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ATMOSPHERIC MODELING FOR ADVANCE WARNING OF WEATHER DISASTERS IN THE BLACK SEA REGION

ABSTRACT. Means for operational regional forecast of catastrophic weather events in the Black Sea region are presented. It is shown that the flooding in Krasnodar Region, Russia, July 7, 2012 was predicted five days before the tragic events, and the catastrophic storm of November 11, 2007 off the coast of Crimea was also predicted three days in advance. Quality of the regional forecast and its advantages over the global forecast are discussed. The operational regional modeling of the atmosphere in the Marine Hydrophysical Institute (National Academy of Sciences of Ukraine) could become an important element of a possible early warning system for weather disasters in the Azov-Black Sea region.

KEY WORDS: forecast of weather disasters, regional mesoscale atmospheric models, early warning system of weather disasters, Azov-Black Sea region, mesoscale atmospheric processes.

INTRODUCTION

Nowadays, EWS (Early Warning Systems) are discussed at the scientific, national and global levels (see, e.g., [United Nations International Strategy for Disaster Reduction, 2006; Basher, 2006; World Meteorological Organization, 2012; Russian Federation. Ministry for Civil Defense, Emergency and Eliminations of Consequences of Natural Disasters, 2013; Shaw et al., 2013]). It is well known how much effort is made to create reliable early warning systems of earthquakes and tsunamis. The structure and principles of EWS are described in a number of papers and documents (see, e.g., [United Nations International Strategy for Disaster Reduction, 2006; United Nations, 2006; Waidyanatha, 2010]). The most successful implementations of the national EWS are given in [Golnaraghi, 2012; Shaw et al., 2013]. Early warning systems of regional and subregional disasters related to weather conditions traditionally focus on warning about violent storms, heavy rainfalls and thunderstorms dangerous for aviation (see, e.g., [Clark et al., 2012]).

Development of a regional early warning system of weather disasters in the Black Sea region would be a natural step both from the point of view of its relevance and of modern prediction capabilities. Flooding of 6–7 July 2012 in the Krasnodar Region, Russian Federation caused a loss of more than 170 lives and huge economic damage [Volosukhin, Schursky, 2012]. However, the forecast of rainfall intensity had appeared five days before the flood at free access on the Internet website [Marine Hydrophysical Institute, 2013]. Regional early warning system would have allowed to make a conclusion about the impending disaster in Krymsk and thus saved many lives.

Another impressive example is a hazardous storm of 11 November 2007 near the Crimean coast. As a result of this disaster, tanker "Volgoneft-139" spitted in half in the Kerch Strait and two thousand tons of fuel oil spilled into the sea. Dry-cargo ship "Volnogorsk" carrying more than two thousand tons of sulfur sank in Port-Kavkaz. Tanker "Volgoneft-123" loaded with oil was severely damaged. Dry-cargo ships "Kovel", "Khash-Izmail", "Nakhichevan" sank and more than 20 members of the crews were missing. This sad list can be continued [Ovsienko et al., 2008]. However, the forecast of the wave height appeared on the Internet in free access on the website [Marine Hydrophysical Institute, 2013] three days before the storm. That allowed to make conclusions about the extreme dangers for vessels in the Kerch Strait, Sevastopol Bay and other coastal areas where many accidents happened.

A key element of an early warning system of weather disasters is an atmospheric model capable of making a reliable short-term forecast of meteorological fields in the region of interest (see, e.g., [Clark, 2012]). Currently, the leading global weather forecast operational centres, such as *NCEP/NCAR* (*National Center for Environmental Prediction/ National center of Atmospheric Research)* and *ECMWF* (*European Center for Medium range Weather Forecast*), are implementing a global weather forecast with a spatial resolution of 50 km and 30 km. This can reliably predict development and movement of synoptic cyclones with a lead time of several days. However, global operational forecasting models underestimate extreme values of wind speed and intensity of precipitation due to their coarse spatial resolution [Clark, 2012]. This fact is critical for predicting regional weather disasters. To improve prediction of extreme weather phenomena, it is necessary to use regional mesoscale models with a more detailed spatial-temporal resolution.

This article aims to present the means of operational regional modelling of the atmosphere, which already exist in Marine Hydrophysical Institute of National Academy of Sciences of Ukraine (MHI), as a possible element of the future system of early warning of weather disasters in the Azov-Black Sea region. The MHI system of short-term regional meteorological forecast is described below as well as the advantages in terms of forecast of weather disasters in relation to systems of global modeling of the atmosphere. The examples above of the two disasters in the Azov-Black Sea region show that the forecast of MHI obviously contained their predictions. The capabilities and reliability of the regional forecast system are discussed.

SYSTEM OF SHORT-TERM METEOROLOGICAL FORECAST

Nowadays, the leading global operational weather centers, such as *NCEP/NCAR* and *ECMWF* make global operational weather forecasts with a lead time of up to 15 days. The forecast is made every 6 hours, four times a day. In order to analyze the state of the atmosphere all available data is used: ground-based measurements, vertical sounding of the atmosphere, satellite data and other (see forecast description given at the websites [Environmental Modeling Center, 2013; European Centre for Medium-Range Weather Forecasts, 2013]). Spatial resolution of the global atmospheric models used for forecast, is currently 50 km for the *NCEP/NCAR* and 30 km for *ECMWF*. This resolution allows us to predict the development and movement of synoptic cyclones reliably with a lead time of a few days. However, global operational forecasting models underestimate the extreme values of wind speed and precipitation due to their coarse spatial resolution.

In order to improve the forecast of extreme weather phenomena, it is necessary to use regional mesoscale models which are run for a single small region and have a spatial resolution up to 1 km. In this case, the results of global forecast are used as boundary conditions for the regional models. *MM5* mesoscale atmospheric model and its more modern variant, *WRF* (Weather Research and Forecasting), have been developed by the U.S. National Center of Atmospheric Research for both scientific research of mesoscale weather phenomena, and for operational forecasts and regional re-analyses [Skamarock et al., 2008]. Mesoscale atmospheric model describes air movement and transfer of heat and moisture in the atmosphere using the high-quality numerical schemes. It realistically accounts the transfer of IR and visible solar radiation, the process of clouds and precipitation formation, cumulus convection, turbulent fluxes of momentum, heat and moisture in the planetary atmospheric boundary layer and in the surface layer, the transfer of heat and moisture in the upper soil layer and other physical processes.

The mesoscale model must be adapted to a particular region, which implies selecting the most appropriate schemes for parameterization of physical processes, as well as a more detailed setting of properties of the underlying surface in the region, especially orographic peculiarities. Among the examples of such adaptation are synoptic and climate researches in the high latitudes of the Greenland and Antarctic [Box et al. 2004], as well as regional operational forecasts for the United States and some parts of Asia, Central and South America, which are given on the web pages [Mesoscale Prediction Group, 2013; Fovell, 2013; Wilson, 2013].

