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Analysis of a storm situation over the southern Baltic Sea using direct hydrometeorological and remote sensing measurements results

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Abstract

The paper presents results of research concerning meteorological and hydrological conditions in the storm related with the Xaver cyclone moving fast over the Baltic Sea. The analyses were based on remote sensing data from radars in Świdwin and Gdańsk-Rębiechowo and hydrometeorological data from direct measurements conducted at the coastal stations of the Polish Navy, marine stations of the Institute of Meteorology and Water Management, hydrometeorological station on the "Baltic Beta" oil rig and the Coastal Research Station of the Institute of Hydroengineering of the Polish Academy of Sciences in Lubiatowo. The assessment of the synoptic situation was made using surface weather charts, satellite images of cloud cover and meteorological radars products.

The measurement data were used to analyze the surface and upper air wind fields for assessment of the hydrological situation (water condition, height and direction of the significant and maximum waves) and evaluation of threats to sea navigation and coastal infrastructure.

Introduction

The horizontal and vertical structure of the wind field depends mainly on the synoptic situation determined by air pressure distribution in the individual atmospheric layers; on environmental conditions, including type and state of ground surface; orography; infrastructure; and on season. Assessment of threats related with extreme winds occurrence requires considering both the magnitude of the area involved, the processes that cause the phenomenon, and its duration.

Occurrence of strong winds in the mid-latitudes – discussed here for the area of the Baltic Sea and northern part of Poland – is related mainly with active cyclones. This means that the strong winds zone is of the synoptic scale, i.e. it extends in an area of over 500 NM across and it lasts for a few days.

According to the World Meteorological Organization classification of weather phenomena, a storm is reported when the wind speed exceeds 17 m/s (34 knots) which is equivalent to at least Beaufort force 8. For this value of the wind speed, the sea wave height is at least 5.5 m, i.e. the sea state is at least 7 of 10 degrees in the Douglas scale. According to both scales, a hurricane (Beaufort force 12) with wind speed exceeding 32.6 m/s (63 knots) develops waves over 14 m high (sea state 9) [1].

Storms cause serious difficulties or they are even threats to safety of sea navigation and work in harbors. They often destroy hydrotechnical devices and coast facilities. Although only a part of the storms are classified as extreme ones, climatological studies indicate that they are relatively frequent on the Baltic Sea. Hydrometeorological support of sea navigation is therefore an important task aimed also to reduce the risk of victims and losses. Direct hydrometeorological and remote sensing measurements results become more and more common data applied to detecting, monitoring and forecasting processes conductive to storms development.

Analysis of storm situations over the Baltic Sea based on climatological studies

The hydrometeorological measurements network is for obvious reasons rare in the sea areas. The measurements are made at coastal meteorological stations, measurement buoys, oil rigs and ships and warships. The measurement data from the vessels are available in the FM 13-XII Ext. SHIP code for the main and intermediate observation times: 00, 03, 06, 09, 12, 15, 18 and 21 UTC. Due to the rare measurement network and significant changes in the data availability from the individual observation times, the authors of the climatological studies have various approaches to the acquired source data and the applied methods of analyses enabling to formulate objective conclusions.

Surface weather charts and 500 hPa height charts at 00 UTC from the period of 1971 through 2009 were the data source in [2] for determining the cases of storms over the Baltic Sea. The authors analyzed the charts for occurrence of surface wind speed exceeding the criterion of storm. The assessment of the surface wind speed was made using calculated speed of geostrophic wind (the average reduction coefficient was assumed at the value of 0.7). It was also assumed that the air density was independent of temperature changes.

For regional differentiation of the number of stormy days, the Baltic Sea was divided into two parts – northern and southern – along the 60°N parallel. The cases of storm wind were assigned to southern or northern part of the Baltic Sea, or to both (Table 1) [3].

The average number of stormy days over the Baltic Sea was 41.9 in the analyzed period of 39 years. The obtained value does not significantly differ from the data available for the North Sea or the Norwegian Sea. The synoptic charts analysis indicates that for both parts of the Baltic Sea, the storm winds occurred in cyclones moving along various routes of which none was significantly more frequent [2].

