Analysis of observations and results of numerical modeling of meteorological parameters and atmospheric air pollution under weak wind conditions in the city of Tomsk

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ABSTRACT

The results of calculation of meteorological parameters using a meteorological model, TSU-NM3, as well as prediction of some indices of atmospheric air pollution in the city of Tomsk obtained from a mesoscale photochemical model are presented. The calculation results are compared with observational data on the atmosphere and pollutants.

Keywords: Air pollution, Weak wind condition, Numerical weather prediction, Photochemical model

1. INTRODUCTION

Air pollution in cities depends on many factors. Among the most significant are: emissions from industrial enterprises, vehicles and meteorological parameters, i.e., direction and velocity of wind, air temperature, temperature stratification, fogs, and precipitation determined by synoptic conditions. Besides, the spread of pollutants is to a considerable degree dependent on local physical and geographical conditions, on the heights of buildings, width and direction of streets, vegetation and water bodies. These factors and terrain obstacles for air flow cause specific meteorological conditions in the city.

The Russian Agency on Hydrometeorology and Environmental Monitoring performs short-term physical and statistical predictions of atmospheric pollution in Russian major cities. They are based on predictions of synoptic conditions, pressure fields, which determine wind characteristics, temperature and moisture in the lower part of the atmospheric boundary layer, which form a pollution background. The predictions of unfavourable meteorological conditions that produce high pollution levels are of special concern.

The numerical weather prediction systems in national forecasting centers have become popular. It is possible to use results of forecasts to predict atmospheric air quality. The modern advanced prediction technologies are based on regional atmospheric models that take into account the parameters of the atmosphere, dispersion and precipitation of basic pollutants including pollution from vehicles. In Europe, for instance, the EURAD (http://db.eurad.uni-koeln.de) system is composed of three models: a mesoscale model, MM5, which makes an assessment of meteorological conditions, the EURAD-CTM model, which predicts chemical processes and transport of pollutant components in the atmosphere, and the EEM-EURAD model, which takes into account the emission of pollutant components into the atmosphere. The system is used both to simulate some cases of air contamination and to make a short-term prediction of air quality in Europe. The calculation of ozone concentration and of some other photochemical pollutants is of special attention in addition to sulfur and ammonia. The system is also used to assess mean daily concentrations of basic pollutants in the European troposphere.

At the Hydrometeorological Centre of Russia modeling systems, WRF/CHIMERE and COSMO-Ru7-ART, are in operating regular computation mode. Calculations are made for central regions of European Russia. The concentration of various pollutant substances (CO, NO_x, O_3 and others) in the atmosphere is assessed 2–3 days ahead (with 1-hour increments). A prognostic map is constructed to ground level concentrations of some pollutant components as well as air temperature, wind velocity and direction.

Testing of the modern numerical prediction models of air pollution shows their errors are in agreement with the physical and statistical methods, used in them, and are caused by the errors in temperature and wind forecasts in the boundary atmospheric layer [1]. The accutacy of the temperature-and-humidity predictions gives a possibility to predict the

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conditions of atmospheric contamination and pollution intensity. Under conditions favourable for air pollution, an accurate computation of temperature and wind characteristics is required. One of the advantages of numerical modelling of atmospheric processes is that it gives a possibility to make detailed investigation of some processes in time and space.

It is now very important to develop new hydrodynamic atmospheric models and improve the existing ones in order to predict meteorological conditions, as well as atmospheric pollution for various components with the required time and high resolution.

To solve this problem, at Tomsk University a modeling system has been developed to incorporate a mesoscale non-hydrostatical model, TSU-NM3 [2], used to predict meteorological fields and a photochemical model [3], which, based on calculated meteorological fields can be used to assess the dispersion of pollutants from sources located within the city of Tomsk. The meteorological model uses a 1 km horizontal resolution and 30 vertical levels. It contains seven land use categories: water surface, surface with modest vegetation, farm land, decidious forest, mixed forest, and coniferous forest, urban area. These categories have the following parameters: roughness height, albedo, thermal-physical properties of the soil, evaporation, emissivity, and temperature at a depth of 2-meters (for the soil). The anthropogenic heat flux is calculated by the following formula: $Q_{urban} = 4.187(5 + 7\max(\sin(\pi(t-6)/18), 0.0))$ W/m^2.