MM5 model, which was adapted to the Black Sea region in MHI, was used for retrospective studies of individual mesoscale atmospheric processes and extreme events – quasi-tropical cyclone of 25–30 September 2005 [Efimov et al., 2008], breeze circulation [Efimov, Barabanov, 2009], precipitation leading to extreme floods in the Crimean rivers [Ivanov et al., 2012b]. The results of *MM5* and *WAM* models calculations were used to analyze the conditions of formation of the 12-meter rogue waves on 1 February 2003, near Gelendzhik [Ivanov et al., 2012a]. Verification of models using direct measurements in the Black Sea region was discussed in [Shokurov, 2011].

Mesoscale operational forecast is made with the use of *MM5* model with a spatial resolution of 10 km. Computational area covers the whole Black Sea (39°–49° N, 25°–45° E) and allows to analyze both weather patterns and mesoscale features. We use the results of the *NCEP/NCAR GFS* operational forecast with the resolution of 0,5°–0,5° for every 6 hours as lateral boundary conditions. Forecast results were repeatedly tested by hindcasts using the *WRF* model.

MHI started to perform the operational weather forecast in the Black Sea region in 2007 using *MM5* model. Spatial resolution for the entire Black Sea region was 10 km with the forecast lead time of 3 days. In the beginning of 2011 we also started making forecasts for the Crimean region with a resolution of 3 km, and in the middle of 2011 the lead time was increased to 5 days. In addition to the weather forecast, wind waves forecast for the whole Black Sea area is made using *WAM* model of wind waves (see, e.g., [WAMDI Group, 1988; Holthuijsen, 2007]. Forecast results are available in graphical and digital formats in open access on the Internet at http://vao.hydrophys.org [Marine Hydrophysical Institute, 2013]. This site shows the fields of pressure at the sea level, air temperature at the height of 2 m, wind speed and direction at the height of 10 m, intensity of rainfall, also heights, periods and direction of waves with discrete time of 3 hours.

During the period of forecast performing, the two above-mentioned major regional natural disasters happened in the Black Sea region – the severe storm of 11 November 2007 off the Crimean coast and the flood of 6–7 July 2012 in Krymsk, Russia. Predictions of both disasters in the form of prognostic fields of wind speed, wave height and precipitation intensity were obtained and presented on the Internet in free access. The information about this catastrophic storm was published 3 days before the event, and the data about the hazardous precipitation rate was published 5 days before.

The forecast system described above can be used as an element of an early warning system of weather disasters in the Azov-

Black sea region. We will use two examples to show that the results of the forecast presented on the site unambiguously mean the predictions of disasters. We will also show that the results of the global forecast did not allow to draw conclusions about the impending disasters.

DISASTROUS STORM OF 11 NOVEMBER 2007

Synoptic situation during the storm was discussed in [Ovsienko et al., 2008]. As follows from the standard maps of operational meteorological analysis based on ground-based observations and satellite images of cloudiness from Meteosat satellite, the disastrous storm of 11 November 2007 was connected with a cyclone passage, which belongs to a category of the so-called "southern" cyclones. Having emerged over the Aegean Sea, it moved to the North-East over the Western part of the Black Sea and the Crimea. Such synoptic situation is typical of the Black Sea region – "southern" cyclones pass over the Western part of the Black Sea quite often. Sometimes they are intense, but they result in catastrophic storms quite seldom. Examples of such extreme events are storms of 9 October 2003 and 9–10 November 1981.

Currently synoptic processes, such as occurrence and movement of cyclones, are reliably predicted for up to three days and even more in the international and national centers of global analysis and forecast of atmospheric circulation. The shape and movement trajectory of the considered cyclone in the global and regional forecasts were almost identical. This is because the cyclone is fairly large in size, and its behavior inside the computational area of the mesoscale model is determined by the boundary conditions, which are taken from the global model of operational forecast. However, coarse resolution of global models (50 km) leads to an underestimation of extreme wind speeds. The use of low wind speeds over the Black Sea as input data for the wave model causes underestimation of the energy of the surface waves and, consequently, underestimation of the danger such storm represents.

Fig. 1a shows a map of wind speed at 10 m above the Black Sea level according to the model of the global operational analysis and forecast of the American center NCEP/NCAR with a resolution of 0,5°–0,5° at the time of 06:00 UTC on 11 November 2007 [NOAA Operational Model Archive Distribution System, 2013]. As it follows from the figure, and also from the calculations using global models for the other time points, wind speed over the Black Sea does not exceed 25 m/s. Fig. 1b shows a map of the wind speed over the Black Sea obtained from the *QuikSCAT* satellite scatterometer at the time of 03:35 UTC, 11 November 2007 [Ocean Surface Winds Team, 2013]. It is obvious in comparing the figures that the real wind speed significantly exceeded the results of calculations with the global model. It is confirmed by standard measurements at the meteorological stations (see Table. 1). These measurements were carried out every 3 or

Table 1. Maximum wind speeds 11 November 2007

Meteorological station	WMO Code	Wind speed, m/s	Time UTC
Simferopol	33946	23(32)	6:00
Chernomorskoye	33924	24(28)	6:00
Kerch	33983	20(27)	9:00
Ai-Petri	33998	27	6:00
Genichesk	33910	35(38)	12:00
Mariupol	34712	20(28)	15:00
Tuapse	37018	10(23)	6:00, 9:00
Sulina	15360	20(28)	00:00
Feodosia	33976	12(25)	6:00