Table 1. The number of stormy days over the Baltic Sea in the period of 1971 through 2009 based on [3]

	Number of stormy days over the Baltic Sea:			
	Northern Baltic	Southern Baltic	Northern and southern Baltic at the same time	Total
Number of days	663	523	448	1634
Average	17.00	13.41	11.49	41.90
Minimum (year)	9 (2008)	4 (2006)	4 (1977)	28 (2005, 2009)
Maximum (year)	32 (1992)	23 (1980, 1988)	19 (1983, 1993)	61 (1992, 1993)

The author of [4] analyzed cases of high speed winds at the Polish coast of the Baltic Sea in the period of 1971 through 1990. Measurement data from four meteorological stations in Świnoujście, Kołobrzeg, Ustka and Łeba were used in the research. The stations are located less than a mile from the coast. The coastline features and surface roughness in the area of the measurement sites were taken into consideration in the analyses. These are important factors in wind speed and direction investigation. Wind speed (with the accuracy of 1 m/s) and wind direction (in 10° ranges) data were obtained from measurements made at the 00, 03, 06, 09, 12, 15, 18 and 21 UTC observation times.

The scope of the research included determining yearly and daily courses of occurrence of wind speed exceeding 10 m/s and 15 m/s; determining maximum wind speed in the analyzed period of 20 years; calculating the 0.95 percentile of the wind speed and determining the longest continuous periods with wind speed exceeding 10 m/s and 15 m/s. The yearly frequencies of their occurrence in the individual Lityński circulation types were also determined.

The following essential conclusions were formulated in [5] based on the research results:

– the highest average number of days with wind speeds exceeding 10 m/s is observed in autumn

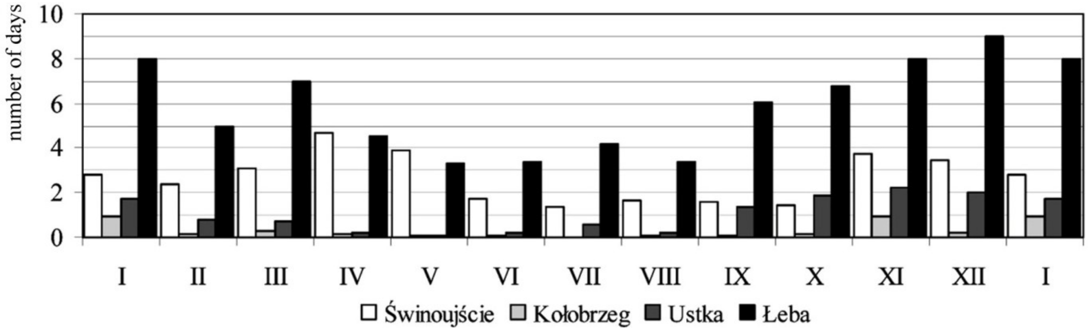

Fig. 1. Annual course of number of days with strong wind (> 10 m/s) at the Polish coast of the Baltic Sea (1971–1990) [5]

Table 2. Maximum wind speed and 0.95 percentile wind speed at the stations at the Polish coast of the Baltic Sea (1971–1990) [5]

Stations	Wind speed [m/s]	Months											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Świnoujście	0.95 percentile	9	9	9	11	11	8	8	8	8	8	10	10
	max.	18	19	18	22	18	19	19	17	18	17	19	19
Kołobrzeg	0.95 percentile	8	7	7	7	7	6	6	6	7	7	8	8
	max.	15	12	13	13	12	12	10	12	12	14	17	12
Ustka	0.95 percentile	9	8	8	7	7	7	8	7	8	8	9	9
	max.	18	15	15	19	12	13	15	16	18	18	22	18
Łeba	0.95 percentile	13	12	12	11	10	10	10	10	12	12	12	13
	max.	25	24	24	22	17	18	16	17	19	20	25	20

and winter, and in Świnoujście also in spring (Fig. 1);

- in the analyzed period of 20 years, the highest wind speeds occurred in the months in which the number of days with wind speeds exceeding 10 m/s was the highest;
- the highest wind speed of 25 m/s was recorded in Łeba on November 25, 1981 and January 15, 1989, these were the maxima in the entire coastal area;
- in Świnoujście the highest wind speed of 22 m/s was recorded on April 10, 1986;
- the 0.95 percentile of the wind speed in the individual months exceeded 10 m/s only in a few cases (in Świnoujście in spring, and in Łeba in autumn and in winter) which proves the small number of cases of extreme winds at the Polish coast (Table 2);
- the influence of the time of the day on the wind speed is slight.

