NUMERICAL PREDICTION WITH HIGH RESOLUTION MESOSCALE MODEL AND INSTRUMENTAL OBSERVATION OF WIND CONDITIONS ABOVE CITY

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Introduction

- Wind affects all industries: on the one hand, it determines the load on buildings and other structures (especially high-rise ones); on the other hand, it causes cooling effect, especially at low temperatures.
- In addition, wind speed and direction determine air exchange and thus affect ecology of the region.
- The wind regime has a decisive influence on the dispersion of pollutants in the atmosphere.
- Areas of higher concentrations of pollutants are created in leeward areas relative to the sources of emissions

The purpose of this work is

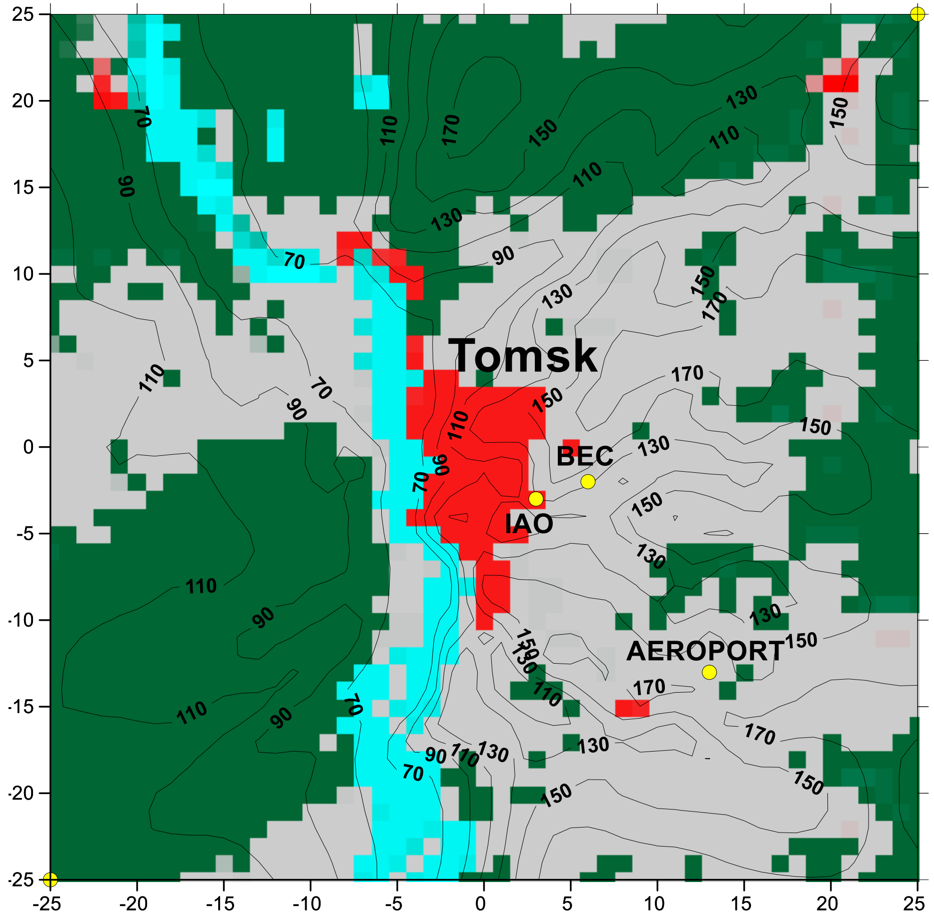
- to use the instrument base of the Research Equipment Sharing Center (RESC) "Atmosphere" of the V.E. Zuev Institute of Atmospheric Optics, Russian Academy of Sciences, Siberian Branch and the mesoscale high-resolution (1km) meteorological model TSUNM3 (Tomsk State University Nonhydrostatic Mesoscale Meteorological Model) to predict the development of extreme weather events in Tomsk and the Tomsk region caused by strong (more than 11 m/s) and weak winds (up to 1 m/s).

