Numerical Forecasting of Squall Lines and Strong Winds on the Territory of Transbaikalia Region, Russia

Eugenia Verbitskaya[1], Stanislav Romanskiy[1], Zinaida Verbitskaya[1]

[1]Far Eastern Regional Hydrometeorological Research Institute, Vladivostok, Russia, werbaem@gmail.com

Abstract

Results of numerical simulations of squall lines in Transbaikalia region of Russia are shown in the article. Simulations have conducted by the advanced version of Weather Research and Forecasting (WRF) model for the events recorded over the period from 2010 to 2017. WRF model is configured to provide calculations on two nested domains with grid spacings of 3 and 9 km. Simulations with two types of planetary boundary layer (PBL) parameterizations are compared (Yonsei University and Mellor-Yamada-Janjic schemes). Approach to determine squalls in model output based on values of simulated vertical and horizontal wind speed is proposed. Description and product samples of operational method for forecasting squall lines and strong winds in Transbaikalia region of Russia are presented.

1 Introduction

Squall lines are one of severe convective weather events. Squall is a local sharp increase in wind speed accompanied by changing in wind direction. Often wind speed in a squall exceeds a value of 20-25 m/s. Duration of squall is a few minutes. Mostly squalls take place during a warm period of a year. Generally squalls are linked to strong Cumulonimbus clouds (squall in an air mass) or cold atmospheric fronts (frontal squall). In both cases horizontal roll vortex takes place in and under clouds. Life cycle of a squall is divided into 4 stages: the formative stage; early mature stage; late mature stage and dissipation stage [1]. A travelling squall line of 100-150 km long may exist in a couple of hours.

Accurate forecasts of squall lines and associated with it strong winds is very important for reducing the impact of these events. Forecasting of squall lines is complicated problem. There are a lot of methods to predict and diagnose squall lines. Some of them are based on statistical patterns of synoptic-scale weather conditions [2] and other analyze output product of a nonhydrostatic numerical atmospheric model to diagnose squall lines by values of energetic and dynamic indices.

Modern nonhydrostatic numerical atmospheric models include an equation for vertical wind vector component and provide ability to simulate squall lines over various time intervals. A method to forecast squalls has to reveal a horizontal roll vortex in model output. The height of this vortex at the late mature stage outreaches 1.5-2 km above ground layer (AGL) and vertical wind speed exceeds values of 2-5 m/s [1]. Therefore, it is very import to examine simulated vertical wind speed (w) in low levels of atmosphere to find out areas of positive and negative values of w.

Horizontal resolution of a grid and parameterizations of microphysics and planetary boundary layer (PBL) of a numerical model are key components to predict convective processes [3]. Convective processes may be adequately represented by a nonhydrostatic numerical atmospheric model with horizontal grid spacings of O(1 km) [4].

In this study the advanced research version of Weather Research and Forecasting model (WRF-ARW) [5, 6] with horizontal grid spacings of 9 and 3 km is used for simulation. WRF-ARW model is configured in two variants to compare impact of parameterizations of PBL as follows: Yonsei University [7] and Mellor-Yamada-Janjic [8].

2 Configuration of WRF-ARW Model

A version of WRF-ARW model with two nested domains (Fig. 1) is used to simulate squall lines on the territory of Transbaikalia region, Russia. The spatial resolution of outer domain (332×250 grid points) is 9 km and for inner

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domain (618×339 grid points) is 3 km. Detailed representation of topography and land use (resolution of data is 30″) in the inner domain allows to get a more realistic mesoscale circulation over the complex-terrain region during a squall event. There are 31 eta-levels in the vertical dimension of model domains with the most detailed resolution in PBL; there are 11 levels for the height of 2 km AGL. Initial and boundary data are given by 3-h interval product of the Global Forecasting System (GFS) [9]. The WRF-ARW model is configured for middle latitudes and recommended parameterizations of radiation (Rapid Radiative Transfer model), microphysics (Thompson scheme), land surface and soil processes (universal Noah model) are set up [5].