Synoptic situation over the Baltic Sea on December 6, 2013

On December 05 through December 07, 2013 the weather over the Baltic Sea was determined by a cyclone called Xaver which moved from the northern Atlantic over the North Sea, southern part of Scandinavia, central Baltic and Estonia in the direction of the northern part of Russia. The analysis of the weather chart on December 04, 2013 at 18 UTC shows that the first closed isobar of 1000 hPa appeared over the northern Atlantic, south of Iceland. Deepening of the cyclone increased the pressure gradient which resulted in increased surface wind speed. The maximum wind speed of about 64 m/s (approx. 130 knots) was recorded in Scotland on December 5, 2013 at 06 UTC. On December 07, 2013 at 00 UTC the cyclone's center on the weather chart was indicated by an isobar of 976 hPa near the Ładoga Lake.

On December 06, 2013 the weather over the Baltic Sea was determined by a deep cyclone with atmospheric fronts which center was over the central Baltic, north of Gotland. At 06 UTC the pressure in the cyclone's center was 962 hPa (Fig. 2). A humid polar air mass behind a cold front was flowing in from north-west over the southern Baltic and the Polish coast (Figs 2 and 3).

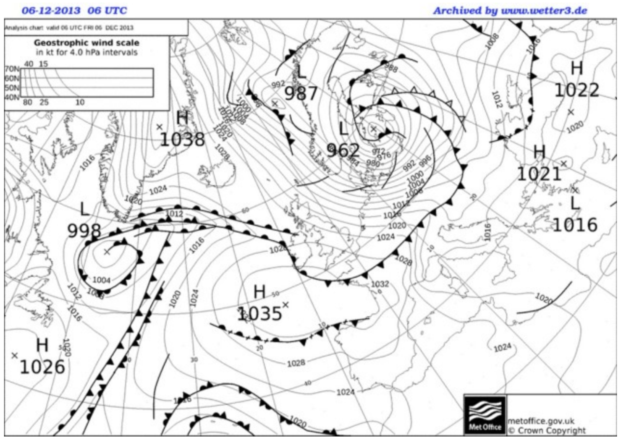

Fig. 2. Synoptic situation on December 6, 2013 at 06 UTC [www.wetter3.de]

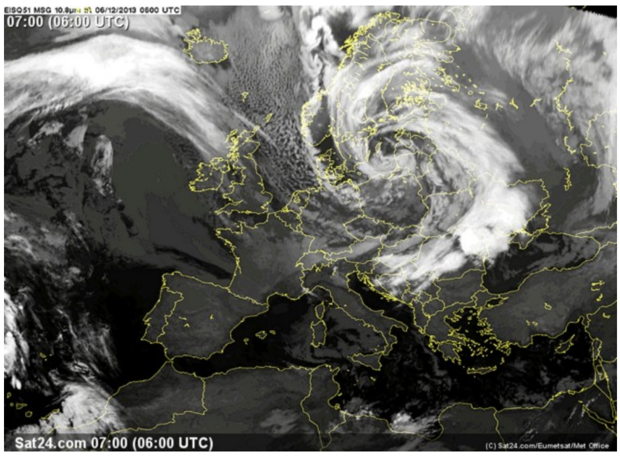

Fig. 3. MSG IR (10.8 μm) satellite image on December 6, 2013 at 06 UTC [www.sat24.com]

Meteorological radars data were also used for the analysis of the synoptic situation in the region. Using data from the classic and Doppler channels of meteorological radars enables quasi real-time analysis of cloud cover, wind field and selected atmospheric phenomena within 100–50 NM from the radar. The radar data are acquired systematically, e.g. every 10 minutes. This compensates to a significant degree the limitations resulting from the fact that it is a remote sensing method in which the interpretation of the results is dependent on selecting empirical relations based on certain simplifications [2, 4].