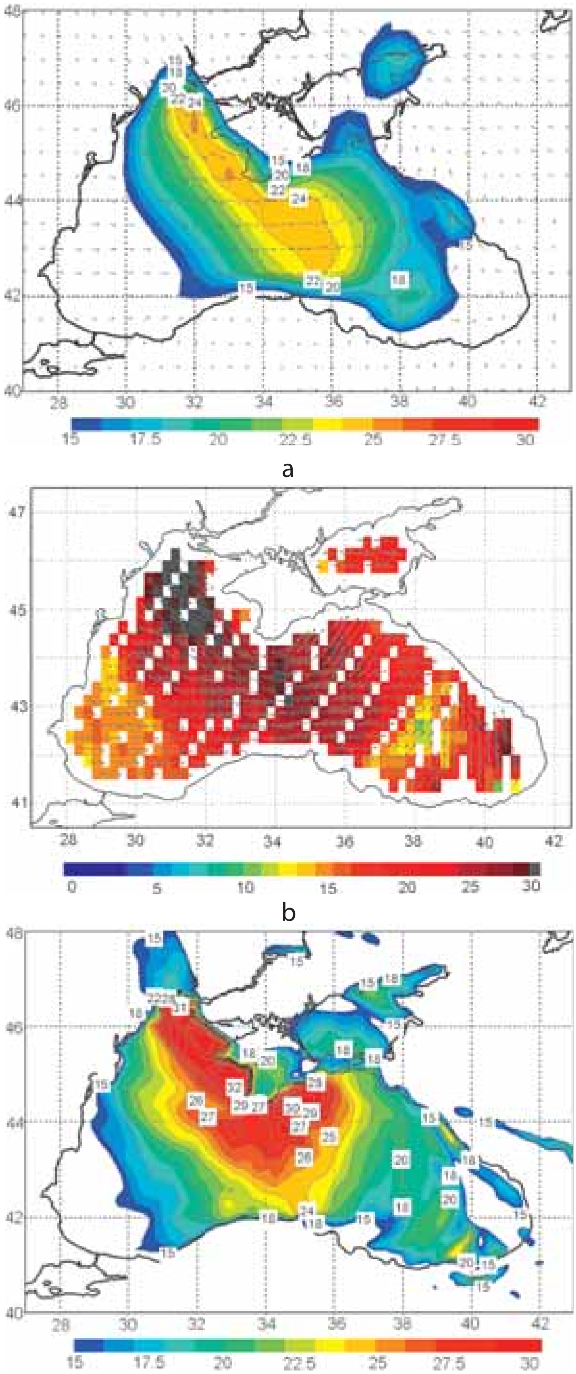


Fig. 1. Wind field during the catastrophic storm.

a – Map of wind speed resulting from global operational forecast NCEP/NCAR GFS with 0,5°–0,5° spatial resolution at a time of 06:00 UTC on November 11, 2007. [NOAA Operational Model Archive Distribution System, 2013].
b – Map of wind speed derived from satellite measurements of November 11, 2007 (QuikSCAT scatterometer, 12,5 km spatial resolution) [Ocean Surface Winds Team, 2013].
c – Map of wind speed resulting from regional operational forecast using MM5 model with 10 km spatial resolution at a time of 06:00 UTC on November 11, 2007. [Marine Hydrophysical Institute, 2013].
Only contours of wind speed exceeding 15 m/s are shown in fig. 1a and 1c

6 hours and lasted for 10 minutes. The table shows the average and maximum (in parentheses) values. The measured values of wind speed reached and exceeded 30 m/s. In particular, the maximum wind speed in Genichesk equaled 35 m/s. Fig. 1c shows the results of the regional forecast for wind speed at 10 m level at the time of 06:00 UTC on 11 November 2007 [Marine Hydrophysical Institute, 2013]. This figure proves that the maximum wind speed reached 32 m/s. For other time points, the wind speed was also higher than in global models.

Results of the atmospheric forecast were used to predict the wind wave field with a resolution of 10 km using the *WAM*. Fig. 2 shows two variants of significant wave height calculations for various inputs of WAM at a time of 10:00 UTC on November 11, 2007. In Fig. 2a the wind speed of *NCEP/NCAR GFS* global model of 0,5° resolution was used as an input. Fig. 2b shows the wave forecast presented on the Internet 3 days before the storm based on the operational forecast of *MM5* mesoscale model of 10 km resolution. Note that the same color scale is used in both figures. According to the figure, the maximum significant wave height in Sevastopol area reached 5 m for the global model and 7 m for the mesoscale model. In the Kerch Strait, where many ships sank, the maximum wave heights were 5 m and 9 m respectively.

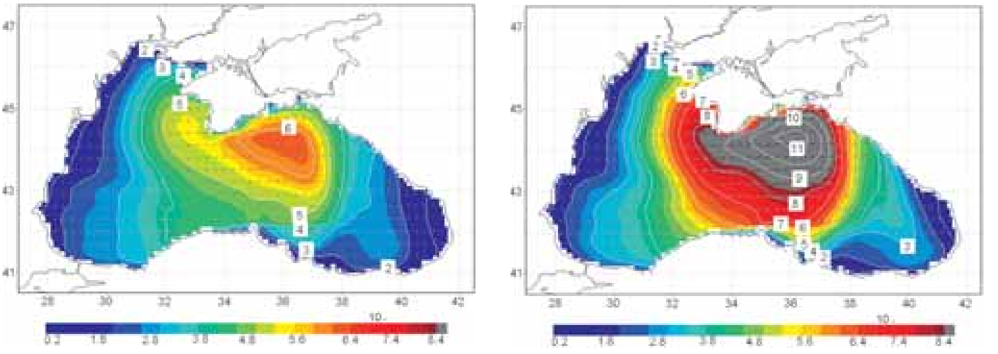


Fig. 2. Results of the forecast of wind waves for November 11, 2007, 10:00 UTC.
a – wind from global operational forecast; b – wind from MM5 forecast with 10 km resolution. Contours show significant wave height, arrows indicate direction of the waves

The maps of wind waves parameters obtained through the forecast allow tracing the evolution of the wave field for the Black Sea basin with 1 hour discreteness. As follows from such analysis, the waves that arrived at the Kerch Strait travelled from the region adjacent to the Bosporus. Note that Fig. 1 and 2 show the fields of wind and waves at 06:00 and 10:00 respectively. However**,** the waves travelled over about 800 kilometers for approximately 24 hours. During this period the cyclone significantly shifted to the North-East. As a result the waves remained under the impact of South-West wind along the entire wave fetch. Thus the wind waves off the Crimean coast appeared as a result of long-term wave development from Istanbul to Kerch. As it is known the significant wave height is approximately proportional to the square of the wind speed (see, e.g., [Holthuijsen, 2007]). Therefore, in this case underestimation of wind speed in the global forecast caused a far more significant underestimation of the wave height. As a result, the global forecast did not contain predictions of an extremely hazardous storm, while the regional forecast based on *MM5* and *WAM* models clearly indicated the impending disaster.

DISASTROUS FLOOD IN KRASNODAR REGION OF 6–7 JULY 2012

Synoptic conditions of the disaster in Krasnodar Region was discussed in [Kuklev et al., 2013] on the basis of baric maps of the global forecast. The cyclone, which caused extreme precipitation in Krasnodar Region, was formed to the East of the Black Sea and slowly moved to the South-West. During 6–7 July, the center of the cyclone almost didn't shift. The authors of [Kuklev et al., 2013] consider this circumstance as the main cause of the heavy rains on a limited area, explaining the "halt" of the cyclone by a process of convection over the heated Sea of Azov. It will be shown below that regional atmospheric modeling allows to obtain a deeper and more adequate interpretation of meteorological reasons of the flood.