The simulation domain is 50 km square 50 km with the city at its center. To simulate pollution transport the domain is split into 10^4 squares of 0,5×0,5 km in size. About 1500 squares are within Tomsk. The rest of the squares are located in the Tomsk territory. Data on the topography and land use, data on emissions from vehicles and industrial enterprises are used for simulations. Emissions of 17 substances, i.e., dust, soot, CO, SO_2, NO_2, NO, CH_2O, C_6H_5OH, CH, C_7H_8, C_8H_{10}, CH_3OH and some others are used.

The predictability of the meteorological model is validated on data from the TOR station of SB RAS [4] (eastern outskirts of the city), meteorological station WXT520, microwave temperature profiler, MTP-5, of the Institute of Monitoring of Climatic and Ecological Systems, SB RAS [5] and observations at the AMSG civil aviation meteorological station in the vicinity of Tomsk Airport (south-eastern outskirts of the City) as well as the “Tomsk South” meteorological station (#29430, 56°26'N 84°58'E, southern part of the city). The photochemical model calculation results are assessed using data of observational stations for atmospheric air pollution located in Tomsk and observational data from a TOR-station and base experimental complex of the Institute of Atmospheric Optics, SB RAS. The base experimental complex of the Institute of Atmospheric Optics, SB RAS monitors the meteo-values, gas and aerosol composition of the air in the Earth’s boundary layer [4].

The purpose of this work is to use this modeling system to investigate the meteorological situation and atmospheric air quality in the city of Tomsk under conditions of weak wind and compare the results with some observational data of October, 2012.

2. RESULTS AND DISCUSSION

Accordingly to observations made at the TOR station of the Institute of Atmospheric Optics, SB RAS in October, 2012, the following time periods of low wind within 24-hours have been recorded: October 1–3, 10–11, 13–16 and 25, 2012. October 10–11 and 13-14 are selected for simulation. The results and the analysis are performed in terms of local time.

Weather conditions

On October 10-11, 2012 the weather was cloudy without precipitation. At night and before noon low-level clouds were observed after 15:00, they gradually ascended to an upper level, and after 18 hours clear sky was observed. The air temperature ranged from -2 ºC at night to 3 ºC in the daytime, the atmospheric pressure raised from 758 mm at the beginning of a 24-hour period to 760 mm at the end of a 24-hour period. Wind velocity during the 24-hour period ranged from 3 to 5 m/sec; wind direction from north-west gradually changed to west in the afternoon, with a reduction in the wind velocity. Approximately the same weather was observed at a civil aviation meteorological station AMSG located at Tomsk Airport. Note, that the maximal temperature in the down town was 1,2 ºC higher than that at the outskirts. The minimal temperature was 0,8 ºC higher than that at the civil aviation meteorological station AMSG.

Fig. 1 presents calculated and measured values of the following meteorological parameters near the underlying surface: wind direction and velocity at the 10-m height, as well as air temperature and humidity at the 2-m height in downtown Tomsk and at Tomsk Airport, which is located in the south-east direction about 25 km from the city. Calculations and observations obtained by the TOR station instruments and at the “Tomsk South” hydro-meteorological station show that a temperature maximum was observed at about 16 hours local time. The wind velocity varied from 1 to 3 m/sec during a 24-hour period with a wind directed to the north-west. At about 18 – 22 hours the wind velocity dropped to less than 1 m/sec.

In general, the calculation results are in a satisfactory agreement with the observations on all of the meteorological parameters. The prognostic values for maximum temperature are slightly higher than the observations. The prognostic values of wind velocity at some periods are 1-3 m/sec lower than the actual ones, while the wind direction values and observations coincide within the statistical error range of the observations. The model slightly changes the 24-hour course of the relative humidity, raising it in the morning and daytime and lowering it at night.