The analysis of the cloud cover and atmospheric phenomena over the southern Baltic Sea on December 06, 2103 was made using radar images from Świdwin and the Gdańsk–Rębiechowo airport. The radar images provided data concerning

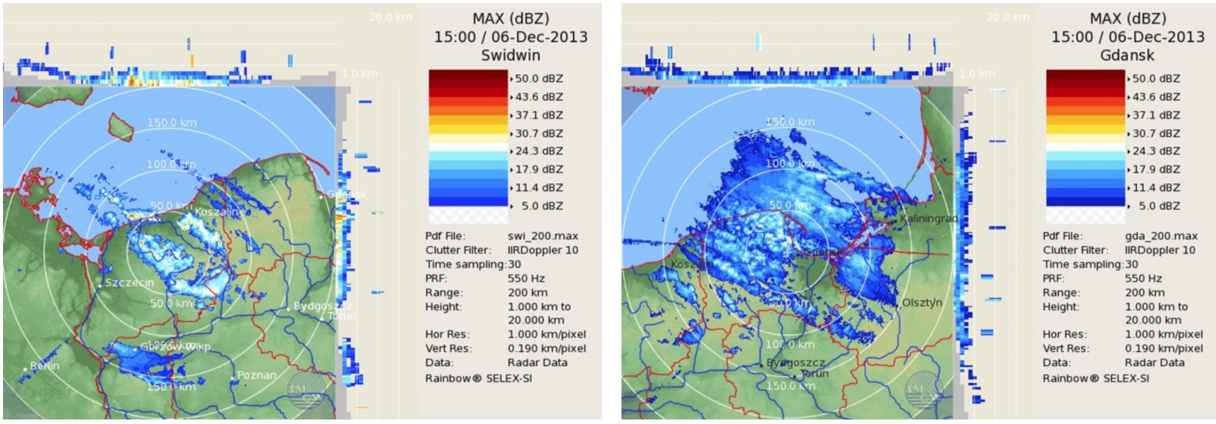

Fig. 4. Radar images of horizontal distribution of maximum radar reflectivity [dBZ] recorded by radars in Świdwin and Gdańsk–Rębiechowo on December 06, 2013 at 15 UTC [www.imgw.pl]

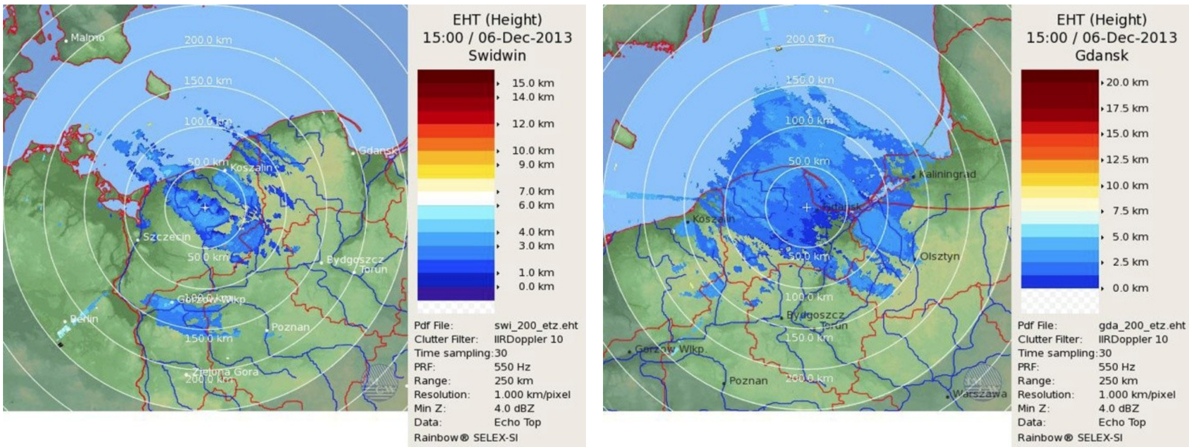

Fig. 5. Radar echo tops height [km] recorded by radars in Świdwin and Gdańsk-Rębiechowo on December 06, 2013 at 15 UTC [www.imgw.pl]