Fig. 3 shows a standard weather map of the cyclone, a map of the average intensity of precipitation over two days, which depicts the localization of catastrophic rainfall, and *Meteosat* satellite images of cloudiness, which describe the evolution of the cyclone in the period under consideration. The map of precipitation was made using the Giovanni online data system [Goddard Earth Sciences Data and Information Services Center, 2013]. The satellite images were obtained from an open site [Dundee Satellite Receiving Station, 2013]. The large-scale features of such synoptic conditions were predicted by both global prognostic models and regional forecast. However, the *NCEP/NCAR GFS* global prediction models showed insignificant quantities of precipitation. It is shown in Fig. 4a where the 2 days sum of precipitation in the vicinity of Novorossiysk is about 60 mm. The

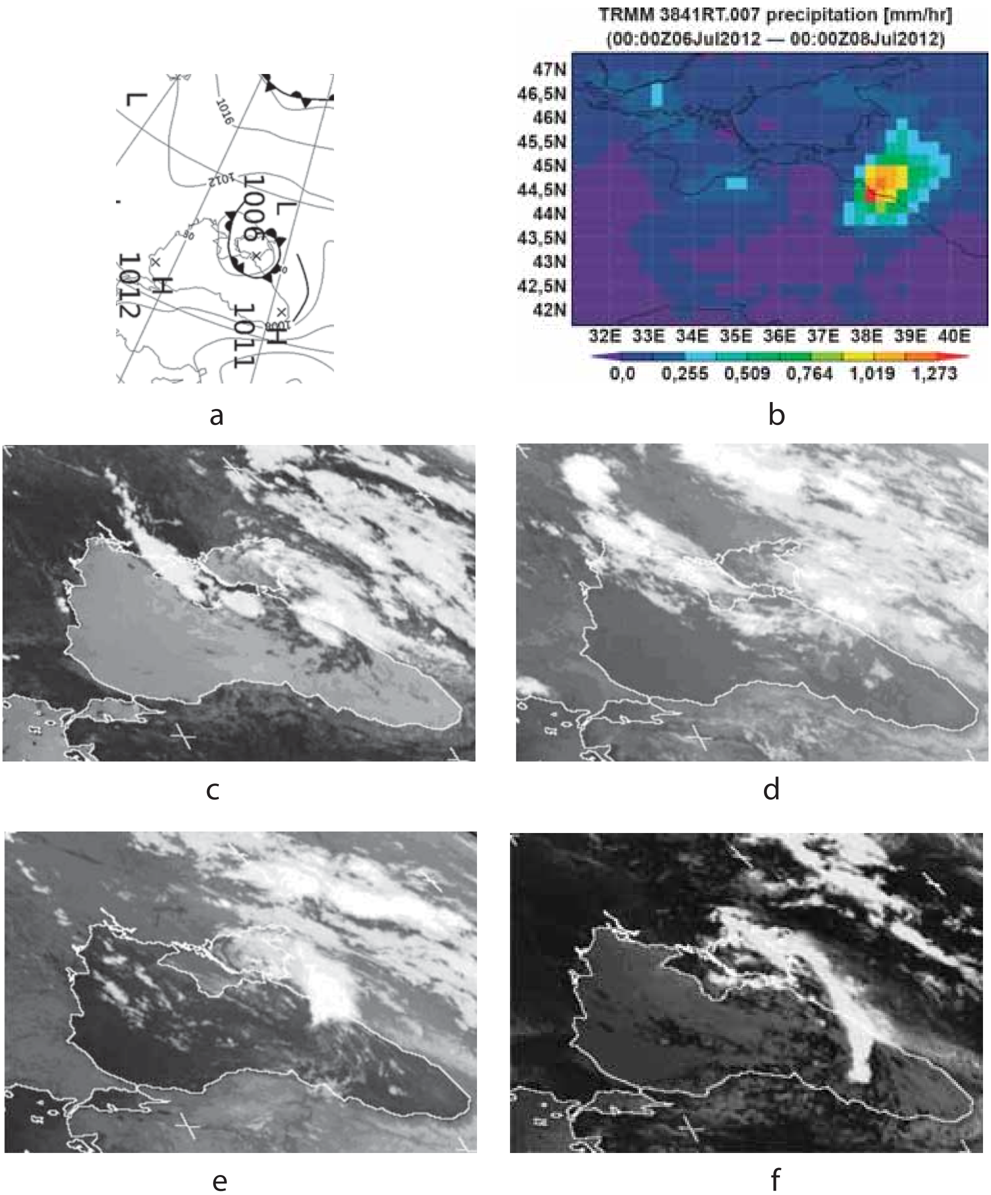
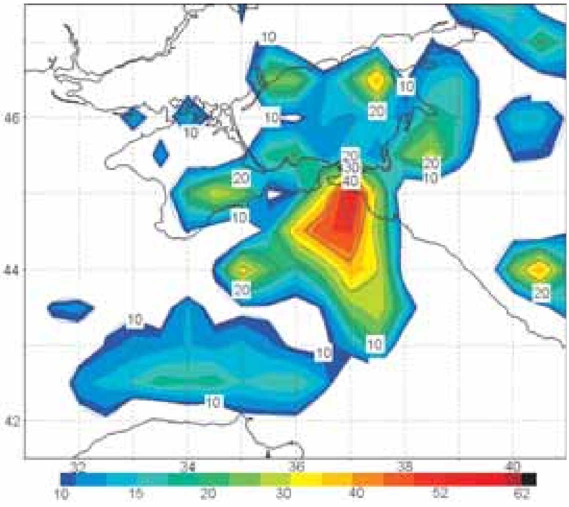


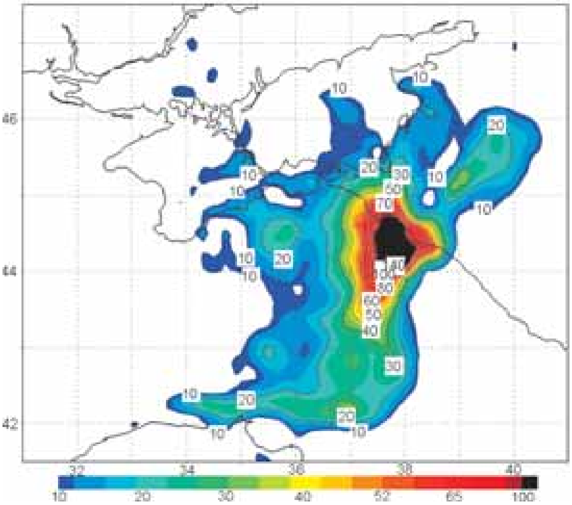
Fig. 3. Characteristics of synoptic situation.
a – Standard map of operational meteorological analysis for 6 July 2012, 12:00 UTC;
b – Map of average intensity of precipitation for two days
[Goddard Earth Sciences Data and Information Services Center, 2013];
satellite images of cloudiness in the thermal range [Dundee Satellite Receiving Station, 2013] for time points (UTC):
c – 6 July 2012, 12:00, d – 6 July 2012,18:00, e – 7 July 2012, 00:00, f – 7 July 2012, 06:00

same quantity of precipitation follows from the map in Fig. 3b. It should be emphasized that this map was obtained through indirect estimates based on the IR-radiometer data [Goddard Earth Sciences Data and Information Services Center, 2013]. However, according to the direct measurements at the meteorological stations, the 2 days sum of precipitation was much higher. It reached 283 mm in Novorossiysk, 275 mm in Gelendzhik, and 171 mm in Krymsk.

