Study of surface-based temperature inversions in the city of Nadym (Western Siberia) with direct measurements and numerical simulation

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Abstract. Frequent surface-based inversions are persistent features of climate in the Arctic and, in particular, in its Russian part. Most favourable conditions for temperature inversion formation during the winter period in this region are observed. Surface-based inversions formed in cities are most interesting for research, because of their impact on people’s health. Besides, “urban” surface-based inversions differ from “rural” ones, because of interactions with the urban heat island (UHI). Actually, urban surface-based inversions in the Arctic are weakly understood due to poor meteo monitoring equipment of most Arctic regions and because the reanalysis resolution is too low for the cities. To estimate the frequency of surface-based inversions and spatial distributions in the city of Nadym (Western Siberia), measurements with gradient complexes during the period from 18.12.2018 to 15.10.2019 have been conducted, and a numerical experiment with a model Advanced Research WRF (ARW) has been performed for the coldest days of the period. In the research, first statistic microclimatic data of vertical temperature distributions in the city of Nadym have been obtained. Such model experiments are realized for that region, and the results obtained for the rural area are compared with microwave temperature profiler MTP-5 measurements.

1. Introduction and motivation
Atmospheric boundary layer temperature inversions are a ubiquitous feature of high-latitude climates (65°N and to the north) [1]. In this region, during the winter period the most favorable conditions for the temperature inversion formation are observed. This time of the year at high latitudes is characterized by shorter periods of insolation; thus, downward shortwave radiation does not compensate for the upward longwave radiation for many days and, as a result, the surface net radiation remains constantly negative during this time. If low wind speeds are observed in this case, so-called long-living inversions can develop [2]. Temperature inversions in arctic and subarctic latitudes are...
characterized by high values of depth (up to several hundred meters) and intensity (up to 30°C per several hundred meters) [2].

Surface-based temperature inversions that develop in cities are of most interest to the study, because the accumulation of pollutants under the inversion layer in certain conditions can pose a serious danger to people’s health [3, 4]. In addition, during the research of urban surface-based inversions it is necessary to take into account the influence of the anthropogenically transformed territory. In the modern world, the city has long become a separate type of landscape with its own landforms (buildings and urban canyons) and with different values of radiation, thermal, humidity, and aerodynamic parameters from the surrounding area. The result of these differences is an increase in the heat balance of the city in comparison with the rural zone and, consequently, the appearance of a difference in the air temperatures between the anthropogenically transformed territory and the slightly altered landscape around, i.e. the formation of an urban heat island (UHI) [5]. For a long time, it was considered that the appearance of a heat island occurs mainly due to the absorption of solar radiation; therefore, in Arctic cities it should be small, and during the polar night it should be completely absent [6]. However, recent studies [7, 8, 9] have shown that at high latitudes the anthropogenic heat flux is the main factor affecting the formation of a UHI [10, 11, 12]. Its influence is so great that even such a relatively small city as Nadym turns out to be warmer than the surrounding landscape by 6-7°C, which is usually typical only for very large cities. Such a strong influence is explained by the delay and subsequent accumulation of anthropogenic heat fluxes in the stably stratified layer of inversion [13].

Now, urban surface-based inversions in the Arctic are weakly understood due to poor meteorological monitoring equipment of most Arctic regions and because the reanalysis resolution is too low for cities.

Thus, the purpose of this work is the estimation of the frequency of surface-based inversions and the spatial distribution in the city of Nadym (Yamalo-Nenets Autonomous Okrug) with direct measurements and numerical simulation. Nadym was chosen for the research because of quite large population for the Arctic region, the location in subarctic climate and a flat relief; thus, orographic inversions can be excluded.

2. Data and methods

2.1. Location of Nadym

The city of Nadym is part of Nadym region, which is part of the Yamalo-Nenets Autonomous Okrug. The area is located in the northern part of the West Siberian Plain, includes the Nadym River basin and the western part of the Taz Peninsula. More than a half of the area of Nadym region is covered with swamps, there are also many lakes on the territory. Permafrost is widespread. The city center has coordinates 65°32’N, 72°3’E and is located at an altitude of 6 meters above sea level [17].

2.2. Gradient measurements

The main problems arising in the study of urban temperature inversions in the Arctic are:

- Low technical equipment of the region: radiosonde stations are usually located on the coast and not always near cities, there are no acoustic sounding stations, meteorological stations are most often located outside the city;
- a relatively small area of cities that does not allow conducting research only using reanalysis databases (the area of Nadym is 185 km², approximately 13,6×13,6 km);
- inability to use satellite information without backing up contact measurement data [11].

