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Characteristics of cyclones causing extreme sea levels in the northern Baltic Sea*

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Abstract

The basic parameters of extra-tropical cyclones in the northern Baltic are examined in relation to extreme sea level events at Estonian coastal stations between 1948 and 2010. The hypothesis that extreme sea level events might be caused not by one intense extra-tropical cyclone, as suggested by earlier researchers, but by the temporal clustering of cyclones in a certain trajectory corridor, is tested. More detailed analysis of atmospheric conditions at the time of the two most extreme cases support this concept: the sequence of 5 cyclones building up the extreme sea level within about 10 days was very similar in structure and periodicity.

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1. Introduction

Sequences of certain weather patterns, rather than single events, cause different extreme environmental hazards in Europe like droughts in the case of anticyclones, or devastating wind-storms and floods in the case of extra-tropical cyclones. These hazards cause the largest economic losses and even loss of life. For the same reason, series or packages of extra-tropical cyclones force extreme storm surges in coastal seas. Mid-latitude storm tracks as regions where extra-tropical cyclones propagate with a higher density than in their surroundings have been a research topic for some time already (Hoskins & Hodges 2002). Most authors associate the spatial densities of cyclone tracks and their temporal changes with climate change. Mailier et al. (2006) show that extra-tropical cyclones do not cluster only in space, but that in certain regions they could also cluster in time. The Baltic Sea lies near the exit of one such region – the North Atlantic storm track – where cyclones are significantly clustered in the cold half year.

A number of factors influence the Baltic Sea level, the most prominent one being the seasonal cycle due to different meteorological and hydrographic factors, causing high sea levels at the end of the year and low levels from March to June as a long-term variability pattern. But sea level is also influenced by changes in the wind field, especially during storm events; by the water exchange between the Baltic and North Sea; by changes in precipitation and evaporation, and hence river discharge; by seasonal changes in water density; and by seiches (Wiśniewski & Wolski 2011). The part played by the different factors depends on the sea region, and especially on the morphometry of its coastline. Extreme sea level events in the Baltic Sea are predominantly meteorologically forced, and the role of tides lies well below 10 cm amplitude against the background of the dominant seasonal cycle (Raudsepp et al. 1999).

A storm surge is an extreme short-term (from minutes to a few days) variation in the sea level caused by high winds pushing against the surface of the sea. As the associated flooding threatens lives and property, this phenomenon has been widely described and studied in terms of its physical aspects, with the aim of simulating and forecasting sea-level behaviour in case of extreme storm surges (Suursaar et al. 2003, 2006, 2011, Wiśniewski & Wolski 2011). Historically, the highest storm surges have reached 5.7–5.8 m above the average water level, and such events can happen at either end of the elongated Baltic Sea: in Neva Bay off St. Petersburg, Russia, and in the coastal region near Schleswig, Germany. The extremely high sea levels in the central Baltic occur in the coastal waters of certain semi-closed sub-basins, open to the west, as the strongest winds in this region blow from this sector.

On the Polish coast the occurrence of extremely high sea levels depends on three components: a high initial sea level prior to the extreme event; a strong onshore wind that causes tangential wind-stress of the right duration and deformation of the sea surface by mesoscale baric lows; and the subsequent production of so-called baric waves, which generate seiche-like variations of the sea level (Wiśniewski & Wolski 2011). Roughly the same idea regarding extreme storm surges is presented by Averkiev & Klevannyy (2010), who have hydrodynamically modelled the Baltic Sea forced by a passing cyclone. Based on model simulations, they discovered the most dangerous trajectories and velocities of passing cyclones causing extreme sea-level events at different locations on the northern Baltic coast. We refer to their approach as the AV2010 conceptual model.

Cyclone Erwin (or Gudrun) crossed the Baltic Sea on 8–9 January 2005, giving rise to the highest historical sea levels at nearly all northern Baltic coastal stations (Suursaar et al. 2006). The temporal variability of single storm surges and their correlations with local wind forcing and large-scale atmospheric circulation have been analysed on the basis of model simulations and data over past decades (Suursaar et al. 2003, 2010, 2011). One of the general conclusions from the aforementioned works is that extreme storm surges in Estonian coastal waters occurred there because the centre of an intense, fast-moving cyclone was propagating northwards from the Scandinavian Peninsula over the Gulf of Finland. The corresponding local wind pattern was SW winds over the central Baltic veering west, pushing water first towards the northern Baltic and then into the Gulf of Finland and Gulf of Riga. Storm surges are the main cause of coastal flooding in the Baltic Sea, although as historical data show, a single storm is not enough to cause extreme sea levels: a series of cyclones are needed (Suursaar et al. 2006).