Results of mesoscale operational forecast of *MM5* model with 10 km resolution are



a



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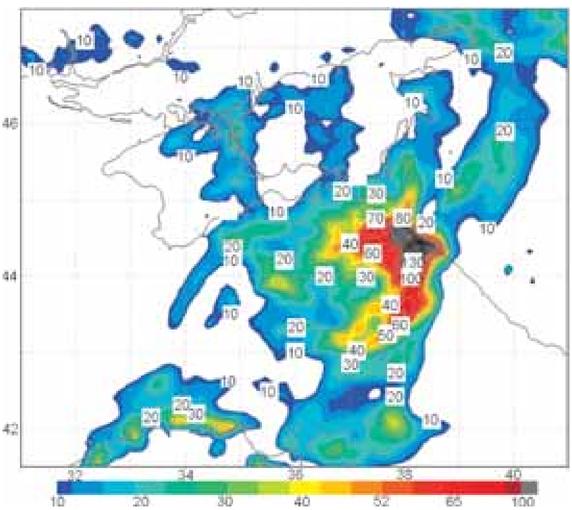


c

shown in Fig. 4b. Exactly the same precipitation map was presented in free access on the Internet 5 days before the disaster. It shows the two days sum of precipitation in the vicinity of Novorossiysk which is three times higher than the predictions of global models and are consistent with the measurements at meteorological stations during the disaster.

Unlike global models, where the processes of cumulus convection are parameterized, regional models perform direct calculation of these processes [Clark et al., 2012]. Apart from clarifying the forecast, it also allows to thoroughly investigate the physics of the phenomena. Such analysis, in turn, allows obtaining an adequate meteorological interpretation of the disastrous weather event. In this case, as follows from the analysis of the calculated three-dimensional fields of atmospheric physical characteristics, the South-West air flow started to move upward after encountering the Markhotsky ridge near Novorossiysk. This air lifting initiated deep cumulus convection and local heavy rainfalls which lasted for several hours. It was this that caused the catastrophic flood.

This explanation of the phenomenon under consideration disagree with the conclusions of [Kuklev, 2013] based only on standard meteorological analysis. This explanation is also impossible in the framework of global modeling, because it requires

Fig. 4. Forecast results of 2 days precipitation sum for 6–7 July 2012.

a – global operational forecast of 0,5°–0,5° resolution;

b – MM5 operational forecast of 10 km resolution;

c – WRF hindcast of 5 km resolution

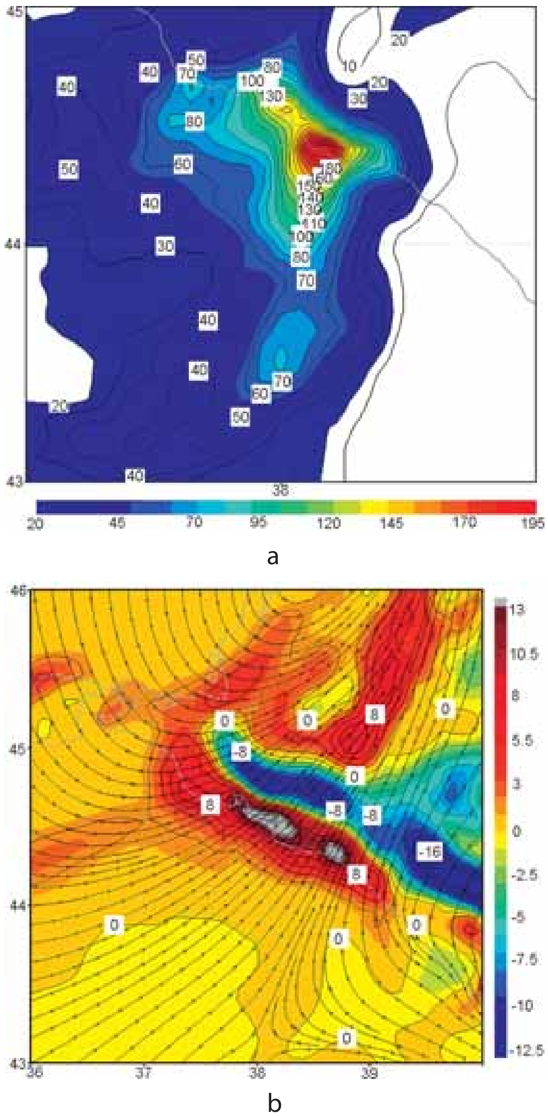


Fig. 5. Localization of catastrophic rainfall and its mechanism

a – zoomed fragment of Fig. 4c (2 days sum of precipitation);
b – air flow speed at the level of 400 meters above the underlying surface for synoptic time of 7 July 2012 00:00 UTC.
Horizontal wind speed is shown using streamlines and vertical velocity is shown in color and contours

accounting for the regional orography. At the same time, this interpretation of the situation is well consistent with the satellite images of cloudiness (see Fig. 3). The brightest areas of the images correspond to the dense cumulonimbus clouds, which visualize the process of deep cumulus convection. According to the figures, deep cumulus convection continued for at least 18 hours, from 12:00 on July 6 up to 6:00 on July 7. It was in this period that the heavy rainfall took place in the area of Novorossiysk.

To illustrate and verify the conclusions which follow from the results of regional forecast, we made a hindcast using the *WRF* model of 5 km resolution. The obtained map of 2 days sum of precipitation is shown in Fig. 4c, while Fig. 5a shows its zoomed fragment. Note that the forecast gives a very small area of localization of extreme precipitation. As it can be seen from Fig. 4c and 5a, the characteristic size of the area, where the two days sum of precipitation exceeded 100 mm is 50 km. However, the heaviest rainfalls, with the two days sum exceeding 200 mm, were localized into only about 20 km area. This circumstance might have led to a quantitative underestimation of rainfall from satellite IR-radiometer data (see Fig. 2b), because the spatial resolution of radiometer is 0,25°–0,25° that is not enough to identify such a small area. At the same time, significant localization of extreme precipitation events was observed actually [Volosukhin, Schursky, 2012, Kuklev, 2013].

