Parametrization of temperature inversion over Krasnoyarsk city

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Abstract. Atmospheric pollution is associated with weather conditions. Meteorological processes make a significant contribution to the creation of unfavorable meteorological conditions (NMU). NMUs are a special short-term combination of meteorological factors contributing to the accumulation of pollutants in the surface layer of atmospheric air. We draw a particular attention to the temperature stratification of the lower layers of the atmosphere which can cause a temperature inversion – an increase in air temperature with altitude. Temperature inversion limits the vertical dispersion of harmful impurities in the atmosphere. Observational data show that the increased level of air pollution in the city of Krasnoyarsk is most pronounced in winter with temperature inversion and weak winds (no more than 1-2 m/s). To predict periods of increased concentration of pollutants in the boundary layer of the Krasnoyarsk atmosphere we consider a numerical algorithm for determining the time intervals of formation and destruction of temperature inversion based on a one-dimensional vertical model.

1 Introduction

High concentrations of pollutants are observed over large settlements. Studies of atmospheric air over the cities of Moscow, Tomsk, Perm are devoted to works [1-3]. The most polluted cities include Krasnoyarsk. It is possible to assess the impact of various types of emission sources on the formation of unfavorable conditions by use of modern calculation models for the transport of impurities in the atmosphere, analysis of ground and satellite measurements and data re-analysis [4-8].

Weather conditions have a significant impact on the concentration, transfer and dispersion of impurities in the atmosphere. The highest influence is caused by wind and temperature modes, precipitation, and solar radiation. The main processes that ensure air mixing in the lower atmosphere are: 1) temperature gradient and 2) turbulence associated with the interaction of wind with the underlying surface. Temperature inversions are of a particular interest. Temperature inversion - an increase in air temperature with height instead of the usual decrease. Temperature inversion prevents vertical air movements and contributes to the formation of smog. Inversion is highly dependent on the local features of the relief. The increase in temperature in the inversion layer ranges from tenths of a degree

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to 15-20° and more. Surface temperature inversions in winter are the most powerful. If the temperature increase begins directly from the surface of the earth, the inversion is called *surface*, if from a certain height above the surface – *raised*.

Mesoscale mathematical models are used to calculate weather over a limited area with a sufficiently high resolution [2, 9, 10]. Mesoscale models include, as a rule, non-stationary three-dimensional equations of hydrothermodynamics and differ in different approaches to parametrization of atmospheric processes.

Mesoscale models have become widespread - Fifth-Generation Mesoscale Model (MM5) were developed at the University of Pennsylvania and NCAI USA and Weather Research and Forecast Model (WRF) were developed by NCAI and NCIOS USA. The papers [2, 9, 10] consider the effect of temperature inversion on the accumulation of pollutants in the atmospheric air. The computer implementation of mesoscale meteorological models is based on the use of non-trivial computational algorithms and requires the use of high-performance computing resources.

2 The data and the methods

Observation data show that the increased level of air pollution in Krasnoyarsk is most evident in winter in the absence of wind. Weather forecasting from global models provides information on air temperature, pressure, direction and the speed of wind near the surface of the earth and at high altitudes – 500, 750, 1000 or more meters over the surface. Therefore, a simplified one-dimensional vertical model is proposed to determine the time intervals for formation and destruction of temperature inversion.

Initial data: short-term forecast (for 4-5 days) of air temperature, pressure and wind. The theoretical basis of the temperature inversion model is the heat inflow equation for weak winds. For adiabatic processes in the atmosphere, the heat influx equation has a form:

$$\frac{\partial T}{\partial t} = -w\left(\frac{\partial T}{\partial z} + \beta_a\right) \tag{1}$$

Here $T\,(t, z)$ is the air temperature (^{0}K), β_a is the adiabatic temperature gradient, t is the time, z is the vertical coordinate, w is the parameter characterizing vertical movements.
Pressure and density are related by the hydrostatic approximation

$$\frac{\partial p}{\partial z} = -\rho g, \tag{2}$$

Temperature, pressure and density are related by the equation of state:

$$p = \rho R T \tag{3}$$

An adiabatic process is a thermodynamic process in a macroscopic system in which the system does not exchange thermal energy with the environment.