Tomsk city

- Tomsk is the oldest city in Siberia, the center of the Tomsk region, an educational, scientific and cultural city, the population of which with its suburbs is about 800,000 people.
- Tomsk (56.5 N, 85.0 E) is located in the east of Western Siberia on the banks of the Tom River
- The central part of the city is located at an altitude of about 120 m. To the east, the area rises up to 170 m.
- The vegetation in the surroundings is varied. The presence of large forests in the vicinity of the city (aspen, birch, fir, cedar, pine) causes a significant macro-roughness of the surface, which contributes to a slight decrease in wind velocity compared to an open area.

TSU Nonhydrostatic Mesoscale Meteorological Model (TSUNM3)

- The TSUNM3 model uses a system of non-hydrostatic equations of motion, heat, and mass transfer in the troposphere and in the upper soil layer.
- TSUNM3 forecasts the components of wind speed, turbulent kinetic energy, and temperature and humidity characteristics in the atmospheric boundary layer at 50 vertical levels (up to 10,000 m) above the territory of 150×150 km and a nested area with a base of 50x50 km (grid step of 1 km with the center in the city of Tomsk).



Starchenko, A.V., Bart, A.A., Kizhner L.I., Danilkin, E.A. “Mesoscale meteorological model TSUNM3 for the study and forecast of meteorological parameters of the atmospheric surface layer over a major population center” Tomsk State University Journal of Mathematics and Mechanics, 66, 35-55 (2020)

TSU Nonhydrostatic Mesoscale Meteorological Model (TSUNM3) takes into account:

- turbulent mixing in the atmospheric boundary layer;
- influence of short-wave and long-wave radiation in the atmosphere taking into account the scattering and attenuation of radiation in a clear sky, absorption of radiation by water vapor, absorption and reflection by clouds;
- formation of raindrops, clouds, snow, ice particles and pellets in the atmosphere in accordance with the WSM6 (Hong, Lim) microphysics of moisture scheme;
- turbulent exchange of momentum, heat, and moisture with the underlying surface.
- Initialization of the TSUNM3 model and supplying it with lateral boundary conditions is carried out based on a numerical weather prediction by the SL-AV (Tolstykh et al.) operational global model of the Hydrometeorological Center of the Russian Federation.

Hong, S.-Y., Lim, J.-O, J "The WRF single-moment 6-class microphysics scheme (WSM6)" J. of Korean meteorological society, 42(2), 129-151 (2006)
Tolstykh M.A., Fadeev R.Yu., Shashkin V.V., Goyman G.S., Zaripov R.B., Kiktev D.B., Makhnorylova S V, Mizyak V.G., Rogutov V.S. "Multiscale Global Atmosphere Model SL-AV: the Results of Medium-range Weather Forecasts" Russ. Meteorol.Hydrol., 43, 773–779 (2018)

Chemical transport model (CTM)

- The non-stationary Eulerian CTM was used to calculate the formation and dispersion of pollutants in the atmosphere.
- The governing equations, along with the non-stationary term, contain terms that represent horizontal and vertical advection and turbulent diffusion, wet deposition, and source terms that model the emissions of primary air pollutants and their chemical reactions.
- To describe chemical and photochemical reactions a kinetic scheme derived from a combination of two well-tested reduced chemical reaction mechanisms (Hurley),(Stockwell,Goliff) was applied. The model calculates the concentrations of such impurity components as carbon monoxide, sulfur dioxide, nitrogen monoxide and dioxide, hydrogen peroxide, etc.

Starchenko A., Shelmina E., Kizhner L. Numerical Simulation of Meteorological Conditions and Air Quality above Tomsk, West Siberia //Atmosphere. 2020. Vol. 11, № 11. P. 1-15.
Hurley, P. TAPM V4. Part 1: Technical Description. In CSIRO Marine and Atmospheric Research Paper No. 25; CSIRO Marine and Atmospheric Research: Aspendale, Australia, 2008; 59p.
Stockwell, W.R.; Goliff, W.S. Comment on «Simulation of a reacting pollutant puff, using an adaptive grid algorithm» by R. K. Srivastava et al. J. Geophys. Res. 2002, 107, 4643–4650.