Given the above problems, the best method for measuring air temperature at different levels is gradient measurements.

In the city of Nadym, the study of the surface structure of the atmosphere was carried out in the period from 12.18.2018 to 15.10.2019. For this goal, gradient observation complexes based on an automatic temperature recorder HOBO MX2303 Two External Temperature Sensors Data Logger
with sensors at altitudes of 1.5 and 3 meters, respectively, were installed. Within the city, a pair of the above-mentioned complexes was installed: directly in the city center (“Dom Prirody”) and in the rural area (airport) (Figure 1). The measurements were conducted every half an hour, with an accuracy of 0.25°. The maximum possible measuring range with such sensors is from -40°C to 70°C [18].

![Figure 1](image-url) (a) An aerial view of Nadym (http://www.russian.fi/forum/showthread.php?t=77750 by Paul’); (b) location of measurement points in Nadym and its rural area; (c) HOBO MX 2303 Data Two External Temperature Sensors Data Logger with which the points are equipped.

During the processing of the data obtained, first deliberately incorrect values were discarded, much higher than the average climatic values and/or more than 10°C different from the measurements of the automatic weather station installed at the airport.

The obtained data were downloaded from the HOBO automatic temperature recorder and processed using Microsoft Excel (from the Microsoft Office 2016 software package). For each gradient complex, the value of the temperature gradient per 1 meter was calculated, \( \Delta T = (T_{1.5m} - T_{3m})/1.5 \).

Cases with negative values of \( \Delta T \) were taken as the temperature inversion. Zero values were considered a state of isotherm [14].

2.3. Description of the numerical experiment

To estimate how accurately the surface temperature inversions in the Arctic cities are reproduced on the basis of numerical simulation, an experiment was performed using the mesoscale non-hydrostatic model ARW (Advanced Research Weather Research and Forecasting (WRF)) version 4.0 (REFERENCE) for the period from 22.12.2018 00 UTC to 24.12.2018 00 UTC. One of the two episodes of the coldest weather conditions during the observation period was chosen for modeling.

2.3.1. Synoptic situation during the numerical experiment. The synoptic situation on 22.12.2018 in Nadym was determined by the influence of an increasing anticyclone, shifting from the Kara Sea to the mouth of the Ob and further south, to the West Siberian Plain. According to the weather station located at the airport in Nadym, on 22.12.2018 the temperature dropped to -45.5°C. The wind speed during the day was low (0-1 m/s), and no precipitation was observed.

On 23.12.2018 the anticyclone increased, but continued its movement to the south, and the atmospheric pressure in Nadym gradually began to decrease. On the periphery of a powerful cyclone centered over the Barents Sea, a secondary cyclone (centered over Severnaya Zemlya) formed and also began to move southward. During the day, the temperature rose, the wind speed reached 3 m / s by the end of the day, and no precipitation was observed.

2.3.2. Experiment parameters. For the calculations, four nested domains with mesh sizes of 18 km, 6 km, 2 km, and 0.5 km (Figure 2) and with a common center in the city of Nadym (65.5°N, 72.3°E)
were used. The city during the research was chosen as the center of the computational domain to reduce the error.

![WPS Domain Configuration](image)

**Figure 2.** Computational domain configuration.

The calculations used a grid of 38 levels. The initial data were taken from the ERA5 reanalysis data with a horizontal resolution of 0.25°x0.25°. The physical parametrizations used in the numerical experiment with the WRF-ARW 4.0 model are presented in Table 1.

**Table 1.** Physical parameterization schemes used during the numerical experiment 22.12.2018–23.12.2018.

| Parameterization schemes                                    |  |
|------------------------------------------------------------|--|
| Microphysics (mp_physics)                                  | Lin et al scheme (for the first domain); WSM 5-class scheme (for other domains) |
| Cumulus parameterization (cu_physics)                      | Kain-Fritsch (new ETA) scheme |
| Longwave radiation (ra_lw_physics)                         | RRTMG scheme |
| Shortwave radiation (ra_sw_physics)                        | Goddard short wave |
| Planetary boundary layer (bl_pbl_physics)                  | Mellor-Yamada-Janjic (ETA) |
| Surface layer (sf_sfclay_physics)                          | Similarity theory (MYJ/Eta) |
| Land-surface model (sf_surface_physics)                    | Noah-MP land-surface model |
The influence of clouds on the optical thickness in the calculation of radiation

Accounting for the impact of snow cover

Number of soil layers

Urban parametrization (sf_urban_physics)

| The influence of clouds on the optical thickness in the calculation of radiation | accounted |
| Accounting for the impact of snow cover | accounted |
| Number of soil layers | 4 |
| Urban parametrization (sf_urban_physics) | Building energy model (BEM) |

The obtained data were visualized on NCL and the data for the background zone were compared with the measurement of a microwave temperature profiler MTP-5.

