Features of formation of local strong squalls in Perm region

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Abstract. This paper describes conditions of formation of three strong (≥ 25 m/s) squalls events which were observed in Perm region in 2015–2016. All these storm events have not been predicted by the Perm Center of Hydrometeorology and Environmental Monitoring. The synoptic-scale conditions of squall formation were very diverse, and one event occurred with non-typical synoptic environments. Some features of the underlying surface increased the wind speed. CFS and GFS reanalysis data are used to calculate the squall-forecasting instability indices. We have found that the SWEAT index, which takes into account thermodynamic instability, wind shear, and wind speed in the middle troposphere, is the most reliable predictor for short-term forecasting of these squall events. The WRF model with 3 and 7.2 km spatial resolution is used for an explicit simulation of squall-generated mesoscale convective systems and wind gusts. The model underestimates the wind gusts or does not reproduce the squalls. Also, the spatial position and timing of a squall have been simulated with significant biases.

1. Introduction

Strong squalls with a wind speed ≥25 m/s are one of the most hazardous weather events in Russia, which can cause loss of life and substantial economic damage. In recent years, the Russian Hydrometeorological Center uses mesoscale atmospheric models (Cosmo-Ru and WRF-ARW) with a spatial resolution of 2.2, 3.0, and 7.0 km for operational forecasting of hazardous convective phenomena [1, 2]. Some instability indices calculated in automatic mode by numerical models are also used for forecast of squalls [3–5].

In Perm region, 1-5 severe squall events occur per year, most of them are local and often missed by weather stations. Short-term forecasting of local strong squalls has a relatively low accuracy. In this study, we consider the synoptic situation and the contribution of local landscape environments for the occurrence of three local squall events (with a wind speed ≥ 25 m/s) which took place in Perm region during 2015–2016. Two squall events were reported by one weather station, and one event was missed by the observation network. We used the instability indices calculated by global atmospheric models data and the WRF mesoscale atmospheric model for short-term forecast of these squall events. Note that the squalls formed under very different synoptic conditions. Two squalls occurred on a cold front, and one in non-frontal environments.

2. Synoptic situation and the contribution of local landscape environments

In this section, we provide the most important actual information related to the events being studied.

First case (June 16, 2015). The squall occurred near the polar cold front associated with a deep quasi-statuonary cyclone (with a sea level pressure of 998 hPa in the centre). The low was located over the Kola Peninsula at 12.00 UTC. The cold front moved from west to east, over the western part of

Perm region. Deep convection was not observed on the cold front, and the environment for frontogenesis was absent. However, a mesoscale convective system (MCS) formed on an instability line at a distance of about 100 km before the cold front. Three growing convective cells with a relatively small diameter (~ 35 km) but an extremely low cloud top temperature (up to –63°C) were identified by an Aqua MODIS satellite image obtained at 10:05 UTC (Figure 1a). The low cloud top temperature indicates the presence of strong updrafts in the convective cells. Then these three cells merged and moved to east-north-east along the mid-level flow. Approximately at 12.00 UTC the MCS passed south of the Berezniki city where a strong squall and large hail were observed. The squall and large hail were reported by eye-witnesses and confirmed by subsequent analysis of the damage. The roofs of some houses were damaged and three people were injured. The wind gust speed was estimated as 27 m/s, however, it could be higher. The Patrinsky pine forest located to the south of the city of Berezniki was damaged on a total area of 500 ha (Figure 2). The windthrow had a length of 13 km and the width range from 1.5 to 2 km. The Berezniki weather station located at a distance of ~12 km to the north of the storm track reported thunderstorm and convective precipitation (3 mm) but not wind gusts.

The local landscape environment could be of great importance for this severe squall formation. The wind speed increased significantly over the large (~6 km) water surface of the Kamskoe reservoir. Forest damage was identified only on the eastern (windward) coast of the reservoir.

