Analysis of the influence of temperature inversions on the ecological situation in Krasnoyarsk

Alexander V. Dergunov[1], Oleg E. Yakubailik[2]

[1]Federal Research Center Krasnoyarsk Science Center SB RAS, Krasnoyarsk, Russia
[2]Institute of Computational Modelling SB RAS, Krasnoyarsk, Russia

Abstract

The paper analyzes the meteorological conditions in the city of Krasnoyarsk in the period from January 1, 2019, to December 31, 2020. The relationship between temperature inversions in the surface layer of the atmosphere and air pollution by suspended solid particles PM_{25} is investigated. The paper uses a set of meteorological data of the NCEP GFS weather forecast model on the air temperature on three isobaric surfaces of 1000, 925, and 850 Mb; on wind gusts and the height of the atmospheric boundary layer. Data on PM_{25} solid particle concentrations and wind speed are provided by the air monitoring system of the KSC SB RAS. The relationship between the presence of temperature inversions in the lower layer of the atmosphere and periods of significant air pollution is shown, as well as the dependence of changes in wind speed and the height of the boundary layer of the atmosphere with changes in the average daily PM_{25} concentration. The results of the data analysis allow us to conclude that there is a high degree of correlation between these parameters. The possibility of using the meteorological data of the NCEP GFS model to study the surface layer of the atmosphere and the periods of its pollution, predicting the deterioration of the environmental situation in Krasnoyarsk, is demonstrated.

Keywords

Temperature inversion, unfavorable meteorological conditions, PM_{25}, GFS, air pollution, Krasnoyarsk.

1. Introduction

Atmospheric pollution is one of the main problems of large cities in the world. As a result of anthropogenic factors, many harmful substances that pollute the air enter the atmosphere [1]. Studies show an association between increased concentrations of particulate matter (PM) in the air and the deterioration of human health [2]. During periods of unfavorable meteorological conditions (UMC), there is a sharp increase in the concentration of pollutants in the lower layer of the atmosphere. We are talking about industrial and automobile emissions, furnace heating, and so on [3, 4]. One of the determining factors of UMC is the temperature inversion in the atmosphere.

Temperature inversions occur because layers of greater or lesser thickness are located at different heights in the surface layer of the atmosphere. The temperature decrease slows down very much, stops, or, conversely, instead of the temperature decreasing with altitude, it increases. Their properties are the height of the lower and upper boundaries, vertical power

SDM-2021: All-Russian conference, August 24–27, 2021, Novosibirsk, Russia
alexdergunov@icm.krasn.ru (A. V. Dergunov); oleg@icm.krasn.ru (O. E. Yakubailik)
0000-0002-2668-4776 (O. E. Yakubailik)

(layer thickness), and intensity (inversion value). Temperature inversions are divided into 3 types: surface (the lower boundary is located at ground level), elevated (the lower boundary is located at some height from the surface), and inversions of the free atmosphere (the height can vary greatly) [5, 6, 7].

There is a need to study atmospheric processes with the help of meteorological data sets to analyze periods leading to environmental degradation.

Sets of meteorological data can be obtained, for example, from ground-based environmental monitoring stations. The advantages of such weather information include a fairly high accuracy of measurements on the spot. However, the disadvantages of such data are that basic parameters limit such data sets, and the ground stations themselves can be located at a great distance from each other, which imposes certain restrictions on the spatial coverage of the problem being solved.

An alternative option is the weather data of various weather forecast models, for example, the Global Forecast System model. These sources provide many different layers of meteorological information on dozens of vertical levels, plotted on regular rectangular grids covering the entire Globe. The spatial resolution of such data can vary from 2.5 to 0.25 degrees and higher [8]. Developers try to improve this parameter regularly.

The purpose of this work is to analyze the influence of temperature inversions in the surface layer of the atmosphere on the formation of an unfavorable environmental situation in the city of Krasnoyarsk in 2019–2020 based on high-spatial-resolution meteorological data of the NCEP Global Forecast System weather forecast model. Identification of the relationship between the periods with the average daily concentrations of PM_{25} particulate matter suspended in the air, exceeding the average daily maximum permissible concentrations (MPC), the speed, wind gusts, and the height of the atmosphere's boundary layer.

The research area in this work is the city of Krasnoyarsk and part of the adjacent territories (Figure 1).