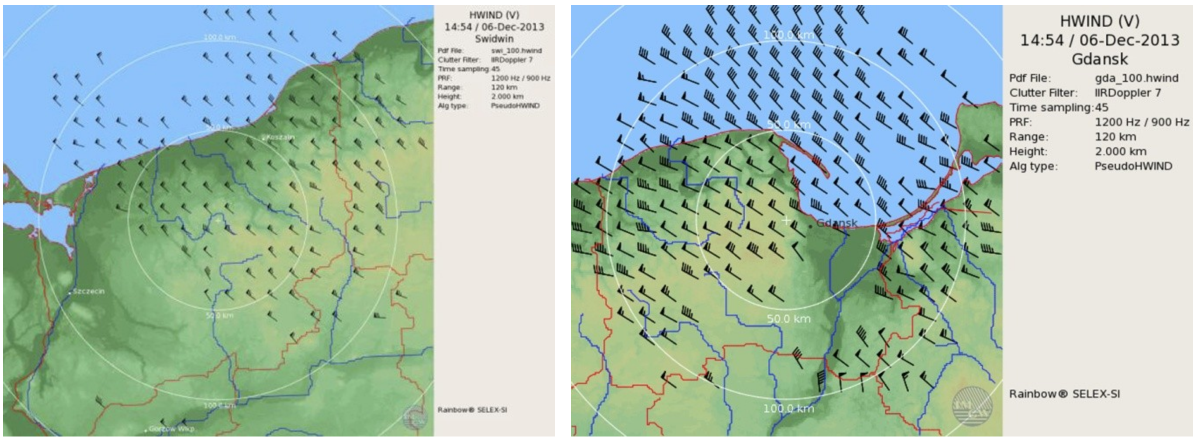

Fig. 6. Wind speed and direction [m/s] at 2 km altitude computed from radar data in Świdwin and Gdańsk-Rębiechowo on December 06, 2013 at 15 UTC [www.imgw.pl]

horizontal distribution of the maximum radar reflectivity (Fig. 4), radar echo tops height (Fig. 5) and wind speed and direction at 2 km altitude (Fig. 6). The analysis of a series of images provided the following conclusions:

– convective clouds developed over the southern Baltic Sea, significantly more intensively in the eastern than in the western part of the sea. The radar reflectivity value over the sea was 20–25 dBZ increasing to 30–35 dBZ over the land. Assessments based on the recorded reflectivity values indicate that light or moderate rain or sleet were possible;
– the radar echo tops height reached 3–5 km. Vertical development of the clouds was hindered by strong wind (exceeding 20 m/s);
– at the altitude of 2 km, the prevailing value of the wind direction was 290–320°, and wind speed 20–30 m/s. In the analyzed synoptic situation, the obtained values of the wind field corresponded with the wind direction and speed of the air mass advection.

The correctness of interpretation of the radar data concerning cloud cover and weather phenomena is confirmed by measurement data acquired from meteorological stations conducting observations at sites along the coast.

Direct meteorological measurements at coastal stations and on the southern Baltic Sea

The assessment of meteorological conditions over the southern Baltic Sea was made using the direct measurements conducted at:

– the coastal stations of the Polish Navy;
– the “Baltic Beta” oil rig of Lotos Petrobaltic SA;
– the Coastal Research Station of the Institute of Hydroengineering of the Polish Academy of Sciences in Lubiatowo.

The coastal stations, professionally supervised by the Hydrographic Office of the Polish Navy (HOPN), are located directly at the coast which ensures that the measurement results are representative for the marine area. The influence of the land on the air masses flowing from the direction of the sea is negligible. The measurement data from the stations in Międzyzdroje, Dziwnów, Niechorze, Kołobrzeg, Darłowo, Jarosławiec, Czołpin, Białogóra and Góra Szwedów were analyzed. The measurements were made every 10 minutes and included wind (direction and speed – minimum, average and maximum values), air temperature and humidity, and atmospheric pressure.

Measurements at the coastal stations on December 06, 2013 indicated that the wind blew from the north-west sector (NW). The stability of the wind direction in the NW sector was caused by decreasing speed of the cyclone movement. The pressure field over the southern Baltic Sea did not change significantly. The anemometers at the coastal stations recorded average and extreme wind speed. The average values at the stations fell into the range of 12 through 20 m/s. The maximum wind speed – instantaneous values of the wind gusts – showed large differences between the stations. The wind speed maximum value of 41.2 m/s was observed at the Darłowo station on December 06, 2013 at 01.30 UTC (Fig. 7).