Fig. 5b illustrates the mechanism of heavy rainfall on a small area. It shows the field of the air flow speed at the level of 400 meters. Horizontal speed is shown with streamlines while vertical speed is shown with color scale and contour lines. The air flow related to cyclone had South-West direction near Novorossiysk. When the air volumes arrived at the Markhotsky ridge, they started rising at a high vertical speed up to 14 cm/s. This, in turn, initiated the deep cumulus convection and heavy local rainfalls. Since the cyclone hardly moved during 6–7 July, the mechanism described above kept working for several hours and it resulted in a disastrous flood.

Thus, the regional forecast taking into account the microphysics of the atmospheric processes presented a correct prediction of disastrous rainfalls in the vicinity of Novorossiysk. At the same time, in the frame of the global forecast or traditional meteorological analysis, such prediction was impossible.

DISCUSSION AND CONCLUSIONS

We shall consider the quality of short-term forecasting for the Black Sea region for all the time of operation of the system in MHI. Fig. 6 shows the results of forecasting of rainfall intensity in the area of Novorossiysk since 2007 till present days (the system temporarily did not work in the period from December 2007 to July 2008). The daily sum of precipitation for the model grid point closest to Novorossiysk is presented depending on time. As follows from the figure, the forecast system does not issue "false alarms". At the same time the graphs leave no doubt that the forecast of abnormal

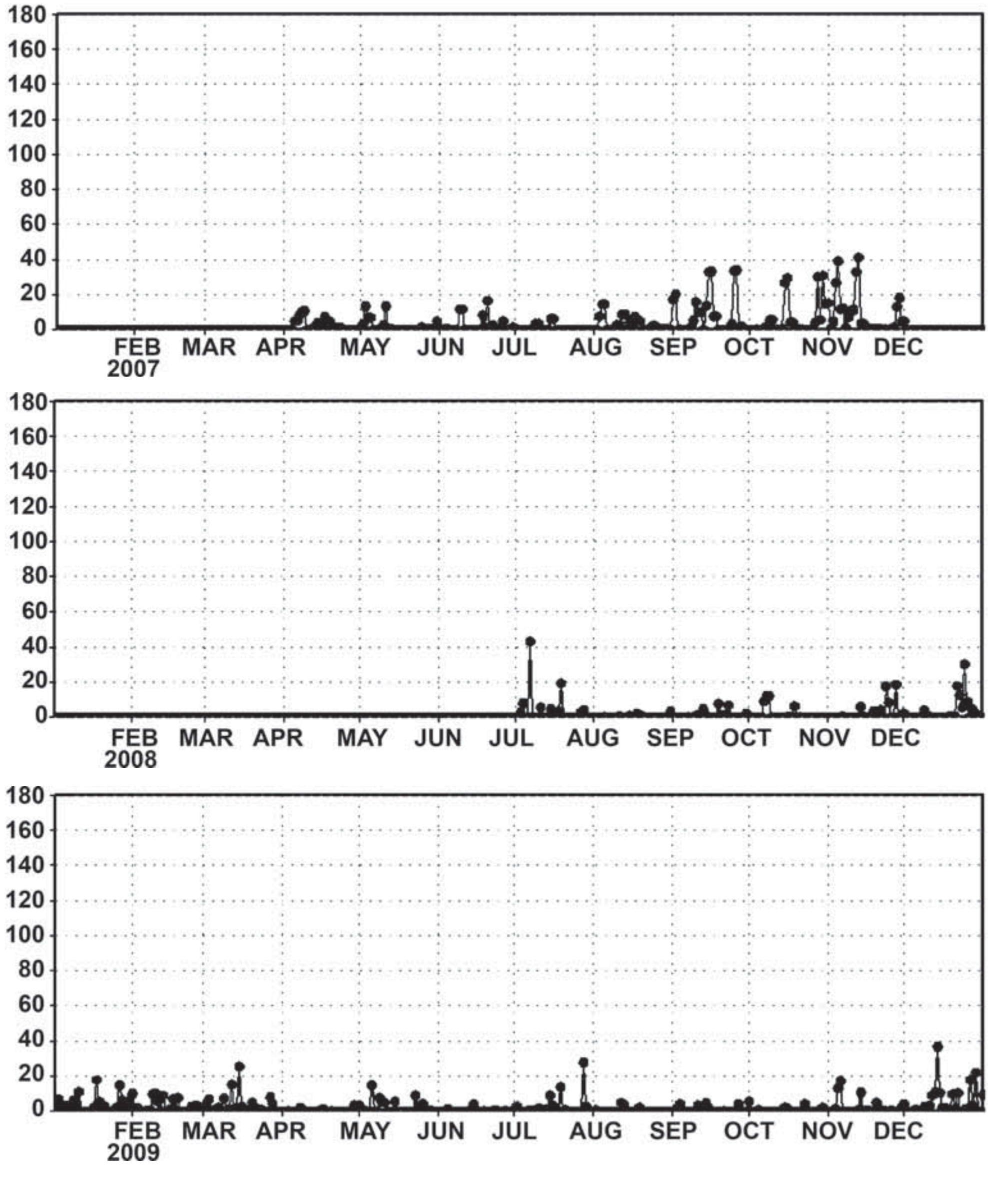
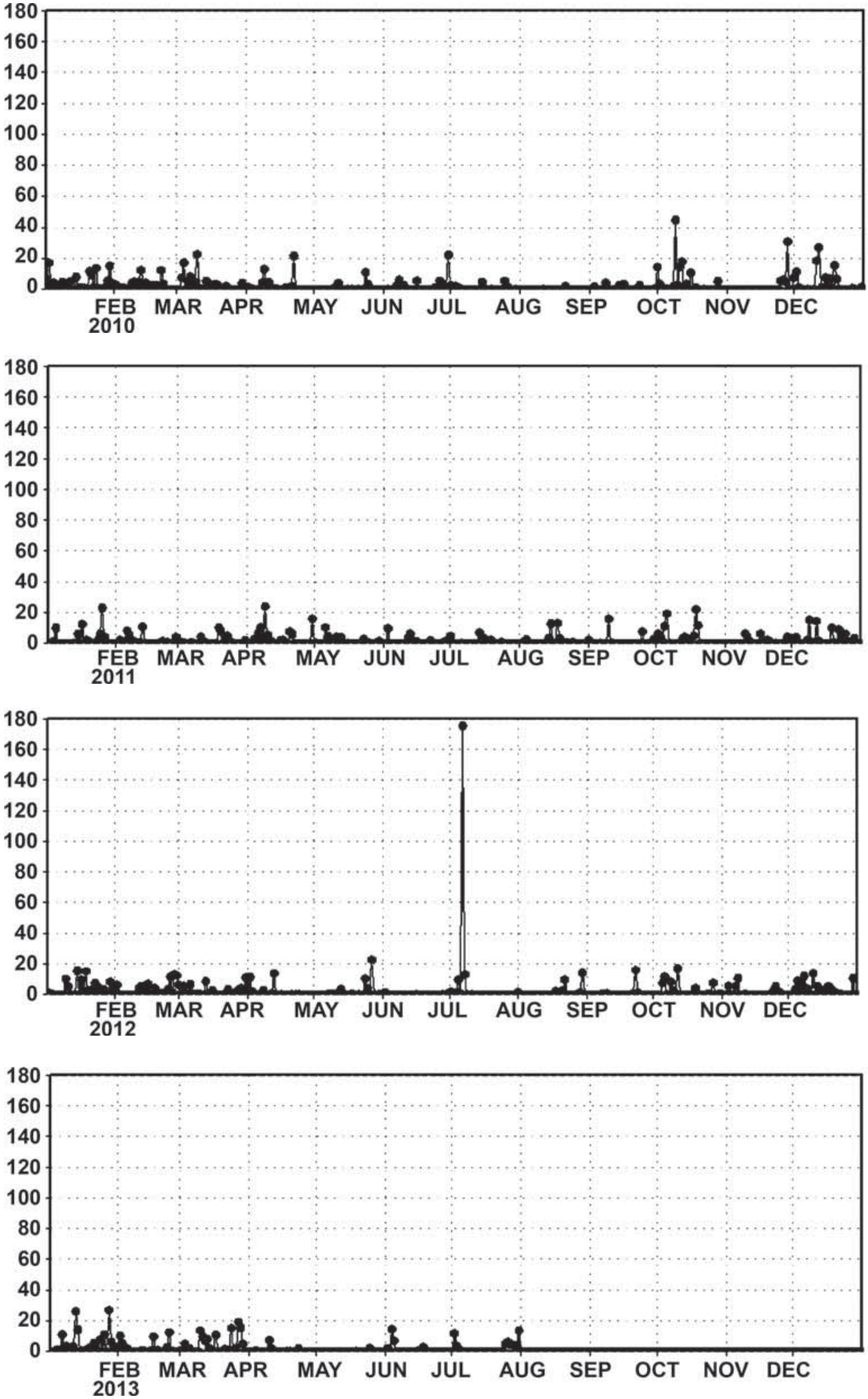