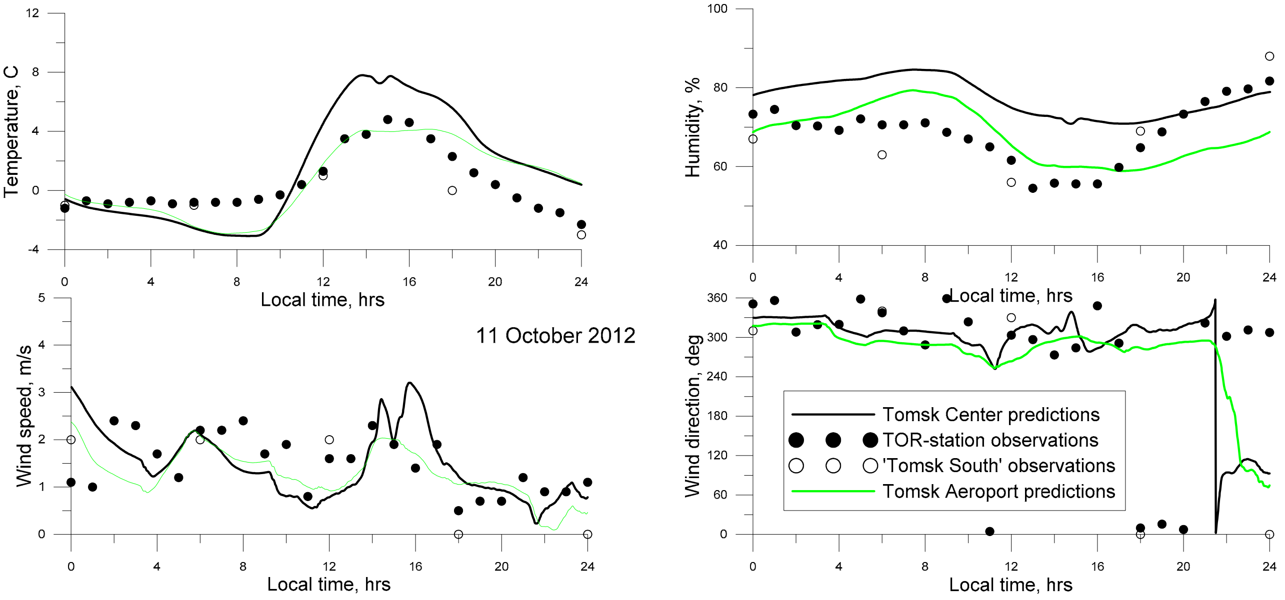

Figure 1. Velocity, wind direction, surface temperature and moisture during 24-hours of October 11, 2012.

According to automatic measurements by a microwave temperature profiler, MTP-5 [5], the vertical temperature profile on October 11, 2012 was characterized by a raised temperature inversion or isothermal conditions at a level of 600-meter and higher starting from 8 o’clock. At some short time intervals the inversion appeared and disappeared. After 18 hours l.t. a near ground surface temperature inversion appeared and persisted in a 50m to 100m layer till the end of the 24-hour period (Fig. 2). The temperature increase in the inversion layer was up to 1,5 ºC. The temperature stratification worsened the ecological situation after 18 hours.

Figure 3 presents surface concentrations of carbon monoxide, ozone, nitrogen dioxide and changes in the air quality index of near surface air. Surface air quality was defined by an aggregate air pollution factor of $AQIndex = \sum_{i=1}^{5} \frac{c_i}{c_{i\infty}}$, where c_i are the calculated pollutant concentrations; $c_{i\infty}$ are instantaneous maximal admissible concentrations, $i=CO, O_3, NO, NO_2, SO_2$. The calculation results are compared with measurements made at the TOR station of the Institute of Atmospheric Optics, SB RAS. The comparison shows that in evening hours of October 11, 2012 a wind decrease was accompanied by a near surface temperature inversion, a growth of the concentrations of basic pollution components near the surface was both observed and numerically predicted. The low wind slows down the pollutant removal while the near ground surface temperature inversion decreases the turbulent mixing in the surface layer thereby causing an accumulation of pollutants in the lower layer. Moreover, according to Figure 3, the changing air quality index of the near surface air during the 24 hours of October 11, 2012 caused the lowest air quality in the center of the city to be appreciably worse between 18 and 24 hours. However, the air pollution in Tomsk was rather low during the time of investigations [6].