Both versions of the WRF-ARW model are calculated on Altix S4700 (peak performance is 0.7 TFlops). One run for lead time of 24 hours takes near 2 hours of machining time. Output production with time step of 1 minute is available for analysis. Procedure of calculations includes three main steps as follow: WRF preprocessing of initial and boundary data provided from GFS output; calculation of the WRF-ARW model; analysis of output WRF data to diagnose squall events.

A significant contribution to intensifications of near ground wind is made by turbulent motion [10]. PBL parameterizations of an atmospheric model resolve turbulence fluxes of subgrid scale. Two variants of parameterizations of surface layer and PBL are examined. These coupled schemes are MM5 similarity with Yonsei University (YSU) and Eta similarity with Mellor-Yamada-Janjic (MYJ) parameterizations respectively. YSU is non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer. The turbulence diffusion equations for prognostic variables include terms which describe flux from the inversion layer and contribution of the large-scale eddies to the total flux. The layer where critical bulk Richardson number equals 0.5 is corresponded to the height of PBL [7]. MYJ is one-dimensional prognostic turbulent kinetic energy (TKE) scheme with local vertical mixing. Prognostic TKE is calculated over entire atmospheric column [8].

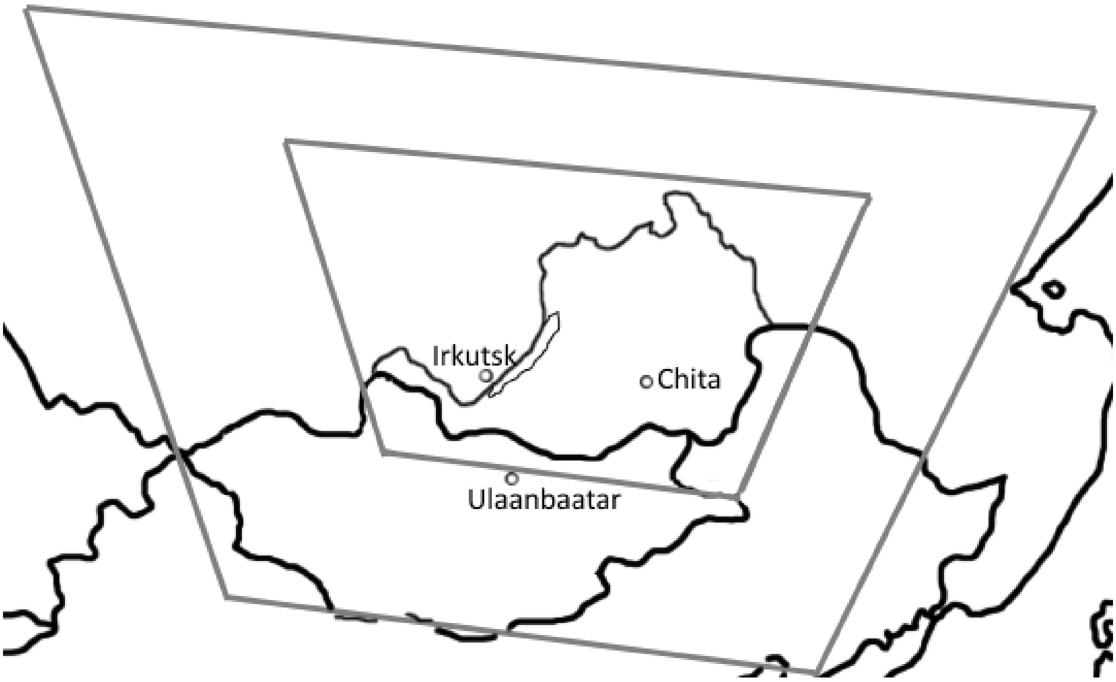

Figure 1: Horizontal domains of the WRF-ARW model (grey).
Thin black line shows the boundaries of Transbaikalia region, Russia.

3 Comparison between Simulations of YSU And MYJ Parameterizations

There are 90 observational stations in Transbaikalia region of Russia; all these points are located within the inner domain. Severe squall events of wind speed above 20 m/s were recorded on these stations for the period of 2010-2017; the sample size is 87 events. However, not all registered events are squalls. Some of them are strong intensifications of surface wind. These events have been eliminated from sampling. Final size of squall sampling is 59 events.