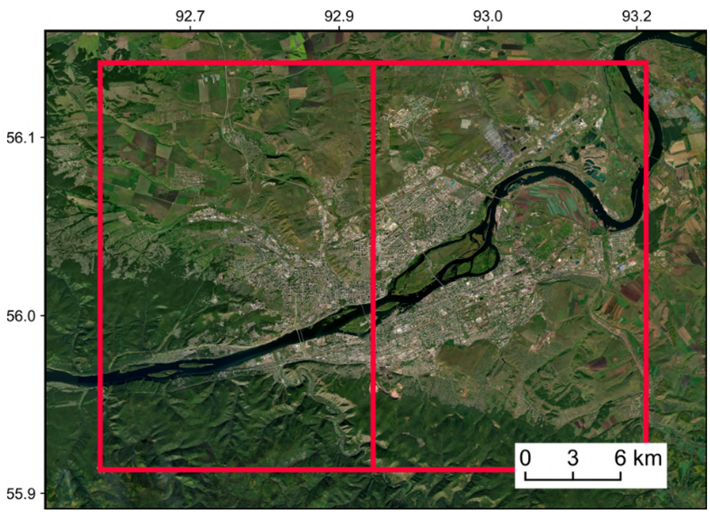

Figure 1: The study area is the city of Krasnoyarsk. Red frames indicate two cells of the regular grid of the GFS model.

Table 1
List of unfavorable meteorological conditions periods from 2019 to 2020.

No.	Dates
1	08–13 February 2019
2	26–28 November 2019
3	05–06 December 2019
4	23–24 December 2019
5	27–30 December 2019
6	10–13 January 2020
7	14–18 February 2020
8	25–27 February 2020
9	27–29 April 2020
10	16–18 November 2020
11	27–30 November 2020
12	26 December 2020 — 02 January 2021

12 periods of UMC were established in the city of Krasnoyarsk from 2019 to 2020 according to the Ministry of Ecology and Rational Nature Management data of the Krasnoyarsk Territory [9]. The periods of UMC are characterized by low wind speed and high particulate matter concentrations, significantly exceeding the average daily MPC equal to 0.035 mg/m^3. The list of UMC periods for the studied time period is presented in Table 1.

2. Materials and methods

The work uses meteorological information from the dataset of the Global Forecast System (GFS) model. This is a numerical weather forecasting system containing a global computer model and variational analysis performed by the US National Weather Service. This model combines four separate models: atmosphere, ocean, land/soil, and sea ice. Dozens of atmospheric and ground-soil variables are available in this data set, from temperature, wind, and precipitation, to soil moisture indicators and atmospheric ozone concentration. This is one of the most famous meteorological models in the world. Global data analysis and forecasting are carried out 4 times a day. The weather forecast is available up to 16 days in advance [8].

The accuracy of the GFS model is constantly improving. In particular, data with a horizontal resolution of 1 degree has been available since March 2004, with a resolution of 0.5 degrees since January 2007. Since January 2015, the horizontal resolution has been 0.25 degrees (about 25 km at the latitude of the city of Krasnoyarsk).

The GFS model data is presented in the grib2 format. This data format is standardized by the World Meteorological Organization (WMO) and is intended for storing historical and forecast weather data [10]. Each file contains more than 500 layers of various meteorological information on more than a hundred vertical levels.

This work used the actual analysis data on the air temperature at three vertical levels corresponding to three isobaric surfaces: 1000, 925, and 850 Mb. Data on the height of the atmospheric boundary layer and information on wind gusts from January 1, 2019, to December 31, 2020, obtained from the GFS model data set, were also analyzed.

During the preliminary processing of the meteorological information of the GFS model, the data was loaded and cropped according to the specified coordinates corresponding to the city of Krasnoyarsk, and the necessary layers with information about the air temperature at the selected vertical levels, as well as about the height of the boundary layer of the atmosphere and wind gusts. Since the spatial resolution of the data is 0.25 degrees, two cells of the regular grid of the GFS model covered the entire city of Krasnoyarsk and part of its surroundings (Figure 1).

Then the received data was converted to the tabular CSV format. These procedures were performed using special scripts written in Python using the wgrib2 program. The wgrib2 program is specially developed by the manufacturer of the GFS model data for reading and converting files of the grib2 format [11].

Inversion layers were detected by obtaining the difference between temperature data at different vertical levels when the difference was negative. For example, with a negative difference between temperatures on isobaric surfaces of 1000 and 925 Mb, the inversion was considered ground-level or elevated; if between 925 and 850 Mb, it was elevated or high-altitude (inversion of the free atmosphere). If the surface elevated and high-altitude inversions were recorded simultaneously, this was considered a powerful inversion.