For adiabatic processes, Poisson's formula holds:

$$\left(\frac{T}{T_0}\right) = \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}. \tag{4}$$

Initial conditions are:

$$T\big|_{t=0}=T^{0}(z) \tag{5}$$

Boundary conditions at the lower boundary:

$$T\big|_{z=0}=T_0(t)\,,\quad p\big|_{z=0}=p_0(t) \tag{6}$$

The boundary conditions at the upper boundary z = H are obtained using relations (2-4):

$$\begin{aligned}\frac{\partial T_H}{\partial t}&=-w\left(\frac{\partial T}{\partial z}\bigg|_H+\beta_a\right)+\\&+\frac{\gamma-1}{\gamma}\frac{T_H}{p_H}\left[\left(1-\frac{\beta_a\cdot H}{T_0}\right)^{\frac{\gamma}{\gamma-1}}\frac{dp_0}{dt}+\frac{\gamma}{\gamma-1}\frac{\beta_a\cdot H}{T_0^2}p_0\left(1-\frac{\beta_a\cdot H}{T_0}\right)^{\frac{1}{\gamma-1}}\frac{dT_0}{dt}\right]+T_a.\end{aligned} \tag{7}$$

Here p is the pressure, ρ is the density, g is the gravitational acceleration, R is the gas constant, γ is the adiabatic index, H is the height of the atmosphere layer under consideration, Δt is the time step, and T_a is the calibration parameter responsible for the external impact at the upper limit.

An additional initial condition is set to define the model parameter w

$$T\big|_{t=Dt}=T^{Dt}(z) \tag{8}$$

From (1) and (8) we obtain:

$$w=-\frac{(\partial T/\partial t)_{av}}{\beta_a+(\partial T/\partial z)_{t=0}} \tag{9}$$

Where $(\partial T/\partial t)_{av}$ is the average vertical derivative.

The numerical solution of the problem (1) is obtained by the explicit Lax scheme:

$$T_j^{n+1}=0.5(T_{j+1}^n+T_{j-1}^n)-\Delta t\cdot w\left(\frac{T_{j+1}^n-T_{j-1}^n}{z_{j+1}-z_{j-1}}+\beta_a\right) \tag{10}$$

Calibration of the parameter T_a requires additional information about the solution. At $z = H$ on the days of prediction:

$$T\big|_{z=H,t=t^n}=T_{H^n{}_i} \tag{11}$$

The calibration was performed by firing. Given initial conditions, a direct problem (1), (5)-(7) was solved. The calculated values were compared to the given values (8). Calibration results have to satisfy the inequality $\left|T\big|_{z=H,t=t^n}-T_{H^n{}_i}\right|\le\varepsilon$.

3 Results and Discussion

The purpose of this work is to assess the characteristics of temperature inversions in the boundary layer of the atmosphere of Krasnoyarsk. We propose to evaluate the thermal structure of the atmospheric boundary layer in Krasnoyarsk using the semi-empirical algorithm described above. Verification and calibration of the algorithm was carried out using the data on air temperature in Krasnoyarsk in December 2021, which was obtained from the stationary profile meter of the Krasnoyarsk Scientific Center of MTR-5 (manufactured by NPO ATTECH) located in the city center. During this time period, a powerful inversion with intensity of more than 20ºC was observed in Krasnoyarsk.

Data on air temperature up to 100 m with increments of 25 m and up to 1000 m increments of 50 m and discreteness of one hour can be obtained from the profile meter. We also used information on air temperature from the website www.ventusky.com, which presents the forecast values obtained from the mesoscale models (GFS, ICON, etc.). Table 1 shows the average daily wind speed, the daily air temperature values measured by the profiler (*Tp_*) and taken from the ventusky-website GFS model (*Tv_*) site, as well as calculated according to the proposed model (*Tcl_*) and the result of calibration of the *Ta* parameter.

We considered several test problems about the formation and destruction of temperature inversions in the atmosphere over the city. As a result, three groups of characteristic time intervals were identified: no inversion (December 13-19), formation of inversion (December 20-24), and destruction of inversion (December 25-30). We compiled the tables of input parameters and calibration results.