The first experiments shown that output data from outer domain (grid size of 9 km) does not allow to identify 90% of recorded squall events. This result confirms the fact that numerical simulation of convective processes requires a horizontal grid spacings of O(1 km) [4]. Therefore, in further experiments only the output data of outer domain (grid step of 3 km) is used.

Some squalls take place in points (like Chita, Mogocha, etc.) where atmospheric sounding products are available. Atmospheric soundings produce valuable information concerning vertical structure of the atmosphere (temperature, humidity, wind profiles). These observations start twice a day at 0000 and 1200 UTC (0800 and 2000 local time of Transbaikalia region). However, atmospheric convection is developing in the afternoon. Therefore, atmospheric sounding shows vertical structure of atmosphere in a point before and after a squall event. Whereas numerical simulation produces model products of such type right in the middle of an event.

We have tested YSU and MYJ parameterizations to define the most suitable scheme of PBL for squall forecasting based on WRF-ARW model. The comparison of output model data for these schemes was conducted. The skew-T aerological diagrams for simulated squalls events were obtained. This diagram shows a vertical profile of temperature, dew point and winds in the atmosphere on particular layers above a point of interest (a point where squall was recorded).

Figure 2 shows simulated skew-T diagrams for Mogocha at 0531 UTC on 14 June 2011 where squall (10-m wind speed of 23 m/s) took place at this time. We calculate some energetic indices to define possibility of convection initiation.