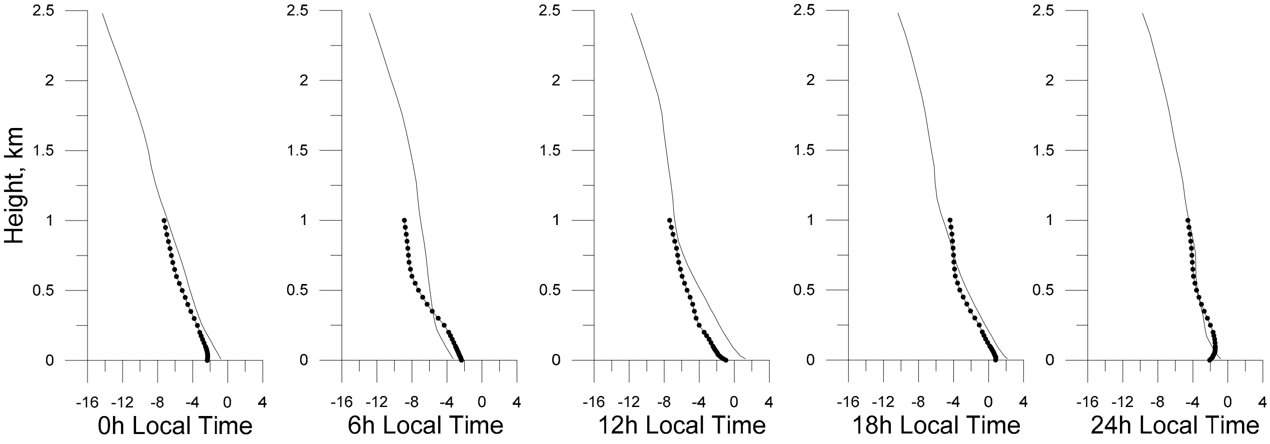

Figure 2. Vertical temperature profile in downtown Tomsk (solid lines are calculated temperatures) and at Tomsk Airport (dots are measurements by MTP-5) on October 11, 2012.

In a second case (October 13 – 14, 2012) selected for the survey, clear sky was observed at the beginning of a 24-hour period, later high-level clouds appeared and in the daytime the sky was cloudy with high-level and medium-level clouds (Ac, As). The air temperature changed from -3 – -5 ºC at night to 5–8 ºC in the daytime (Fig.4). By the end of the period the temperature increased by 2–5ºC. Atmospheric pressure was 765–758 and it gradually dropped down during the period; the wind was southerly, low (up to 3–4 m/sec in the daytime, from zero wind to 2 m/sec at night and in the morning). On October 14 the maximal air temperature in the city was 1,1 ºC higher than that at AMSG of the Tomsk Airport while the minimal temperature was 0,8 ºC higher than that in the city. Thus a light urban heat island is detected, which is more expressed in the daytime.