Chemical transport model (CTM)

- CTM takes into account emissions of pollutant components in the atmosphere due to the elevated point sources and the linear land-based sources.
- The calculations were performed at the same intensity of elevated point and linear (automobile roads) sources located in the considered area. The intensity of the point and line sources corresponded to the annual emissions of the main pollutants in the Tomsk region for 2019.
- Changes in the normalized vehicle emission intensity $I_{vehicle}(t)$ during each calculation day were modeled according to the following law:

$$I_{Vehicle}(t_h)) = \begin{cases} 0,05 + 0,95\sin\left(\pi(t_h - 6)/18\right), t_h \in [6, 24], \\ 0,05, t_h \notin [6, 24], \end{cases}$$

Chemical transport model (CTM)

- to assess the air quality above the considered area the Air Pollution Index (API) was used. The API values are calculated based on the predicted concentrations of CO, SO_2, NO_2, NO, and O_3 with the following equation.

$$\mathrm{API} = \sum_{i=1}^{n} \left(\frac{C_i}{C_{i\infty}} \right)^{a_i},$$

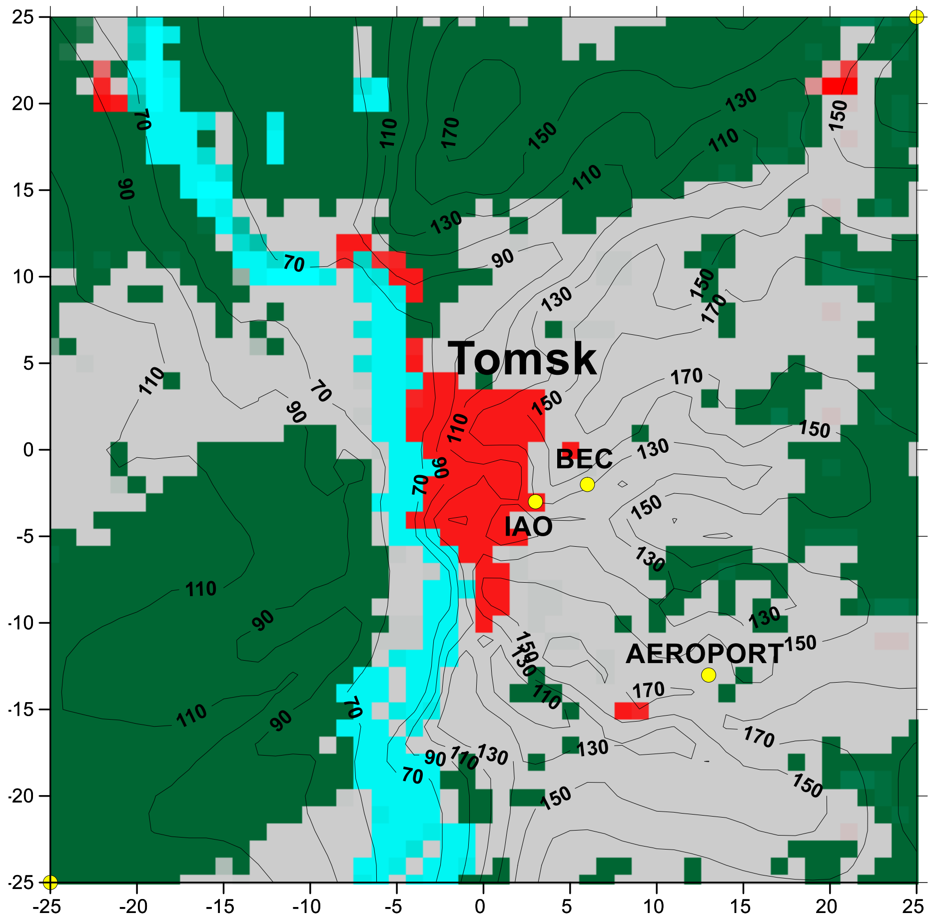
- where C_i is the concentration of the i-th substance, mg/m^3, values of $C_{i\infty}$, mg/m^3, and the dimensionless constants a_i are presented in Table 1.