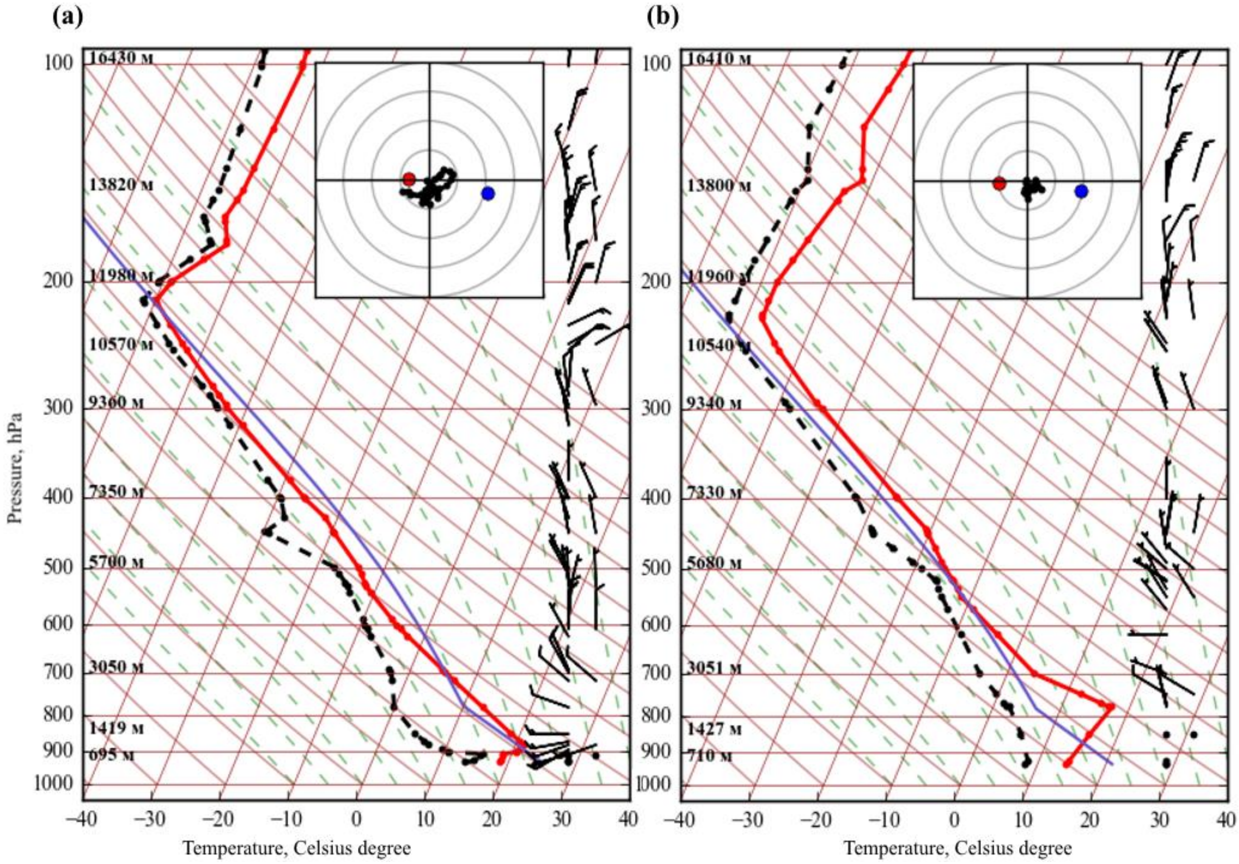

Figure 2: Simulated skew-T aerological diagrams for Mogocha at 0531 UTC on 14 June 2011 for MYJ (a) and YSU (b) parameterizations of PBL. Temperature – red line, dew point – black line, parcel trajectory – violet line, isobars – horizontal straight brown lines, isotherms – diagonal brown lines, saturation mixing ratio lines – steep diagonal green lines, wind speed – flags (short line is 2.5 m/s, long line is 5 m/s). Hodograph – vector diagram of vertical wind profile is in upper right corner.

Main indicator of atmospheric instability is convective available potential energy (CAPE). CAPE is the positive buoyancy of an air parcel. We use mixed layer CAPE; this index is calculated for air parcel from 100-mb layer AGL. The vertical resolution of squall vortex is near 1.5-2 km AGL and mixed layer CAPE shows how many energy is available here for developing of convection. Convective inhibition (CIN) is a negative buoyancy of an air parcel. It describes the power of inhibitory layer (air parcel has to overcome this layer to initiate convection).

$$CIN = g\int_{z}^{LFC} \frac{T_{v,p} - T_{v,e}}{T_{v,e}} dz,$$
$$CAPE = g\int_{LFC}^{EQL} \frac{T_{v,p} - T_{v,e}}{T_{v,e}} dz \qquad (1)$$

where z – start height, LFC is level of free convection, EQL – equilibrium level (level of neutral bouncy), Tv,p – virtual temperature of parcel, Tv,e – virtual temperature of environment, g is 9,81 m/s.

CAPE and CIN for squall event in Mogocha (at 0531 UTC on 14 June 2011) for both PBL schemes are noticeably different. Value of CAPE is 784 J/kg and CIN is -176 J/kg for simulation with MYJ parameterization. For YSU scheme values of these indices are near zero (parcel trajectory does not cross temperature line on Fig. 2b). Figure 2 also shows that 0-1 km wind shift is 16 m/s and 2 m/s for MYJ and YSU schemes respectively. Therefore, MYJ generate stronger atmospheric convection than YSU scheme.

Further analysis of simulated skew-T aerological diagrams during the squalls shows that YSU scheme of PBL generate weaker convection (based on mixed layer CAPE and CIN) and associated wind in comparison with MYJ parameterization. Simulations with MYJ scheme spawn more squall events, sometime 10-m wind speed in these events is above 27-30 m/s, but YSU scheme generates wind speed no more than 25-27 m/s.

Skew-T diagrams provide a lot of information but vertical wind speeds do not take into consideration. To take into consideration vertical wind speed we develop special method for identification of squalls in model output.

3.1 Automatic Squall Identification Method

On pilot stage we tested several methods to identify squall events from model output [11]. The most successful method requires the calculation of special parameter V1 at every grid point (i, j):

$$V_1(i, j) = \max(M_{10m}, M_1) + \sum_{k=1}^{N} \left(\max(w_{rd}) - \min(w_{rd})\right), \tag{2}$$

where M1 – wind speed at the closed to the ground model level, M10m – wind speed at 10 m, wrd – values of vertical wind speed inside a circle of radius 30 km centered at point (i, j), k – number of a model level (numbering from bottom to top), N – number of vertical levels under consideration.