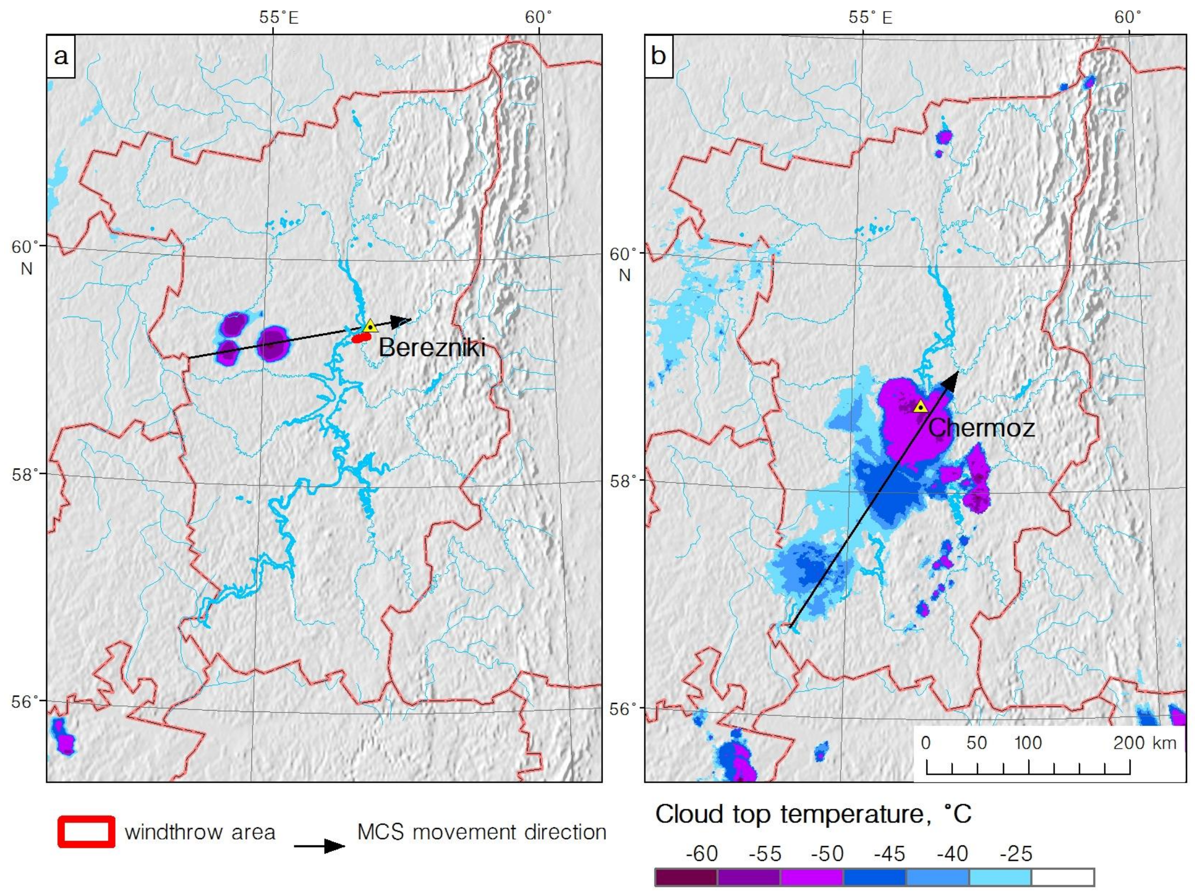

Figure 1. Cloud top temperature according to Aqua MODIS data: a) 10:10 UTC on June 16, 2015; b) 9:30 UTC on August 4, 2016.

Figure 2. Forest damage caused by severe wind gusts in Patrinsk pine forest on 16 June 2015.

Second case (July 12, 2015). A squall occurred in the front part of a large and deepening "sounthwestern" cyclone which formed over the Middle Volga region and moved from southwest to northeast. At 12.00 UTC the cyclone center with a SLP of about 980 hPa was located over Kirov region. The main cold front passed through the southern part of Perm region between 8:00 and 10:00 UTC. A linear MCS with a length of more than 300 km formed on the cold front and passed trough Perm Region with heavy rainfalls, thunderstorms, local hailstorms, and wind gusts of up to 20 m/s. However, stronger wind gusts were associated with a secondary cold front in the rear part of the cyclone. A local convective cloud moved over the Chernushka town (in the south of Perm region) and caused wind gusts of up to 28 m/s at 11:00 UTC. An important additional factor for the strong squall formation was an increase of the pressure gradient in the rear part of the cyclone. The strong squall was very local and did not cause significant damage.

In this case the landscape features could also be of significant importance for the severe squall occurrence. The Chernushka weather station is located on an open treeless terrain where the wind speed may substantially increase. The average annual wind speed maximum at this weather station (22.5 m/s) is higher than at the other weather stations of Perm region.

Third case (August 4, 2016). A squall occurred at a considerable distance from the atmospheric fronts, in a tropical air mass with 850 hPa at a temperature of up to 18°C. In the afternoon the southern and eastern parts of the Perm region were under the western periphery of the anticyclone, which was located over the south of Western Siberia. The northern and western parts of the area under study were under the influence of the warm sector of the cyclone. At MSL the low was located over the Komi Republic at 12:00 UTC. Environments for intense deepening of the cyclone were absent. The cold front associated with the cyclone did not generate any convective storms.