We also used data on the concentrations of PM_{25} in the air and wind speed according to ground-based monitoring stations obtained at the ICM SB RAS geoportal.

Data on PM_{25} concentrations were averaged per day for all available observation posts in the city. Thus, the average daily values of the PM_{25} concentration for the entire city of Krasnoyarsk were obtained.

3. Results and discussion

As a result, an archive of meteorological information was created according to the GFS model for the territory of the city of Krasnoyarsk for the period from 2019 to 2020. The archive includes data on the air temperature on three isobaric surfaces of 1000, 925, and 850 Mb, the height of the atmosphere's boundary layer, and wind gusts. The archive also contains information from ground-based monitoring stations on the average daily concentrations of PM_{25} particulate matter suspended in the air and wind speed.

3.1. Analysis of temperature inversions and periods of high atmospheric pollution in Krasnoyarsk

Based on the analysis of air temperature data at various vertical levels, the number of days was compared with temperature inversions by month for 2019 and 2020 (Figure 2, a). You can pay attention to the fact that in April, May, and November, the number of days with inversions is greater in 2020, in the remaining months in 2019, there are more days with temperature inversions, except for March when both in 2019 and in 2020 their number was the same and equal to 10 days.

A comparison of the number of days during which the average daily concentration of PM_{25} exceeded the average daily MPC by month for 2019 and 2020 is shown in Figure 2, b. In 2019, there were more days with pollution of the atmosphere than in 2020 by 15 days.

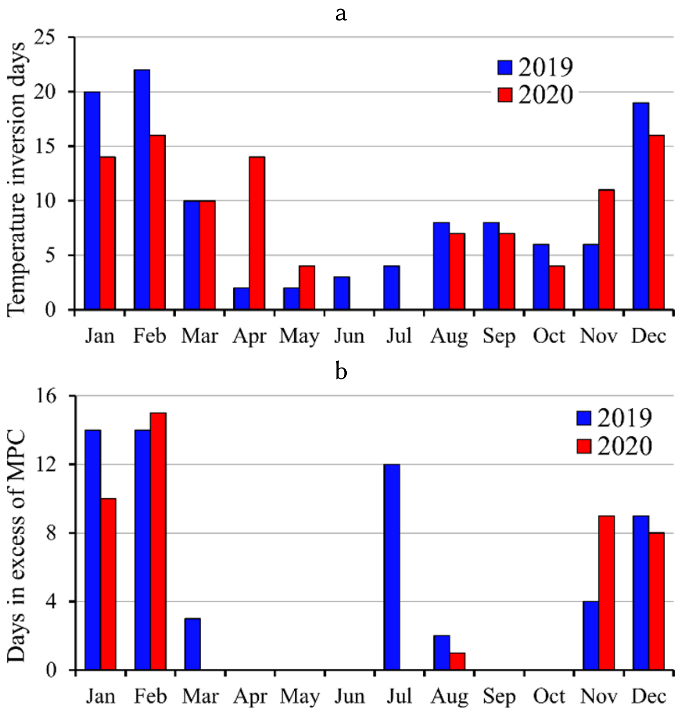

Figure 2: The environmental situation in Krasnoyarsk by month in 2019 and 2020. a — distribution of the number of days with a temperature inversion; b — distribution of the number of days with an average daily concentration of PM_{25} exceeding the average daily MPC.

Table 2 provided information on the total number of days with temperature inversions and periods when the average daily concentration of PM_{25} exceeded the average daily MPC in 2019 and 2020.

The number of days of the study period is 731 days. Of these, 29% are days with a temperature inversion, and 14% are days with a high concentration of PM_{25} in the city's atmosphere.

The total duration of days in the UMC periods indicated in Table 1 was 47 days. Of these, the days when PM_{25} pollution exceeded the average daily MPC is 38.

Monthly comparison of the number of days characterized by an average daily concentration of PM_{25} exceeding the average daily MPC and the number of days with the same characteristic, but with the existence of a temperature inversion for 2019 and 2020, was carried out (Figure 3). The months when increased air pollution was not recorded are not displayed.

Table 2
The number of days with temperature inversions and periods of PM_{25} pollution in Krasnoyarsk in 2019 and 2020.