Fig. 6. Results of the operational forecast of MHI for 2007–2013. →



Daily precipitation totals in grid point of the model which is the closest to Novorossiysk

rainfall intensity on 7 July 2012 could be easily identified. Fig. 7 shows the results of forecast of significant wave height near the Kerch Strait in the point with coordinates 45° N, 36,6° E. As can be seen in the figure, the catastrophic storm on 11 November 2007 is easy to detect in the form of abnormal values of the forecast. Fig. 6 and 7 confirm high reliability of the system for short-term regional forecast implemented in MHI.

It is known that the quality of the forecast can be improved using parallel calculation of several variants of numerical models [Clark et al., 2012]. At present, MHI has already implemented a short-term weather forecast for the Azov-Black Sea region with the

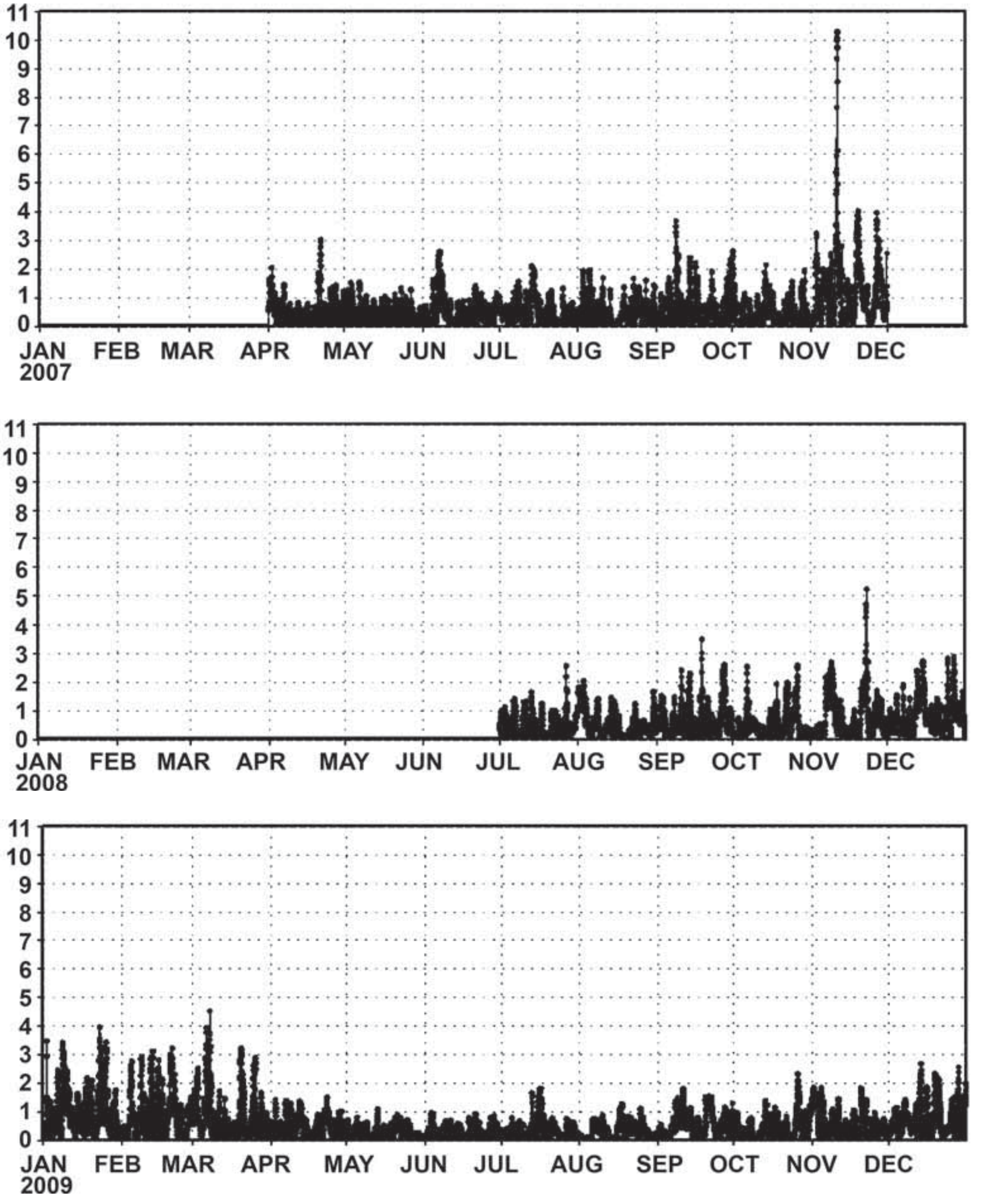
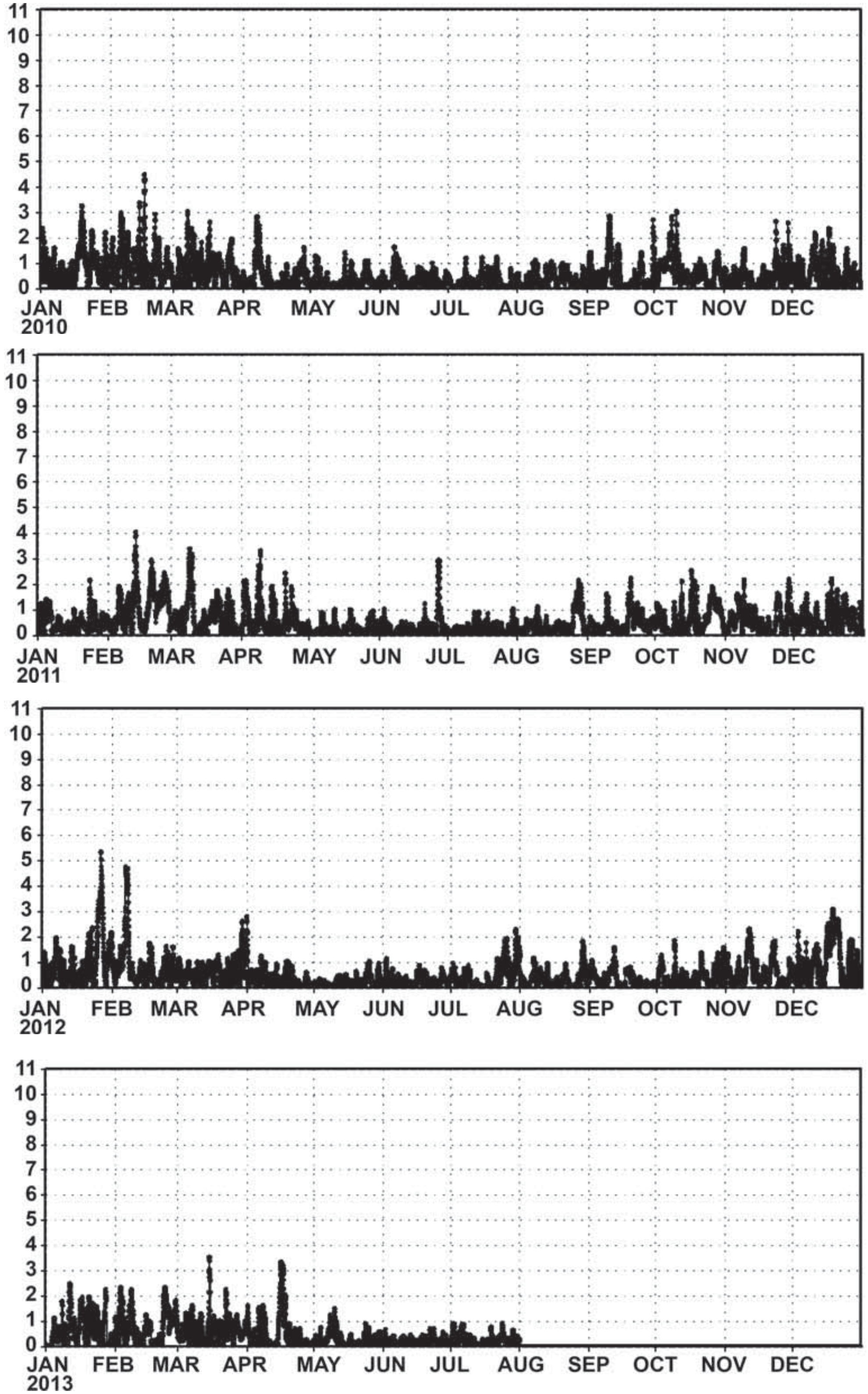


Fig. 7. Results of the operational forecast of MHI for 2007–2013. →



→ **Significant waves height in the Black Sea in area near the Kerch Strait** parallel use of *MM5* and *WRF* mesoscale atmospheric models.

It should be stressed that for flood forecasting in mountainous areas, precipitation forecasts with a high spatial resolution are not enough. In addition to the results of the forecast, a realistic model of river flow is needed, which uses the results of mesoscale atmospheric modeling