Table 1. Wind speed, air temperature according to www.ventusky.com (*Tv*) and profile meter (*Tp*) and calculated values (*Tcl* , *Ta*) at December 2021, Krasnoyarsk.

	Wind (m/s)	***Tv***		***Tp***		***Tcl***	***Ta***
		surface	**H=500m**	**surface**	**H=500m**	**H=500m**	
13 Dec 21	1	-16	-18	-14.97	-21.93	-17.7	-0.75
14 Dec 21	1	-14	-17	-18.10	-20.81	-22.6	0
15 Dec 21	2	-17	-20	-20.63	-22.09	-22.2	0.5
16 Dec 21	4	-10	-11	-7.85	-13.43	-17.3	0.8
17 Dec 21	4	-7	-8	-5.62	-11.88	-10.15	-0.5
18 Dec 21	4	-4	-5	-2.42	-8.47	-12.24	0.8
19 Dec 21	2	-11	-13	-8.15	-15.27	-11.13	-0.5
20 Dec 21	2	-19	-23	-19.35	-20.07	-20.67	1
21 Dec 21	1	-19	-21	-23.41	-22.55	-24.76	0.5
22 Dec 21	1	-20	-17	-21.87	-18.29	-22.15	2.5
23 Dec 21	2	-20	-18	-23.15	-15.07	-15.26	1
24 Dec 21	2	-18	-11	-22.04	-9.23	-9.75	1
25 Dec 21	1	-11	-6	-14.64	-4.40	-4.2	0.75
26 Dec 21	1	-12	-11	-19.93	-6.89	-11.98	2
27 Dec 21	1	-12	-11	-18.66	-14.00	-9.38	1
28 Dec 21	2	-8	-9	-11.77	-9.58	-10.23	0.5
29 Dec 21	2	-7	-6	-6.29	-6.71	-7.72	-1
30 Dec 21	3	-9	-10	-5.60	-11.41	-6.26	-1

According to natural data, the temperature inversion occurred on December 20 (at 3:00) with the intensity of $\Delta T = 2–10\ ^0$C. According to the proposed algorithm, the inversion was formed on December 19 (at 18:00) with the intensity of 1–3 degrees.

Figures 1 - 3 show the graph of measured and calculated air temperatures at different altitudes for the selected time intervals.

Figure 4 shows the measured and calculated vertical air temperature profiles for some dates.

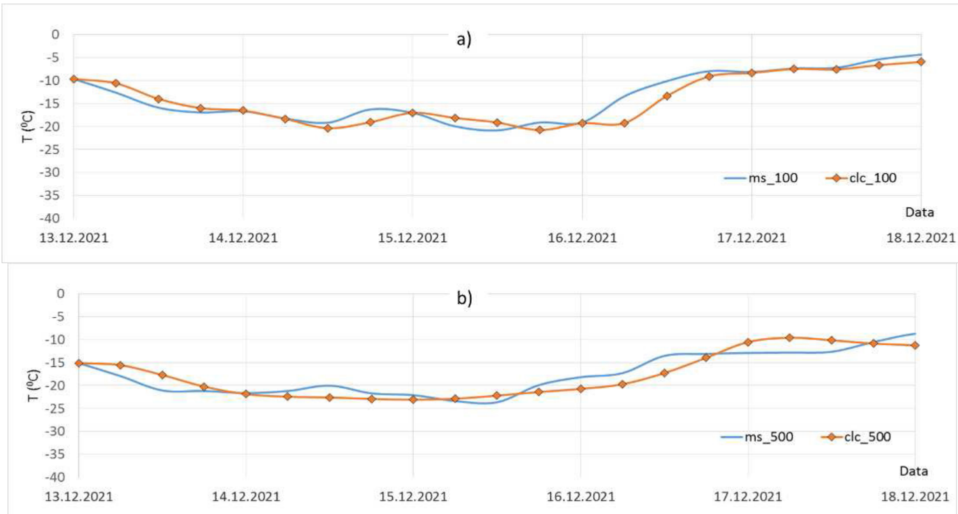

Fig. 1. Measured (profiler) —— and calculated —◆— air temperature during the period of no inversion for altitudes of 100 (a) and 500 m (b).