The “Baltic Beta” oil rig is equipped with a MAWS automatic weather station measuring air temperature and humidity, atmospheric pressure, and wind speed and direction (average and maximum). The measurement results in 10-minute intervals are available at their web site. The “Baltic Beta” oil rig is located about 39 NM north of Jastrzębia Góra. The oil rig’s coordinates are: 55° 28' 47" N, 18° 10' 48" E.

The results of wind measurements on December 06, 2013 show that the direction changed slightly from west (W) (before noon) to north-west (NW) for the rest of the day and the following day. The average wind speed in the analyzed period ranged from 20 to 26 m/s. However, at 05.30 UTC

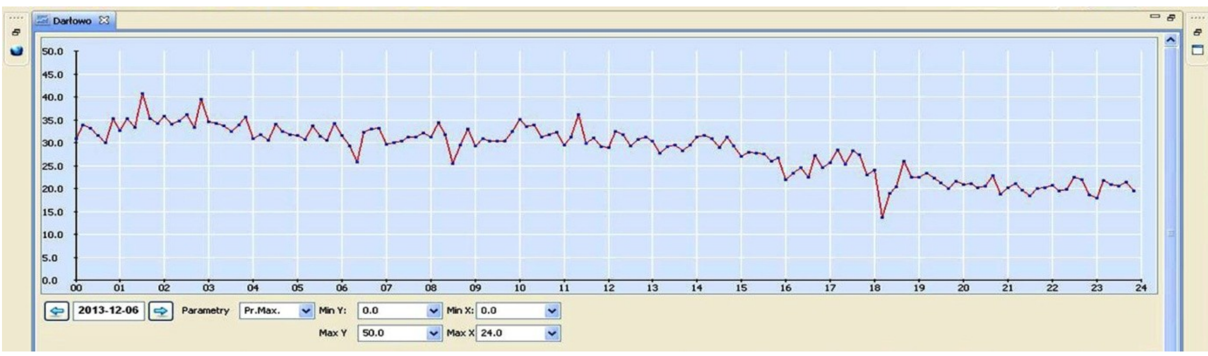

Fig. 7. Wind speed maximum values [m/s] at the Darłowo station on December 06, 2013 [HOPN]

the value of the maximum wind speed (gust) was 34.5 m/s (Fig. 8).

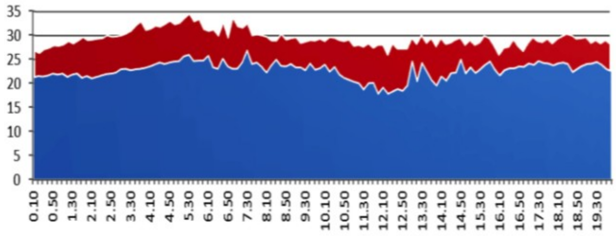

Fig. 8. Maximum and average wind speed [m/s] recorded at the "Baltic Beta" oil rig on December 06, 2013 [prepared using data acquired from www.imgw.pl]

The Coastal Research Station of the Institute of Hydroengineering of the Polish Academy of Sciences in Lubiatowo conducts systematic meteorological measurements (air temperature and humidity, wind speed and direction) and wave measurements. The laboratory is located about 8 km east of the Stilo beacon (according to the Polish coastal mileage: KM 163.73).

The record of the wind speed changes on December 05 through 07, 2013 in Lubiatowo is presented in figure 9. In the analyzed period, the wind speed increased from 8 m/s (gusts of 18–20 m/s) in the afternoon on December 05, 2013 to 12 m/s (gusts of 32 m/s) at 02–04 UTC on December 06, 2013. On December 06, 2013 between 06 and 20 UTC no measurements were made due to power supply failure. The wind direction changed from south-west (SW) (in the afternoon on December 05, 2013) to west (W) (in the morning on December 06, 2013) and to north-west (NW) for the rest of the analyzed period.

Direct hydrological measurements at marine stations and on the southern Baltic Sea

The assessment of hydrological conditions over the southern Baltic Sea was made using the direct measurements conducted at:

- the marine stations of the Institute of Meteorology and Water Management (IMWM);
- the "Baltic Beta" oil rig of Lotos Petrobaltic SA;
- the Coastal Research Station in Lubiatowo of the Institute of Hydroengineering of the Polish Academy of Sciences.