2.4. Microwave temperature profiler (MTP-5)
The meteorological temperature profiler MTP-5 is a device designed for remote measurements of the atmospheric temperature profile in the range of heights from the device installation level to 1000 m.

Measurements are carried out at a wavelength of 5 mm (the microwave wavelength range) with a frequency of 5 min. In the 0-100 m layer the measurement resolution is 25 m, and in the 100-1000 m layer the resolution is 50 m. The range of measured temperatures is from -50°C to +50°C, and the measurement accuracy is 0.5 h [19].

The MTP-5 was installed in the airport of Nadym at 2018 by scientists of the Department of Meteorology and Climatology of MSU, the Research Computing Center of MSU, and the A.M. Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences. The device provides measurements of the vertical structure of the atmosphere in an anthropogenically slightly altered zone.

3. Results and discussion

3.1. Results of gradient measurements
The gradient measurements in the city of Nadym were carried out in the period from 18.12.2018 to 15.10.2019. After the data processing and filtering (except for cases when the temperature difference between the upper and lower sensors was less than the device error), the following graphs were obtained (Figure 3).

**Figure 3.** Temperature vertical gradients' frequency in the city of Nadym and its rural zone during the winter period (left – daytime; right – nighttime).
Figure 3 shows the distribution of the temperature gradients observed in winter in the city of Nadym and its rural zone during daytime (left graph) and nighttime (right graph) observation periods. It can be seen that the distributions for the urban and rural zones have a very similar form; however, in the case of the rural zone the distribution is shifted towards stronger negative temperature gradients. This is due to the presence of a heat island in the city, which weakens the temperature inversion at the ground. At night, the distribution, both for the rural zone and for the urban zone, shifts towards a more stable stratification. This is due to the most powerful radiation cooling in the winter conditions in the subarctic climate where Nadym is located.

In the future, it will be possible also to take into account the specific location of each measurement point (in what conditions of development, vegetation, and other factors of microclimate they are located). In addition, the conclusions will become more accurate if we consider a longer series of measurements and solve the problem of sensor overheating in the sun.

3.2. Results of comparison of the numerical experiment with MTP-5 measurements for Nadym rural area

Figure 4 shows deviations of the modelled profiles for 22.12.2018 from MTP-5 measurements in the rural area. The modelled values were interpolated to the measurement levels due to a coarser vertical resolution of the observed profile.

![Figure 4. Model temperature deviations from vertical temperature profile measurements using the MTP-5 (local time specified: GMT+5).](image)

The temperature profile deviation was positive all day long. In the second half of the day the temperature had the largest errors near the surface, which is related to the complexity of modeling of the urban surface layer in stable conditions [15]. Besides, the error value changed as the stability of the boundary layer changed: its minimum was observed at 14:00 (when mixing was most developed) and maximums were observed in the morning (08:00) and in the evening (20:00, 23:00). Similar problems with calculations in conditions of high pressure, weak wind, and temperature inversion were observed in older versions [16].

In general, the results of the experiment are still preliminary. To get more reliable ideas about the quality of surface layer modeling in Arctic cities using WRF ARW 4.0, it is necessary to perform a longer numerical experiment to compare days with stable and unstable stratification. In addition, it is possible that the error in reproducing the vertical structure of the boundary layer in Nadym is due to the poorly chosen parameterization of the influence of the urban environment. In this regard, in the future it would be interesting to carry out several experiments with different parametrizations of the urban influence.
4. Conclusions
In this study, gradient observations in urban and rural zones of the city of Nadym were analyzed. For this, distributions of temperature gradients for the urban and rural zones in the winter period during the day and night observation periods were estimated. Based on the results of the analysis, the following conclusions can be made:

- Frequency of surface-based temperature inversions in the nighttime is more than 90%, frequency in the daytime is more than 80%.
- In the nighttime, the temperature distribution is shifted towards strong negative temperature gradients both in the city and in the background zone, which can be explained by the presence of a powerful radiation cooling observed in the subarctic climate zone where the city is located.

For the first time, some model experiments have been realized for that region, and the results obtained for the rural area have been compared with MTP-5 measurements. The deviations of the temperature values calculated by the model are maximum in the morning and evening, when stable stratification is observed, and are minimum in the daytime, when stability is weakened.

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