Hovewer, at about 04.00 UTC an MCS formed over the Udmurt Republic and moved to the central part of Perm region along the southwestern mid-level flow. The MCS formation was induced by a strong convective instability (see Table 1) and weak low-level convergence over Udmurtia and Middle Volga region. At 07.00 UTC the 2-m temperature in the central and southern parts of Perm Region increased to 30–32 °C, and the dewpoint temperature slightly decreased (to ~15 °C). Thus, the environments (high temperature and significant dew point depression in the surface layer) were favorable for the severe wind gusts.

The MCS passed over Perm region between 07.00 and 10.00 UTC and caused mostly weak precipitation (up to 5 mm), moderate thunderstorms, and wind gusts up to 17–19 m/s. The most active cell formed in the northern part of the MCS. It was identified by an Aqua MODIS image obtained at 9.25 UTC (Fig. 1b) as a local area with a cloud top temperature lower than –60°C (overshooting top).

The Chermoz weather station was on the track of this cell and reported a wind gust of up to 25 m/s and heavy rainfall (23 mm). However, the occurrence of a strong squall in Chermoz can be explained not only by the features of MCS formation and motion, but also by some influence of the landscape environments. The Chermoz weather station is located on an open treeless terrain (as well as the Chernushka meteorological station), and it is also characterized by a relatively high average annual wind speed maximum (~ 22 m/s).

3. Convective instability indices

In the present study we used 11 convective instability indices (see review [6] for more details). All indices were calculated by the CFS (Climatic Forecast System) and GFS (Global Forecast System) reanalysis data, with a 0.5° grid resolution. The OpenGrADS 2.0.2 software package was used to perform calculations and build skew-T diagrams (Figure 3). Table 1 shows the calculated values of the indices.

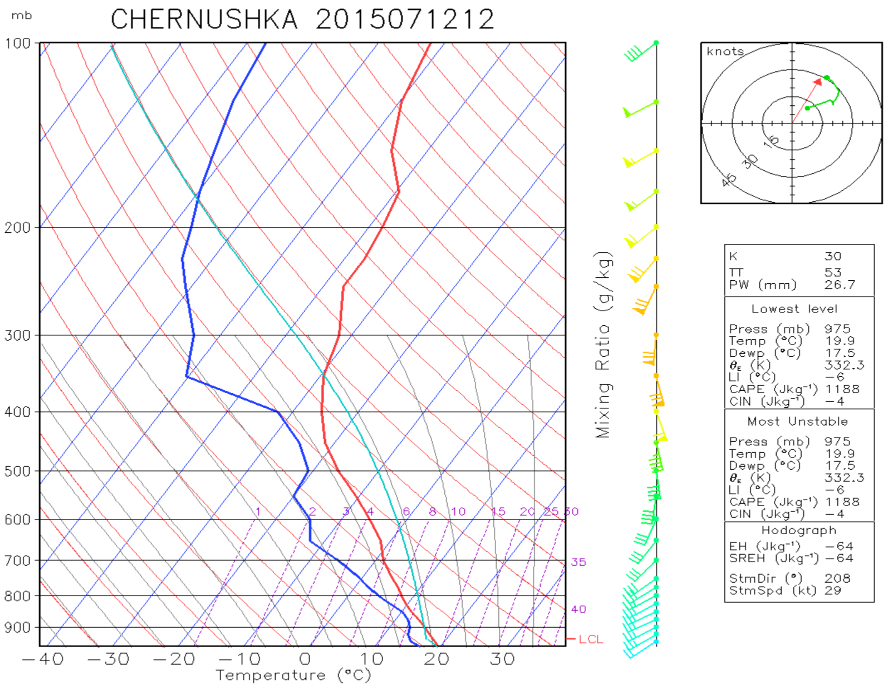

Figure 3. Skew-T diagram for Chernushka weather station according to CFS model data (12 July 2015, 12:00 UTC).

Based on a skew-T diagram analysis, we found that the alternation of wet and dry air layers is a typical feature of all three studied cases. Above the boundary layer moist layer 1.5–2 km in thickness lies, and higher the humidity decreases significantlty. Another common feature of all three cases is that the SWEAT (Severe Weather Threat) index exceeds the critical value (250) or is close to it. The The SWEAT index takes into account the convective instability, wind shear, and wind speed in the middle troposphere. In the first case (June 16, 2015), high values of 0–3 km storm relative helicity (SRH) indicate a high risk of formation of supercell storms.

Table 1. Values of the instability indices calculated by GFS and CFS objective analysis data.