The marine stations of the Institute of Meteorology and Water Management make routine hydrological measurements and observations: condition of water, water temperature, sea state and ice. The hourly measurement data of the condition of water from the stations in Świnoujście, Kołobrzeg, Ustka, Łeba, Władysławowo and Hel were analyzed for the period of December 06, 2013 through Decem-

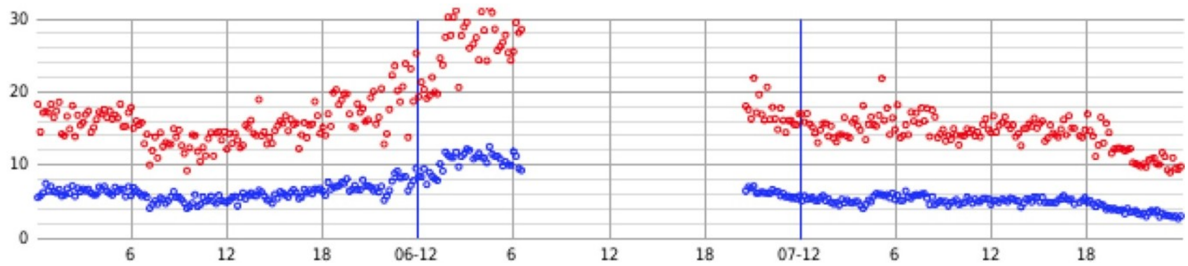

Fig. 9. Maximum (red) and average (blue) wind speed [m/s] recorded at the Coastal Research Station in Lubiatowo on December 05 through 07, 2013 [www.ibwpan.gda.pl]

Fig. 10. Water condition (blue) recorded in Władysławowo on December 06, 2013 00 UTC through December 08, 2013 12 UTC. Brown line indicates warning water condition [prepared using data acquired from www.imgw.pl]

ber 08, 2013. The average water conditions for the stations were found to be within the range of 475 cm to 536 cm. On December 06, 2013 in the morning the water condition reached nearly 550–560 cm which are warning conditions. It was caused by strong wind blowing for over a day. The westerly and north-westerly persistent wind with maximum speed over 20 m/s caused that the wave height increased and more sea water flowed into the coastal area. The first warning water condition was reached and exceeded in Władysławowo at 14 UTC on December 06, 2013 (Fig. 10), then in Świnoujście (Fig. 11). The remaining stations recorded warning water conditions at night on December 06/07, 2013 which held until afternoon on December 07, 2013. The longest period with exceeded warning water conditions was recorded in Władysławowo – until 07 UTC on December 08, 2013 (Fig. 10).

The sea state observations were made at the "Baltic Beta" oil rig. The sea state of 7 of 10 degrees in the Douglas scale (high), which is equivalent to the wave height of 6 to 9 m, was recorded in the hydrometeorological messages.

The Coastal Research Station in Lubiatowo conducts wave measurements by means of the Directional Waverider DWR-7 Mk.III buoy. The buoy is anchored about 1.5 NM from the shore; the water depth there is about 18 m; the coordinates: 54° 50.360' N, 17° 50.301' E.

The direction of waves propagation (red in figure 12) changed from west to north-west in the period of December 05 through December 07, 2013. The wind direction change was related with cold front that passed the measurement site at about 18 UTC on December 05, 2013 (Fig. 12).

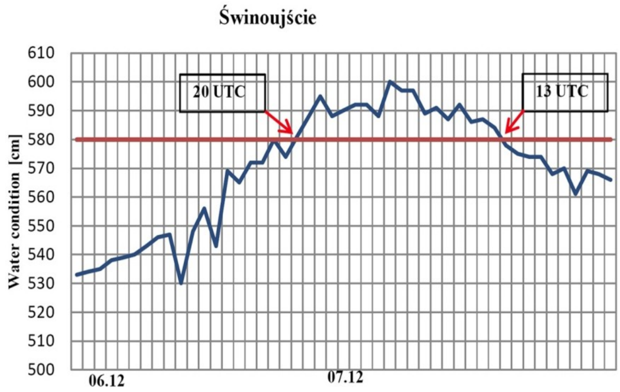

Fig. 11. Water condition (blue) recorded in Świnoujście on December 06, 2013 through December 07, 2013. Brown line indicates warning water condition [prepared using data acquired from www.imgw.pl]

The buoy in Lubiatowo recorded the significant wave height and maximum wave height. On December 05 through December 07, 2013 the wave height increased along with the wind speed from 2–3 m to 6–8 m which is equivalent to sea state 7 (Fig. 13).