Parameter V1 takes into consideration difference between maximum and minimum values of vertical wind speed at model levels in PBL within the circle centered at a point of interest. Thus, last term of (2) captures characteristics of a horizontal roll vortex. Values of V1 are calculated with time step of 1 minute automatically during a run of WRF-ARW model.

We suggest that a model squall in grid point (i, j) takes place if the value of V1 in this point exceeds threshold of 18 m/s no longer than 30 minutes. A model squall is suggested to be correct if it locates within the circle of radius 30 km centered at the point where observed squall is recorded, maximum value of V1 in this area exceeds 18 m/s and time difference between simulated and observed squall events takes no more than 3 hours.

Maps of parameter V1 are plotted to find out the position of squall lines and define accuracy of simulations. Figure 3 shows position of squall lines based on values of V1. The squall took place (10-m wind speed is 24 m/s) on point 30823 at 0815 UTC on 28 July 2010. Maximum values of V1 are 20-21 m/s and 22-25 m/s for YSU and MYJ parameterizations respectively.

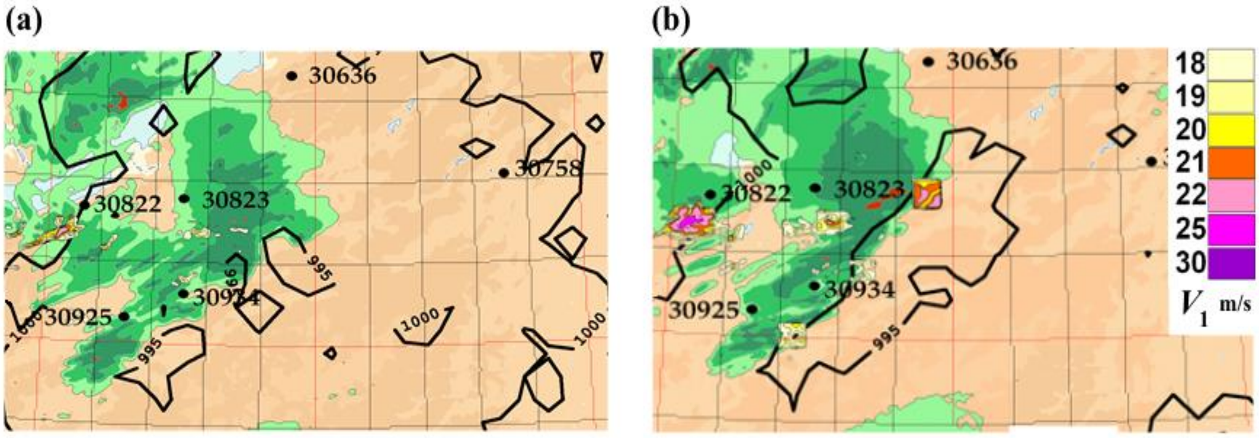

Figure 3: Simulated values of V_1 YSU (a) and MYJ (b) schemes of PBL at 0700 UTC on 28 July 2010. Green areas are zones of precipitation.

Analysis of V_1 maps shows that both PBL parameterizations integrated to WRF-ARW model sometimes spawn false squalls (especially MYJ scheme). The amount of false alarms varies depending on a year but it exceeds 50% and 70% for YSU and MYJ schemes respectively.

However it should be understood that meteorological observational points record no more than 10-15% of squall events. Majority of false alarms is possible to eliminate through the analysis of wind regime of every geographical distinct of Transbaikalia region (i.e., prolonged strong winds are blowing along the west coast of lake Baikal). Therefore, false alarms are not major challenge.

3.2 Measures of Skill in Squall Forecasting

Standard measures of skill in dichotomous categorical forecasts are used to compare the quality of model simulations. We take into consideration values of critical success index (CSI) [12], probability of detection (POD), false alarm ratio (FAR) and bias:

$$CSI = \frac{x}{x+y+z}, \quad POD = \frac{x}{x+y}, \quad FAR = \frac{z}{x+z}, \quad bias = \frac{x+z}{x+y}, \tag{2}$$

where x is a number of correct forecasts, y is a number of missed events and z is a number of false alarms. CSI and POD measure skill in squall forecasting, bias compares number of simulated and observed events and FAR shows false alarms. These measures are suitable for forecasting of rare events because of a large number of correct rejections do not take into consideration and total sampling size does not affect result.