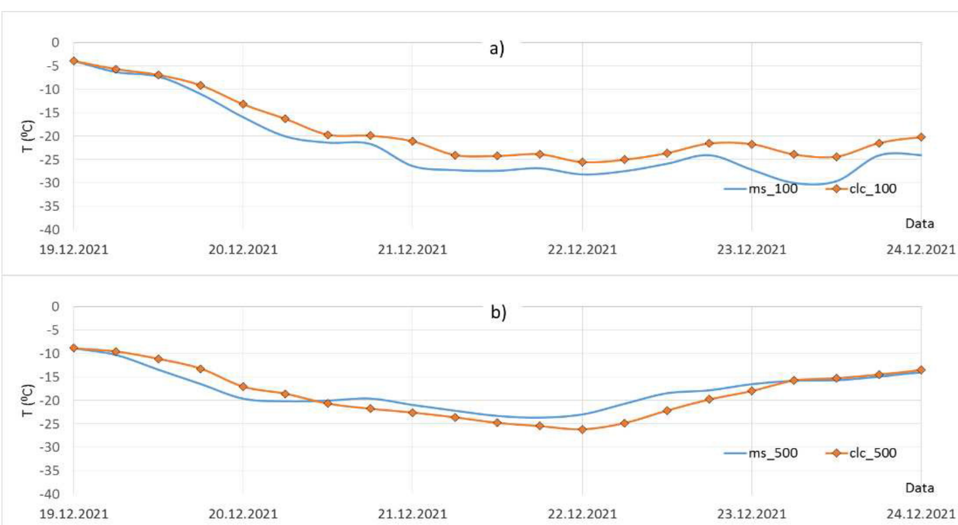

Fig. 2. Measured (profiler) and calculated air temperature during the period of inversion formation for altitudes of 100 and 500 m.

Fig. 3. Measured (profiler) —— and calculated —◆— air temperature during the period of inversion destruction for altitudes of 100 and 500 m.

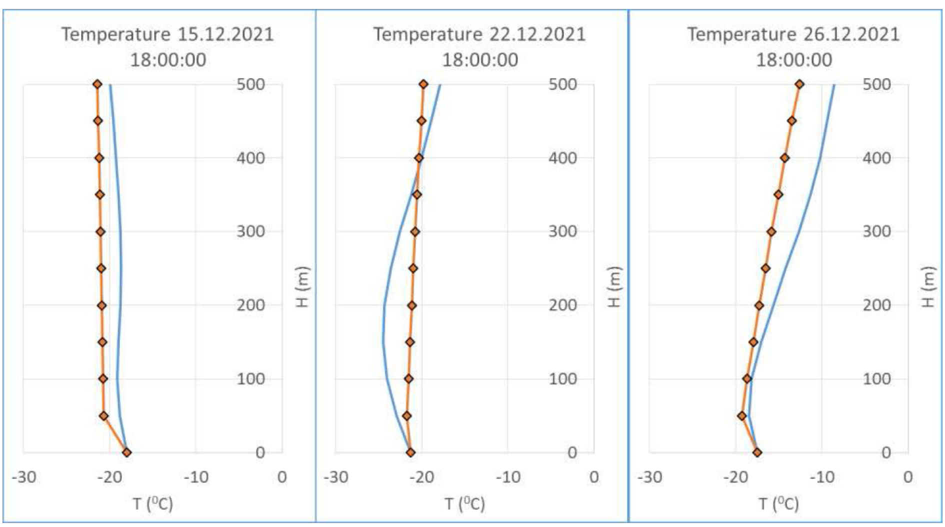

Fig. 4. Vertical profiles of measured (profiler) —— and calculated —◆— air temperature.

4 Conclusion

There is no information on vertical temperature profiles in weather forecasts. The proposed method allows us to determine from the weather forecast whether a temperature inversion will occur or collapse. It became possible to use the data of supercomputer modeling of the atmosphere in winter for joint analysis with the results of numerical experiments on a simplified model.

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