as an input. Such system is already implemented for the South Crimea area (see, e.g., [Ivanov, 2012b]). It should also be noted that *WAM* can only be applied for wave forecast in the deepwater part of the Azov-Black Sea basin, where the depth exceeds half the length of dominant surface waves (see, e.g., [Holthuijsen, 2007]). In order to involve the Azov Sea and North-Western part of the Black Sea in the forecast area, the wave model should be supplemented by appropriate *SWAN* or *WAVEWATCH* models [Holthuijsen, 2007]. These are the obvious directions of improvement for the MHI forecast system.

This paper uses the examples of two catastrophic weather events in the Black Sea region to demonstrate the high quality and reliability of mesoscale atmospheric predictions, and their advantages comparing to the global forecast. The use of such forecasts could lead to significant reduction in human losses and economic damage from catastrophic weather events. The means of operational regional modeling of the atmosphere in the Marine Hydrophysical Institute of the NAS of Ukraine could become an element of a prospective early warning system for weather disasters in the Azov-Black Sea region.

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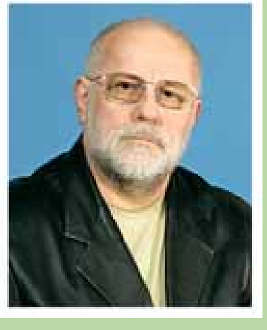

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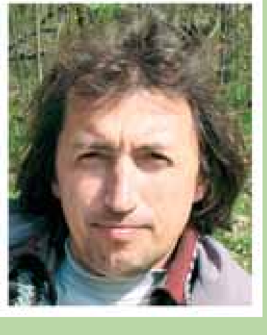

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