Table 1 shows the measures of skill in squall forecasting for both variants of WRF-ARW model. Probability of detection is 39% and 67% for YSU and MYJ schemes respectively. CSI value of YSU is better than for MYJ according to large values of false alarm ratio and bias. WRF-ARW model with MYJ scheme generates no more than three times that really observed squalls.

Table 1: Measures of skill in squall forecasting of WRF-ARW model with different types of PBL parameterization.

PBL scheme	CSI	POD	FAR	bias
YSU	0.26	0.39	0.57	0.77
MYJ	0.21	0.67	0.77	2.9

Table 1 reveals that main problem of the method are missed events: 33% of events are not predicted for WRF-ARW model with MYJ scheme. The problem will be partially eliminated if spatial resolution of the model will be increased to 1 km. However, it is very hard to simulate correctly devastating squall events with wind speed of 30 m/s and more.

4 Operational Method for Squall and Strong Wind Forecasting in Transbaikalia Region

After operational testing from May to October of 2016 and 2017 proposed method for squall forecasting based on WRF-ARW model with MYJ scheme of PBL was introduced into practice. Today forecasting starts twice a day at 0000 and 1200 UTC from May to October.

End-users get not only hourly forecasting maps of parameter V1 but also text messages for every point of interest about strong wind events and maximum wind speed. Single wind events are divided into following classes [11]: squall, short-term and prolonged intensifications of surface wind. A squall event means that the duration of an event is less than 30 minutes. Duration of short-term intensification of surface wind lay between 30 minutes and 2 hours. If duration of an event exceeds 2 hours it should be categorized as a prolonged intensification of surface wind. If some single events at a point of interest are happened in sequence during the period of no more than 3 hours than these events combined to one vent by next rules:

(a) sequence of events is named “squall” if total duration of single squall events (with breaks) is no more than 30 minutes;

(b) sequence of events is named “squall wind” if total duration of single squall events is more than 30 minutes but period of breaks is no more than 30 minutes;

(c) sequence of events sequence of events is named “gust of wind” if duration of breaks among single squall events is between 30 minutes and 3 hours;

(d) sequence of events is named “short-term intensification of wind” if short-term intensifications of wind and squalls are happened in a sequence and period of breaks is no more than 3 hours;

(e) sequence of events is named “prolonged intensification of wind” if prolonged intensification of wind and any other single event are happened in a sequence and period of breaks is no more than 3 hours.

Examples of such classification are shown in Table 2.

Table 2: Sample message with strong wind forecast for Transbaikalia region, Russia.

Point	Time, UTC	Type of event	With speed, m/s	District
948	0041-0211	Squall wind	18	South
933	0814-0831	Squall	21	South

4.1 Future Projects

New cluster CRAY XC-40 was installed in Regional Specialized Meteorological Center of Khabarovsk, Russia (RSMC Khabarovsk) in 2018. This cluster includes 60 nodes of two 18-cores Intel Broadwell processors with Dragonfly topology and has total peak performance of 76 TFlops. Therefore, we get new directions to improve current method for squall and strong wind forecasting. We plan to use the latest stable version of WRF-ARW model of one domain with grid step of 1 km not only for the territory of Transbaikalia region but also extend the forecasting area to Amur region where strong squalls take place as well. Furthermore, vertical resolution of WRF-ARW model will expanded to 45-60 levels to improve representation of temperature, humidity and wind profiles.

Some new parameterizations of PBL are introduced in WRF model like the Mellor-Yamada-Nakanishi-Niino level 2.5 (MYNN) [13] and one local total energy mass flux (TEMF) [14]. Parameterizations of microphysics are also of interest. New WRF single-moment 7-class microphysics (WSM7) is developed by introducing the hail hydrometeor as an additional prognostic water substance [15]. Sometimes squall lines are accompanied by hails and this microphysics scheme tends to enhance convective activities in the leading edge of the squall line, whereas the precipitation intensity in the trailing stratiform region decreases [15].

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