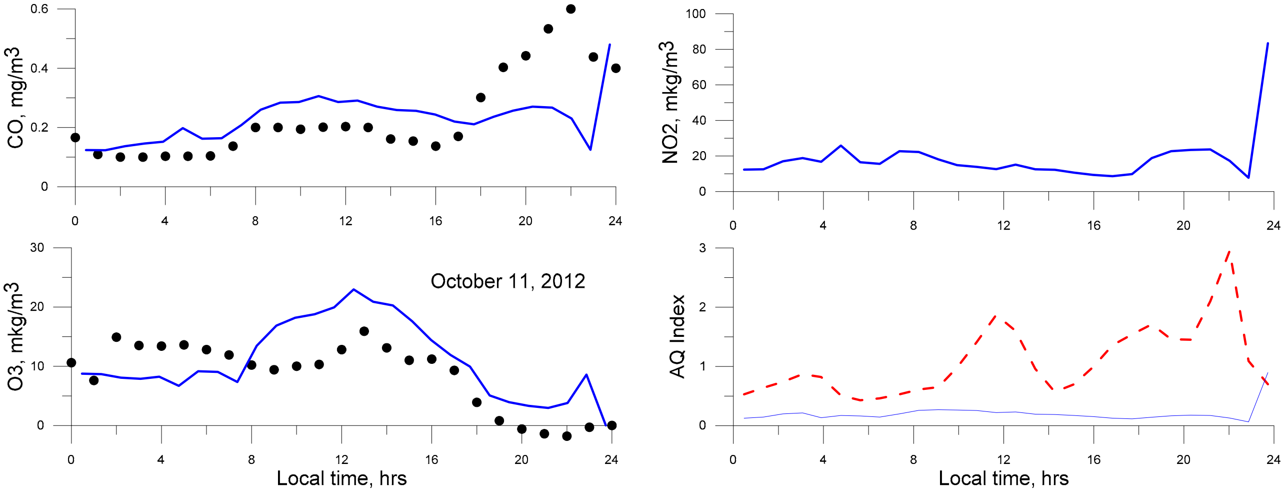

Figure 3. Concentrations of basic components of pollution (CO, O_3, NO_2) in the vicinity of TOR station of the Institute of Atmospheric Optics, SB RAS during the 24-hours of October 11, 2012; dots are the measurements, lines are calculations. The dashed line shows calculated values of the air pollution index in downtown Tomsk.

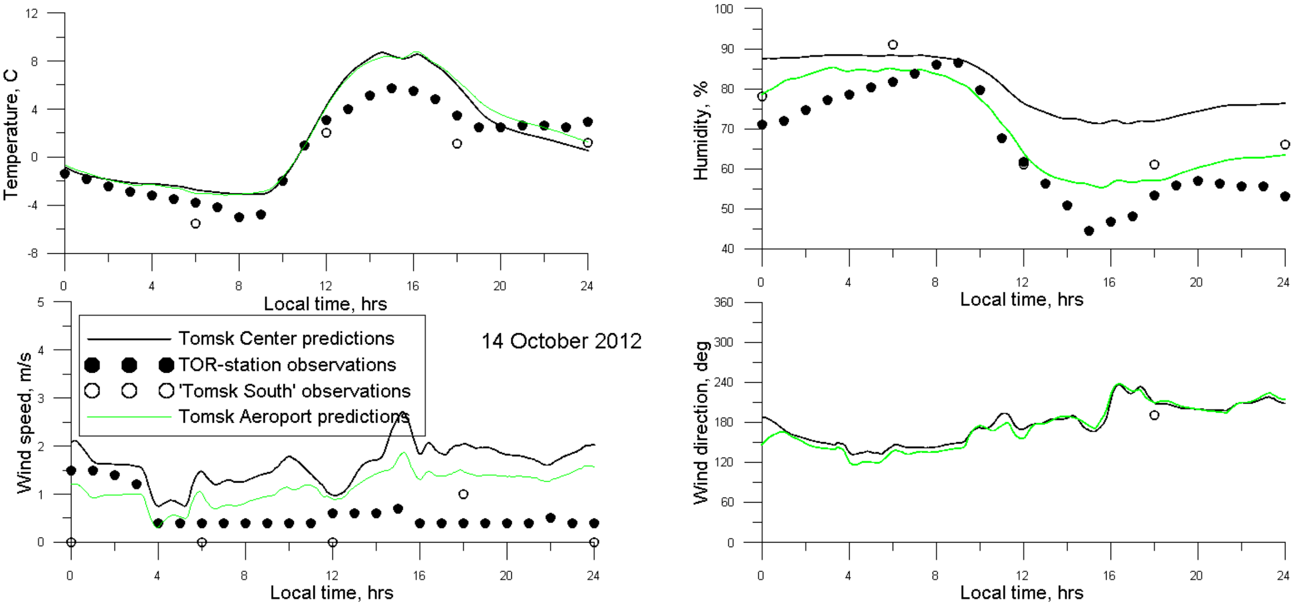

Figure 4. Wind velocity, direction, surface temperature and humidity in the city and at outskirts during the 24-hours of October 14, 2012.