Total number of days	2019	2020
With temperature inversion	110	103
With atmospheric pollution	58	43

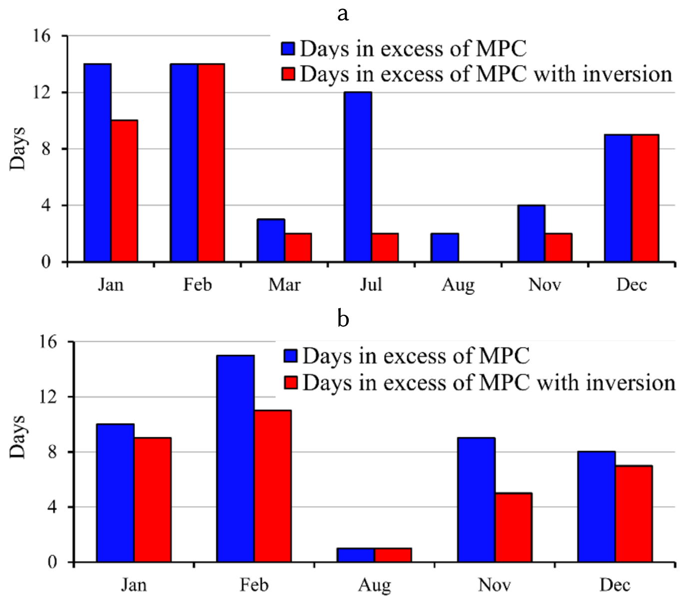

Figure 3: Monthly comparison of the number of days with an increased pollution level and with a temperature inversion for 2019 (a) and 2020 (b).

In 2019, increased atmospheric pollution was observed for 7 months; in 2020, during 5 months. Data analysis showed that in 2019, the difference between the number of days characterized by the average daily concentration of PM_{25}, exceeding the average daily MPC, and the number of days with the same characteristic, but with the existence of a temperature inversion, was 19 days. A big contribution to this difference was made by July when 12 days with increased atmospheric pollution were registered, while there were only 2 days with a temperature inversion in such a period; this is due to non-regular reasons — smoke from remote forest fires that covered the city at this time. In 2020, the difference was 10 days.

3.2. The relationship of meteorological parameters with periods of high air pollution

Data analysis showed a stable relationship between changes in the average daily concentration of PM_{25} particulate matter suspended in the air and wind gusts according to the GFS model. As an example, this relationship is presented for February 2020 (Figure 4).

In Figure 4, the orange stripe indicates the period when the concentration of PM_{25} exceeded the average daily MPC. The blue stripe indicates the official periods of UMC. Temperature inversions were observed on all days in the selected periods, except for February 5 and 26, as well as PM_{25} high concentrations. It is shown that when the wind speed increases, the level of pollution decreases and vice versa.

The level of correlation between the wind speed obtained from the data of the ground monitoring station and wind gusts according to the GFS model is 0.82.

The variation of the height of the planetary boundary layer of the atmosphere is compared with the wind speed obtained from the data of the ground monitoring station. The correlation

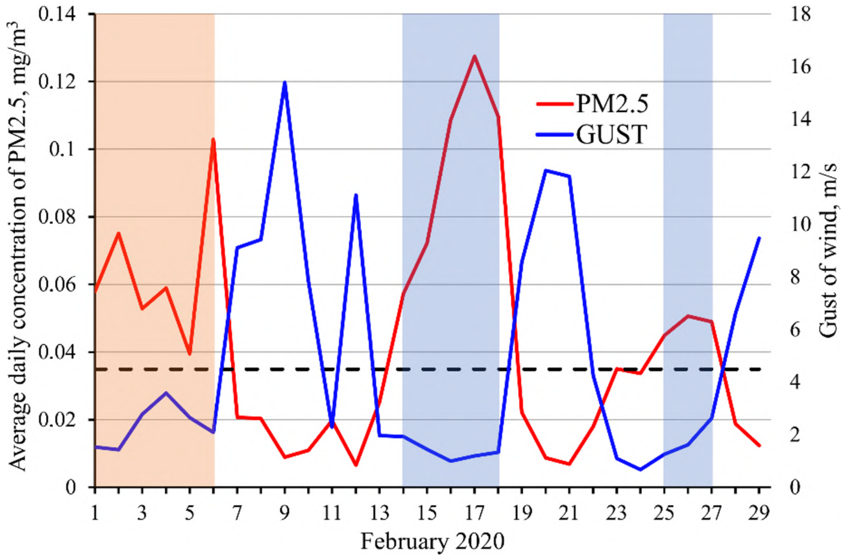

Figure 4: The meteorological situation in Krasnoyarsk in February 2020. The red graph indicates the change in the average daily concentration of PM_{25}. The blue graph indicates the change in the speed of wind gusts. The dotted line indicates the average daily MPC equal to 0.035 mg/m^3.

coefficient was 0.79. This is because, at high wind speed, the atmosphere's stability decreases, turbulence increases, which leads to an increase in the height of the boundary layer [12].

