighed contributions of the two age groups, we estimated the relative decreases in total temperature-dependent mortality for different regions in Russian subarctic. Under the strong radiative forcing scenario RCP8.5, we predicted a 4.5% (95% CI 1.1%; 7.9%) decrease in non-accidental mortality in Murmansk, a city with marine climate; a 3.1% (1.1%; 5.1%) decrease in Archangelsk, a city with transitional climate, and a 3.6% (0.3%; 7.0%) decrease in Yakutsk, a city with extremely continental climate, by the end of the 21st century. For the same RCP and projection period, Gasparrini and co-authors reported a 0.6% (-1.6%; 2.3%) decrease in non-
accidental mortality in North Europe; a 1.2% (-1.4%; 3.6%) decrease in Australia (the largest decrease reported in [12]); and increases in non-accidental deaths in all other regions of the globe. Thus, the projected decrease in mortality in Russian Subarctic can be 3 times greater than that in Australia and 6 times greater than in North Europe, which is consistent with the “polar amplification” phenomenon. This result confirms non-uniform distribution of health risks and benefits of global warming across the globe.

Previous projections of annual temperature anomalies between 2010-2019 and 2090-2099 under RCP8.5 showed rather wide confidence intervals; for example, ΔT=4.9°C (95% CI 3.2°C; 6.3°C) in North America and 3.4°C (2.8; 5.4) in North Europe [12]. North America has more continental climate than North Europe, and the climate in North America is more similar in this respect to the climate of Russian Subarctic than the climate of North Europe. The relative standard errors (RSE) of the reported estimates of annual temperature anomalies are 16% and 19%. The confidence intervals around the temperature anomalies used in our study are considerably smaller. For the same RCP and the same decades, the annual temperature anomalies were 5.4°C (5.0; 5.7) in Murmansk, 5.6°C (5.2; 6.0) in Archangelsk and 5.7°C (5.3; 6.1) in Yakutsk. RSE of our estimates was about 3%. It is worth noting that the temperature anomalies reported for North America are in good agreement with those projected for Russian Subarctic and used in this research.

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