Constants	CO	SO_2	NO_2	NO	O_3
$C_{i\infty}$	5.0	0.5	0.2	0.40	0.16
a_i	0.9	1.0	1.3	1.0	1.7

The API calculated with the Equation was recommended for the urban air quality assessment by The Federal Service for Hydrometeorology and Environmental Monitoring (Rosgidromet).

Experimental setup of RESC Atmosphere

- the "Meteo-2" ultrasonic weather stations located at the following points:
  - **IAO**, roof of the laboratory of the Institute of Atmospheric Optics of the SB RAS; measurement level is 17 m above the underlying terrain and 5 m above the roof level, urban land.
  - **BEC**, Basic Experimental Complex of IAO of SB RAS; measurements at heights of 5 m ("BEC-5") and 10 m ("BEC-10"), natural landscape.
- **AEROPORT** is located in the suburbs 18 km southeast of the city center. The measuring complex AMIS-RF is located near the runway, has standard instruments for observing meteorological values relevant to aviation (http://rp5.ru).



Choice of cases (Weak wind)

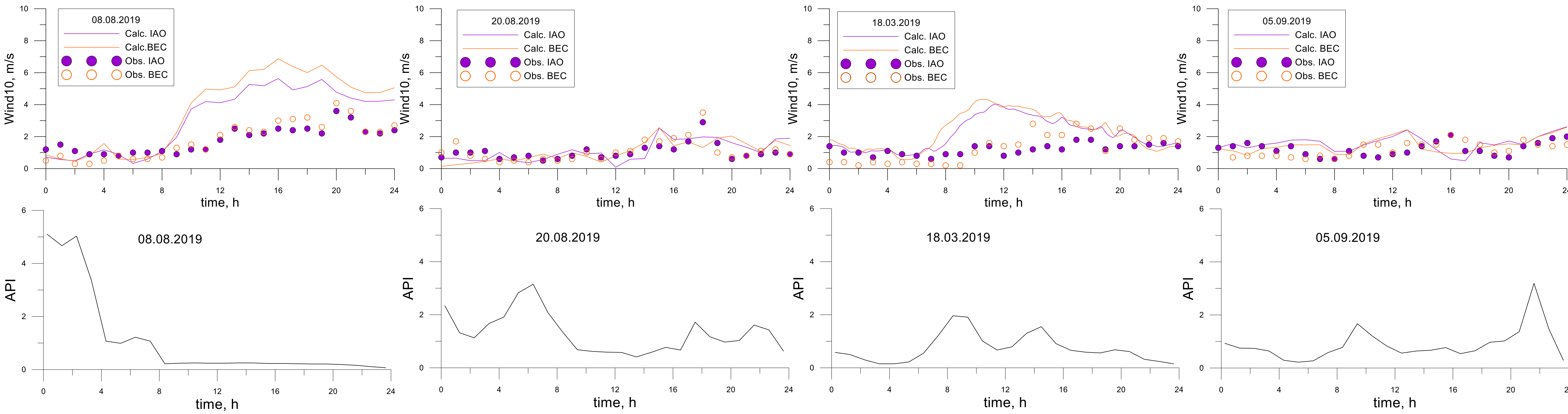
- Meteorological parameters averaged over a 10-minute time interval were used for the analysis (initial experimental data were obtained approximately 10 times per second).
- The choice of episodes with "calm conditions" was made by selecting those cases when the horizontal wind speed (Vh) was simultaneously less than 1 m/s at all observation points in comparable 10-minute time intervals.
- At the same time, the duration of such periods should have been at least 3 hours. For the period from 01.01.2019 to 31.10.2019, there were 17 such episodes. They occurred mainly in the warm season (March – May, July – September).
- The most striking cases were observed on 18.03.2019 (03:35-09:35), 23.07.2019 (03:05-08:55), 08.08.2019 (01:55-07:35), 12.08.2019 (02:35-07:15), 20.08.2019 (03:15-08:45), 05.09.2019 (05:35-08:25).