According to automatic measurements by the MTP-5 of the Institute of Monitoring of Climatic and Ecological Systems, SB RAS (Fig. 5) the vertical temperature profile during the night of October 14, 2012 showed the presence of inversions in a surface layer up to 200 m and above 600 m with up to 2 ºC mean intensity, which was maximal, up to 4 ºC, in the morning. Starting from about 10 o'clock the inversion lifted due to warming of lower air layers. The height of the lower boundary increased gradually up to 100 m. In the afternoon the temperature in a lower, up to 300 m, layer decreased with height. The layer above 600 m had stable stratification. In the evening, after 18 hours, the near ground surface inversion reappeared. Thus, on October 14, 2012 the temperature stratification of the atmosphere did not prevent the accumulation of air pollutants, especially at night and in the morning.

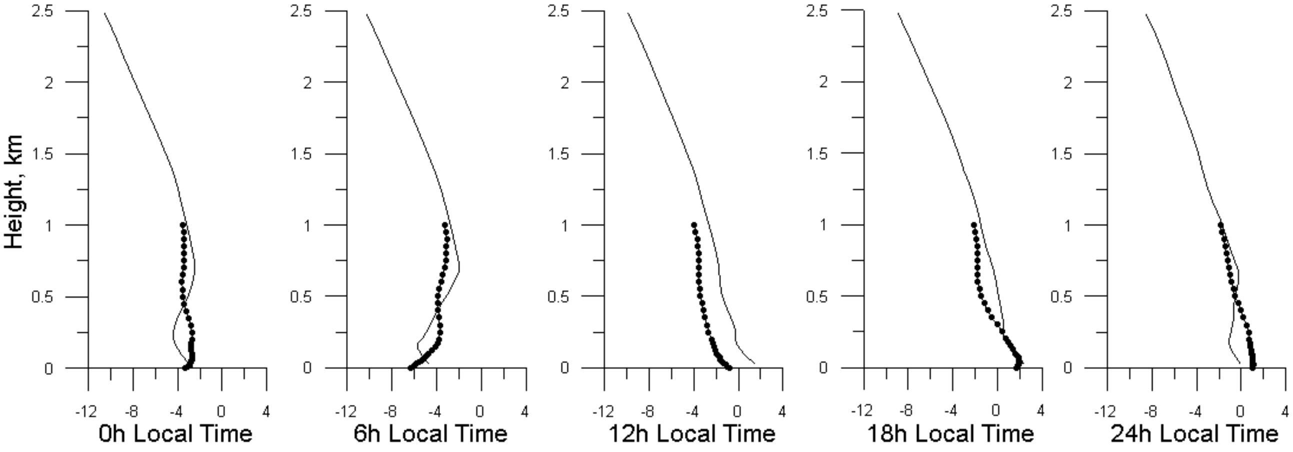

Figure 5. Vertical temperature profile in the central part of Tomsk (lines are calculated values) and near the Tomsk Airport (dots are measurements by MTP-5) on October 14, 2012.

Figures 4 and 5 show that during October 14, 2012 the agreement between calculations and measurements is good for all of the parameters. Vertical temperature profiles in the central part of Tomsk and in the vicinity of Tomsk Airport do not differ significantly in stratification and in magnitude (Fig. 4, 5). The observations by civil aviation meteorological station AMSG, at the "Tomsk South", and the calculations by the model confirm the presence of a urban heat island of insignificant intensity (1–2 ºC) in the lower layer of 100–200 m thickness with about 10 km horizontal size during a 24-hour period which is caused by city heating sources. The urban heat island was detected on a vertical section of the temperature profile from the west to the east through the center of Tomsk.

