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Observations and modelling of downslope windstorm in Novorossiysk

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ABSTRACT

We present a comprehensive study of the three-dimensional structure of the Novorossiysk bora, a severe downslope windstorm on the north-eastern coast of the Black Sea. The analysis is based on observational data obtained from the Russian Hydrometeorological Service, automatic weather stations, sodar system, microwave temperature profiler and 10-m mast. In addition, WRF-ARW simulations are performed to verify and complement the observations. The data permit us to investigate major features of the flow over mountain ridges during several bora episodes. The qualitative and quantitative characteristics of the Novorossiysk bora were compared with those of other downslope winds, such as the Adriatic bora, the Boulder windstorm, and the Alpine foehn.

1. Introduction

The Novorossiysk bora is one of the most striking manifestations of downslope winds. It occurs on the lee side of the mountain ranges Caucasus and Markhotsky, on the coast of the Black Sea, which are aligned mainly in the north-west to south-east direction. Bora is observed mainly during the cold season between the Russian cities of Anapa and Tuapse (Fig. 1b), but the highest wind speeds (10-min average speed up to 35–40 m s^{-1}) usually occur in the Novorossiysk and Gelendzhik region (Fig. 1a). Such intense windstorms pose a great threat to the population in the area and can be catastrophic to vessels moored in the Novorossiysk harbour.

Complex studies of downslope windstorms using different observation systems were carried out mainly in the framework of large international projects such as ALPEX (Davies and Pichler, 1990), PYREX (Bougeault et al., 1997), MAP (Lothon et al., 2003; Jiang et al., 2005) and T-REX (Grubišić et al., 2008). The most studied and well-known downslope winds, similar to the Novorossiysk bora, are chinook (e.g. Brinkmann, 1974; Durran, 1986; Neiman et al., 1988), Alpine foehn (e.g. Furger et al., 2001; Jiang et al., 2005; Richner and Hächler, 2013), and Adriatic bora (e.g. Belušic et al., 2004; Boldrin et al., 2009; Davolio et al., 2016).

Many previous studies of the Novorossiysk bora rely heavily on the mesoscale numerical modelling (Toropov et al., 2012; Efimov and Barabanov, 2013; Toropov and Shestakova, 2014; Gavrikov and Ivanov, 2015). In a general form, simulation results allowed to investigate various types of flow behavior on the lee side of the ridges - the predominance of shooting flow with hydraulic jump in the Tsemess Bay (Fig. 1a) and the elevated bora jet (with boundary layer separation and formation of rotors) when lee waves are present (Shestakova et al., 2015; Efimov and Barabanov, 2013).

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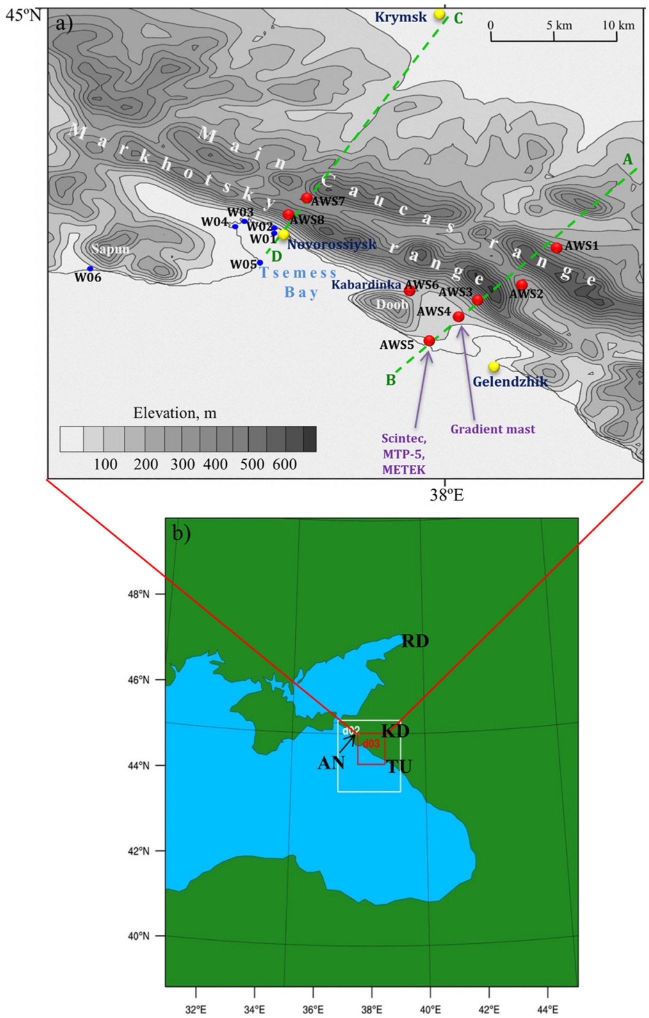

Fig. 1. a) Meteorological observations in the research area: RHS network stations (yellow dots), AWS (red dots), KHS wind sensors (blue dots); b) The computational domains with grid spacings of 15 km, 3 km (d02, white box), 600 m (d03, red box). The towns shown are Tuapse (TU), Anapa (AN), Krasnodar (KD), and Rostov-on-Don (RD) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

There have been some attempts to investigate physical mechanisms (namely hydraulic and wave mechanisms) of the phenomenon, using flow regime diagrams and wave drag calculations (Shestakova et al., 2018). From modeling results and indirectly from observations, it was found that the mechanism of Novorossiysk bora is essentially mixed. On the one hand, it is expressed in the simultaneous presence of such structures as a hydraulic jump (a jump-like change of the free surface height (an elevated inversion in the atmosphere)), and internal gravity waves (IGW) breaking zone. On the other hand, the variability of the contribution of the wave drag to orographic drag is very high, i.e. in some cases the wave mechanism does not work (when the elevated inversion is too strong and the mean state critical level is too low), but hydraulic mechanism does (Shestakova et al., 2018). Hydraulic mechanism implies the transition of flow regime from subcritical to supercritical over the lee slope under certain combination of parameters of the incoming flow (wind speed, inversion height and intensity), as well as wave regime changes from linear to nonlinear depending on the incoming flow (wind speed and low-level stratification) (Durran, 1986). Thus, both mechanisms are very sensitive to changes in the state of the incoming flow. The most important feature of the incoming flow during Novorossiysk bora is the permanent presence of an elevated temperature inversion with a lower boundary near the maximum height of the ridges (Shestakova et al., 2015, 2018). Stratification of the lower layer is usually close to neutral or weakly stable. Wind reversal with height (in average at altitude 5–6 km) is observed in 90% of cases, sometimes in the lower troposphere (similar to the shallow Adriatic bora (Grisogono and Belušić, 2009)).

In this paper, we would like to supplement already existing information about the physical mechanisms of Novorossiysk bora, the incoming flow and downslope flow behavior, obtained mainly on the basis of the modeling results, with observational data in order to get a full picture of the phenomena.

This paper aims to investigate the three-dimensional structure of the Novorossiysk bora derived from surface measurements, boundary layer soundings with a sodar and a microwave profiler and gradient mast observations. To the best of our knowledge, it is