Choice of cases (Strong wind)

- The average values of the horizontal wind speed V_h and the kinetic energy of turbulence E_k, which determines wind gustiness in each 10-minute interval at all observation points, were calculated for the specified period (01.01–31.10.2019) based on the obtained experimental data.
- $G = V_h + 3*E_k^{0.5}$ characterizes the scale of wind gusts (*).
- The choice of episodes with "strong wind gusts" was made by selecting those cases when the G values simultaneously exceeded the level of 11m/s at all observation points in comparable 10-minute intervals.
- We selected 12 days when there were cases of G>11 m/s (only the dates and months of 2019 are specified): 26.04, 28.04, 29.04, 30.04, 18.05, 19.05, 20.05, 25.05, 26.05, 20.09, 24.09, 29.10. These cases also relate mainly to the warm period of the year.

*Byzova N.L., Ivanov V.N., Garger E.K., “Turbulence in atmospheric boundary layer,” Hydrometeoizdat, 263 (1989). (in Russian)

Some results of predictions of weak wind and air quality in Tomsk



The observed periods of time during the considered day when the wind speed at the observation points decreased below 1m/s are almost always confirmed by calculations. So, on August 8, 2019, it was observed at 01:55-07:35; August 20, 2019 - at 03:15-08:45; March 18, 2019 - at 03:35-09:35; September 5, 2019 - at 05:35-08:25. The time is local.

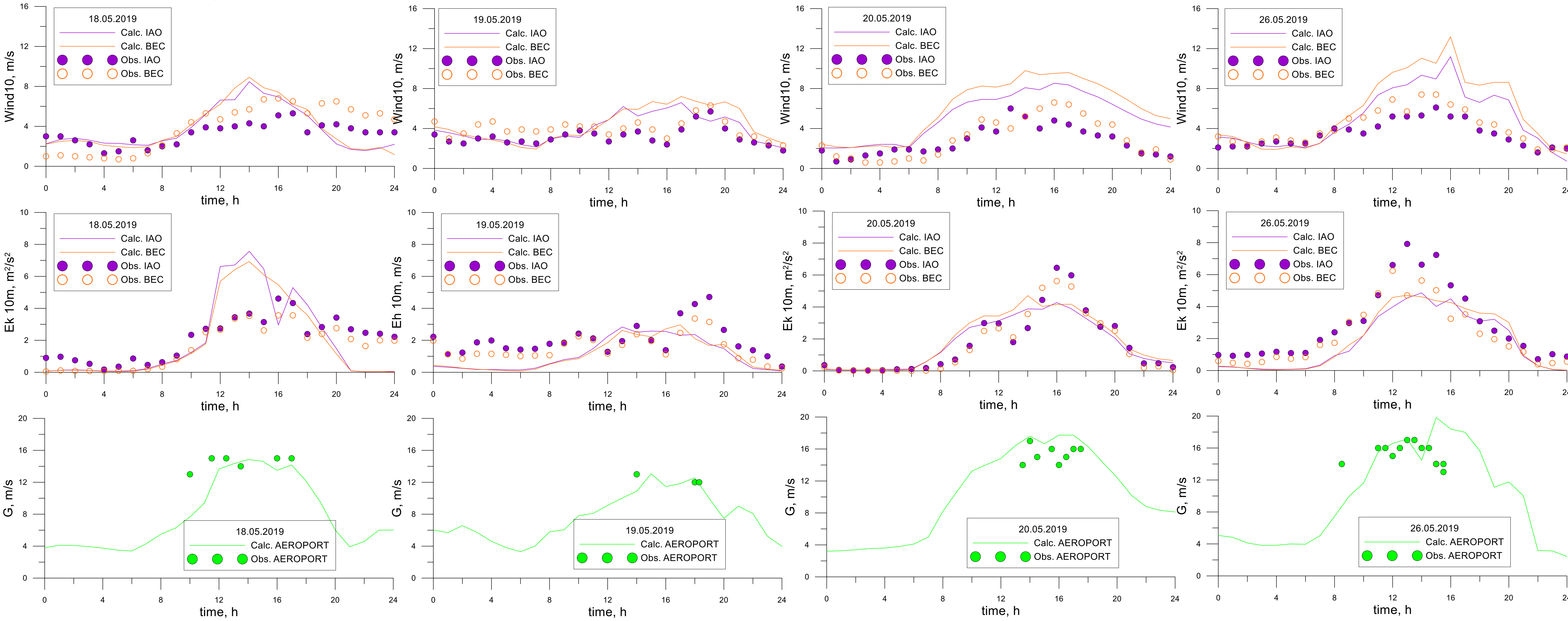
The correspondence between the predicted vertical temperature profile and API