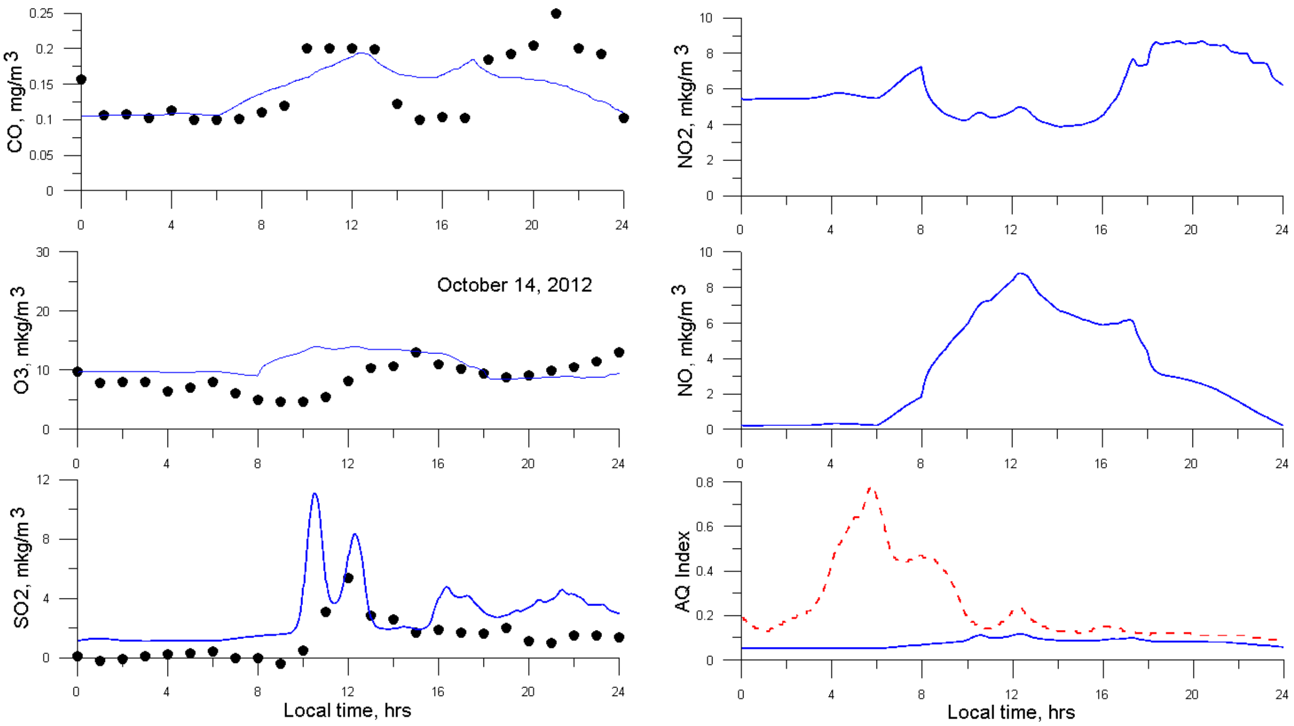

Figure 6. Concentrations of basic components of pollution at TOR station of the Institute of Atmospheric Optics, SB RAS during the 24-hours of October 14, 2012; dots are measurements, lines are calculations. The dashed line is the air quality index calculated in the central part of the city.

Figure 6 shows that in general, the modeling system provides a good agreement of calculations and observations on carbon monoxide, sulfur dioxide, and ozone at the TOR station of the Institute of Atmospheric Optics, SB RAS, with relatively low local concentrations. The modeling system shows the dominating role of zero-wind conditions in a combination with surface inversion of the temperature they play in the air quality degradation in the central part of the city (dashed line in Fig. 6)

3. CONCLUSIONS

The calculations have demonstrated that, in general, the mesoscale model gives a good prediction of the meteorological conditions including low wind in the evening of October 11, 2012 and conditions close to zero-wind in the morning of October 14, 2012. The model also gives a stable state of the atmosphere at night, in the morning and in the evening, and the deviation from the actual vertical temperature profile does not exceed 2^{o} C. The 24-hour changes in temperature, humidity and wind behaviour at the ground surface have been successfully simulated.

The photochemical model presented above also gives a good approximation of the propagation processes for various pollutants within a specific area depending on meteorological conditions. A slight effect of city's anthropogenic sources on the temperature in the city has been detected with; no impact was detected on the other meteorological parameters. The calculations show a noticeable change in the level of air pollution both by primary and secondary pollutants during 24-hours under favourable ecological conditions. Comparison of the calculations and the observations shows that there exists an increased level of pollution of surface air under weak wind in Tomsk in a combination with a near surface temperature inversion.

4. ACKNOWLEDGMENTS

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