4. Conclusions

As a result of the work done, the relationship between temperature inversion in the surface layer of the atmosphere and the periods of significant air pollution by PM_{25} solid particles in the city of Krasnoyarsk in 2019 and 2020 was shown.

The largest number of days with a temperature inversion is observed in the cold period (December, January, February), the smallest — in the warm season (May, June, July). In 2019, inversions were registered in all 12 months of the year, and in 2020, there were no inversions only in June and July.

The total number of days with an inversion of air temperature in 2019 was 110 and in 2020 — 103. The total number of days with inversion was 29% of the number of days of the entire study period. The most common type of inversion is surface or elevated.

The greatest number of days with the average daily concentrations of PM_{25} particulate matter suspended in the air, exceeding the average daily MPC, were recorded in the cold season (December, January, February). In April, May, June, September, and October, periods of significant air pollution were not recorded in 2019 and 2020.

The total duration of the days of the UMC periods was 47 days. Of these, the days when the PM_{25} pollution exceeded the average daily MPC is 38.

The total number of days with polluted air in Krasnoyarsk in 2019 is 58. Of these, 39 days during the temperature inversion. In 2020 — 43 days, of which 33 days during the temperature inversion, the total number of days with average daily concentrations of PM_{25} exceeding the average daily MPC was 14% of the number of days of the entire study period.

The relationship between changes in wind speed and the height of the atmospheric boundary layer with changes in the average daily PM_{25} concentration in Krasnoyarsk in February 2020 is shown. As the wind speed increases, the level of pollution decreases, which is also true in the opposite direction.

The correlation between the wind speed obtained from the data of the ground monitoring station and the wind gusts obtained from the data of the GFS weather forecast model is 0.82. The difference between the wind speed and the height of the boundary layer is 0.79. Data on the height of the boundary layer can serve as an additional indicator when studying UMC periods in Krasnoyarsk.

The analysis of meteorological data of the GFS model contributes to solving problems related to the study of the lower layer of the atmosphere, its pollution and can play an important role in more accurately identifying periods of unfavorable meteorological conditions and forecasting them.

References

[1] G. Zarubin, Y. Novikov, Hygiene of the city, Medicine, Moscow, 1986.

[2] Y. Kaufman, D. Tanré, O. Boucher, A satellite view of aerosols in the climate system, Nature 419 (2002) 215–223. doi:10.1038/nature01091.

[3] A. Becker, T. Agaev, Protection and control of environmental pollution, Gidrometeoizdat, Leningrad, 1989.

[4] A. Eremkin, I. Kvashnin, Y. Junkerov, Standardization of emissions of pollutants into the atmosphere, Publishing house of Ass. builds. universities, Moscow, 2001.

[5] L. Matveev, General meteorology course. Atmospheric Physics, Gidrometeoizdat, Leningrad, 1984.

[6] E. Bezuglaya, G. Rastorgueva, I. Smirnova, What does an industrial city breathe?, Gidrometeoizdat, Leningrad, 1991.

[7] V. Zuev, N. Krasnenko, V. Fedorov, M. Fursov, Acoustic sounding of the atmospheric boundary layer, Dokl. Akad. Nauk SSSR 257 (1981) 1092–1096. URL: http://mi.mathnet.ru/eng/dan44384.

[8] The Global Forecast System (GFS) Documentation, 2021. URL: https://is.gd/KJHKbK.

[9] Unfavorable meteorological conditions in Krasnoyarsk. regional departmental information and analytical data system on the state of the environment of the Krasnoyarsk Territory, 2021. URL: http://www.krasecology.ru/Nmu.

[10] NCEP WMO GRIB2 Documentation, Version 23.0.0, 2019. URL: https://www.nco.ncep.noaa.gov/pmb/docs/grib2/grib2_doc/.

[11] wgrib2: Utility to read and write grib2 files, 2021. URL: https://www.cpc.ncep.noaa.gov/products/wesley/wgrib2/.

[12] Y. Wang, H. Sayit, A. Mamtimin, J. Zhu, C. Zhou, W. Huo, F. Yang, X. Yang, J. Gao, X. Zhao, Evaluation of five planetary boundary layer schemes in WRF over China's largest semi-fixed desert, Atmospheric Research 256 (2021). doi:10.1016/j.atmosres.2021.105567.