Index	16.06.2015 12.00 UTC		12.07.2015 12.00 UTC		4.08.2016 9.00 UTC	
	CFS	GFS	CFS	GFS	CFS	GFS
SB CAPE (J kg^{-1})	43	865	1118	870	71	1341
SB CIN (J kg^{-1})	–16	–32	–3	0	–88	–3
ML CAPE (J kg^{-1})	8	113	596	300	8	953
DLS (knot)	35	40	12	6	15	9
LI (°C)	1	–3	–6	–6	0	–4
ML LI (°C)	2	0	–4	–3	1	–3
LLS (m/s)	18	15	6	2	12	10
SCP	–	1	–	–	–	–
SRH in a layer of 0–3 km (m^2/s^2)	167	146	–	21	99	76
SWEAT	233	251	303	238	214	258
THOMPSON	34	37	36	35	32	39

*****Outlined values indicate a high probability of occurrence of severe weather events [6].

4. WRF model simulation

The WRF-ARW v3.8.1 non-hydrostatic numerical model was used to simulate the squall formation [7]. The model was run on the computational cluster "PGNIU-Kepler", which consists of 8 computer nodes iDataPlex DX360 M4 based on IntelXeonE5 processors and NVidiaTeslaK20 graphics cards. The WRF model settings are given in [8].

Explicit modeling of deep convection allows one to simulate the evolution of MCSs which caused strong squalls. Validation of the simulation results is based on actual data on the location and time of the occurrence of squalls and Terra/Aqua MODIS images (which provide information about the MCSs position). In addition to calculating the wind gust by the WRF model, the errors for the position and time of the squall occurrence were also estimated. A similar object-based approach to estimating the forecast accuracy was used in earlier studies on the convective storms simulation [9, 10–12]. The main simulation results are shown in Table 2.

In the first case (June 16, 2015), the WRF model with a 7.2-km spatial resolution was used to simulate the MCS above the central part of the Kamskoe reservoir (~ 80–100 km to the south of the actual MCS position and the storm track) at 13:00 UTC, which was two hours after the actual time of the squall occurrence. The maximum simulated gust speed was 16 m/s. The WRF model with a 3-km spatial resolution also simulates the MCS at 13:00 UTC and ~ 100 km to the south of the actual position, but the maximum wind speed (20 m/s) was simulated near the town of Dobryanka.

In the second case (July 12, 2015), the model simulated the formation of the linear MCS associated with a cold front over the southern and eastern parts of Perm region, between 10:00 to 12:00 UTC. Simulation with a 3-km spatial resolution gives the maximum wind speed (24 m/s) near the city of Kungur (170 km to the north of the actual position of the squall event). At the same time, a squall with a wind speed of 28 m/s occurred at the Chernushka weather station, and it was associated with a secondary cold front. Unfortunately the WRF model did not predict it.

This squall was also simulated with the use of 0,5° GFS forecast data as the WRF model input. The WRF model with a 7.2-km spatial resolution simulated a squall associated with a secondary cold front (maximum wind speed: 20 m/s). It can be considered a successful forecast, since the wind gust speed is usually underestimated with this spatial resolution. However, under the same initial conditions but with a spatial resolution of 3 km, the model did not forecast the squall occurrence.

In the third case (August 04, 2016), the WRF model does not simulate the formation of the MCS and squall at different input data and grid sizes (with a 7.2 and 3-km spatial resolution, with the use of GFS and CFS initial data). The quality of the forecast is unsatisfactory. It can be assumed that this is due to an underestimation of the convective instability in the warm sector of the cyclone, which was the main trigger of the MCS formation.

Table 2. The results of the WRF simulation of strong squalls (the numerator and denominator correspond to the values obtained with 7.2 and 3 km model grid size, respectively).

Date	Actual wind speed, m/s	Maximum simulated gust speed within a 100 km radius around the position of the squall occurrence (m/s)	Spatial error of the simulated squall occurrence, km	Time error of the simulated squall occurrence, h
16.06.2015	27*	16/20	100/100	2/2
12.07.2015	28	15/24	170/140	1/0
12.07.2015**	28	20/23	50/140	0/0
04.08.2016	25	No squall	–	–
04.08.2016**	25	No squall	–	–

* Wind speed was estimated by the Beaufort scale
** GFS forecast data are used as the initial conditions for the WRF model run

5. Conclusions
This paper presented a preliminary study of the influence of local landscape environments on the evolution of squalls which occurred in Perm region. One of the limitations of the results obtained is the lack of radar-based characteristics. Also, some additional squall events should be studied to identify the patterns of landscape environments that influence the wind speed.

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