- A table was compiled showing the relationship between the presence of inversion (isothermy) and increased (an increase of) API at weak wind conditions.
- Each case corresponds to the time when API and vertical temperature profile were calculated. The data is presented in the table.

Inversion	API course		Total
	Increased (increase)	Not increased (not increasing)	
There is inversion, isothermy	13 (31)	7 (17)	20 (48)
No inversion, isothermy	0 (0)	22 (52)	22 (52)
Total	13 (31)	29 (69)	42 (100)

- So, in 83% of the cases, there is a direct relationship between the presence (absence) of inversion and the increase (non-increase) of API. In 17% of the cases, API did not increase if there was inversion. If there was no inversion, there was no increase in API observed.

Some results of predictions and measurements of strong winds in Tomsk



*G=Wind10m+3*sqrt(Ek10m)* Byzova N.L., Ivanov V.N., Garger E.K., “Turbulence in atmospheric boundary layer,” Hydrometeoizdat, 263 (1989).

Conclusions

- Meteorological situations over the city of Western Siberia accompanied by weak (<1 m / s) and strong (> 11 m / s) surface wind were investigated with the help of three ultrasonic meteorological stations "Meteo-2" of the RESC "Atmosphere" and the TSUNM3 mesoscale model of numerical weather forecast with a horizontal resolution of 1 km.
- The continuous use of weather stations from July 1 to October 30 of 2019 made it possible to identify periods when the surface wind speed for three hours at all observation points was less than 1m / s. For these dates of 2019, numerical simulations of weather conditions and air quality in the city were carried out. Comparison of calculations with observations showed that the TSUNM3 model in most cases confirms by calculations the duration and the very fact of weak wind conditions. However, in some cases, the TSUNM3 model overestimates the values of the surface wind speed in comparison with the observational data. Application of the developed model of atmospheric air quality confirmed the relationship between weak surface wind and deterioration of air quality in the city. This is especially shown in the combination of a weak wind with the conditions of stable stratification of the surface air layer.
- Also, using the meteorological stations of the RESC "Atmosphere", episodes of the first ten months of 2019 were identified, when the scale of wind gusts estimated from observations exceeded 11 m / s at all observation points. For the selected dates, numerical weather modeling was carried out, which showed, in general, the correspondence of the measured and calculated values of the averaged velocity and turbulent kinetic energy of the surface wind. Using these values, the magnitude and duration of wind gusts were estimated. It was found that they correspond to the values and time of observations to wind gusts at the aviation meteorological station at the airport in Tomsk.

Thank you for attention!