Conclusions

The initial results indicate that continuation of the research may provide more detailed and comprehensive study of wind conditions over the Polish coast and the Baltic Sea. Climatological studies supplemented with analyses of measurement results in individual synoptic situations are a source of

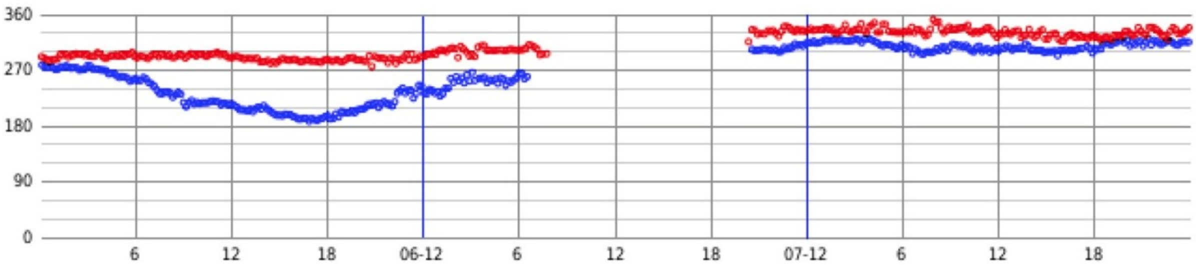

Fig. 12. Wind direction (blue) [°] and wave energy peak direction (red) [°] recorded in Lubiatowo on December 05 through December 07, 2013 [www.ibwpan.gda.pl]

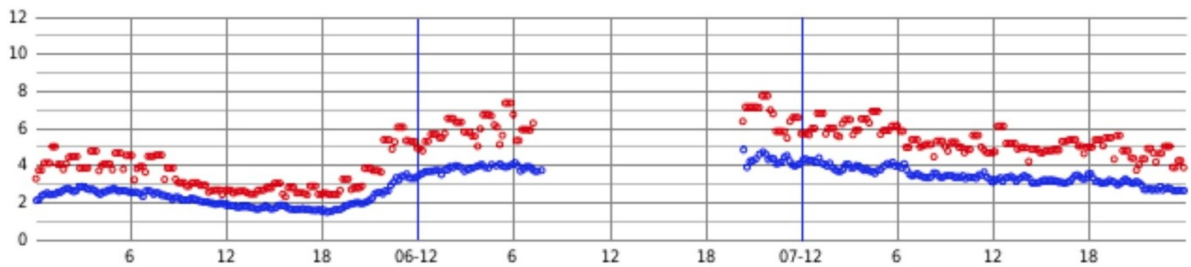

Fig. 13. Significant wave height (blue) [m] and maximum wave height (red) [m] recorded in Lubiatowo on December 05 through December 07, 2013 [www.ibwpan.gda.pl]

knowledge about wind conditions over the Polish coast. Learning the conditions of strong wind development will enable to prepare efficient forecasts of potential threats to sea navigation safety and better protection of people and infrastructure.

Improvement of quality and efficiency of hydrometeorological support to sea navigation on the Baltic Sea requires expanding the direct hydrometeorological measurements network in the area of the reservoirs, i.e. installing automatic weather stations on buoys, oil rigs and research platforms, ships and along the coastline. The measurement results should be available in real time for all services which performance influences sea navigation safety. They would also be input data for numerical weather prediction models providing forecasts of sea state and water conditions.

Mobile meteorological radars and radio-acoustic systems play an important role in acquisition of data concerning the state of the atmosphere because they enable to set up measurement sites in areas representative for specific synoptic situations. These methods of remote sensing of the atmosphere provide data with high frequencies and in relatively large areas.

Increased sea navigation safety is inseparable from development of measurement methods and improvement of forecasts used in hydrometeorological support. The observed trends in these methods development include acquisition of more data concerning the real state of the atmosphere and developing numerical models for objective processing of measurement data for meteorological and hydrological forecasts.

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