Hydrodynamically, extreme storm surges have been thoroughly studied and their different aspects well simulated by models, ranging from conceptual and semi-empirical ones (Suursaar et al. 2002) to operational 3D numerical simulations (Lagemaa et al. 2011). Although sea levels around the average are well represented and validated, extreme sea levels are frequently captured with much poorer accuracy (Raudsepp et al. 2007). This problem could be addressed using an ensemble modelling approach, which gives a measure of uncertainty to estimated sea level extremes; probably, however, this still does not improve the physical understanding of the occurrence of extremes. We find that the real trigger of these extreme events comes from atmospheric conditions, which give rise to a situation where cyclones with similar tracks and the deepest phase location are clustered in time: it is this periodicity that is the true driver of sea level extremes. These atmospheric factors of such events have not yet been described in great detail. This brings us to the aim of our paper, which is primarily to study the statistics of the physical properties of single cyclones and their tracks that have caused 40 high storm surges on the Estonian coast, measured at Pärnu and Tallinn, and to show how variable the key properties are for dangerous cyclones, as pointed out by the AV2010 model. To that end, we use the characteristics of cyclones from the database of Northern Hemispheric cyclones in Gulev et al. (2001). The second task of the paper is to test the hypothesis that a series of cyclones is needed to force extreme sea levels on northern Baltic Sea coasts. To do so, we analysed in greater detail the properties of a series of cyclones in October 1967 and January 2005, when the two highest sea levels occurred at Pärnu.

2. Data and methods

In this paper we have used extreme sea level events for the years 1948–2010 from two Estonian sites, Pärnu (Gulf of Riga) and Tallinn (Gulf of Finland), and tried to characterise the cyclones that could have generated sea level extremes. For our analysis of extreme sea level events, we chose the 20 highest sea level values from both stations, 31 events in total, as 9 of the days were the same for both sites (see Table 1). The threshold for extreme sea level is +100 cm and +150 cm above the mean level at Tallinn and Pärnu respectively. Because of the river delta and the suitably orientated bay for heavy SW and W storms, high sea levels in Pärnu are naturally higher. The two most extreme sea level events at Pärnu occurred in October 1967 and January 2005 (see Figure 1 for the more detailed temporal variability of both cases). The values of these extremes were +250 cm and +275 cm, in October 1967 and January 2005 respectively.

Averkiev & Klevannyy (2010) simulated extreme sea level events for the entire Gulf of Finland using the BSM6 hydrodynamic model of the Baltic Sea with meteorological forcing from HIRLAM (SMHI). They used cyclone Erwin as a prototype for a 'dangerous cyclone', as almost all sea level measurement stations in the observed region registered historical maximum levels during its overpass. Those authors found the following properties of 'dangerous cyclones': coefficients a and b for the linear approximation ($y = ax + b$) of the cyclone's track with a straight line in the longitudinal belt 10°E–30°E, and the latitude and longitude of the cyclone's centre at the moment of its maximum depth (shown in Table 2). We compare these numbers with the values of real cyclones that can be associated with high storm surges at Pärnu and Tallinn.

Table 1. Characteristics of extreme sea level events and the cyclones causing these, selected from the period 1948–2010. The sea level is shown only if it exceeded +100 cm and +150 cm at Tallinn and Pärnu respectively. Sea level pressure, geographical coordinates, and velocity at the deepest position of the cyclone are listed in columns 4–7. The coefficients of the linearly interpolated cyclone track in longitude (x) and latitude (y) coordinates and r^2, the square of the correlation showing the accuracy of linear interpolation, are shown in columns 8–10. The two last columns give the number of cyclones during the 60-day periods beginning 29 days before the storm surge ($N60\_c$) or with the storm surge ($N60\_b$)

Date of storm surge	Sea level height [cm]		Deepest phase of cyclone				Linear interpolation coefficients			$N60\_c$	$N60\_b$
	Tallinn	Pärnu	Pressure [hPa]	Long. E	Lat. N	Velocity [km h^{-1}]	a	b	r^2		
16.01.1952	101		962.5	11.3	63.0	59.51	−0.03	62.62	0.29	12	12
15.10.1955	100		987.5	8.3	57.4	14.94	−0.35	59.89	0.17	8	4
30.03.1961		172	974.8	25.5	58.9	43.76	0.17	56.59	0.45	8	8
06.12.1961		150	970.1	10.1	59.5	52.55	0.38	56.06	0.98	12	8
13.02.1962		152	948.8	18.8	58.9	37.37	−0.02	59.69	0.10	11	12
16.11.1963		152	973.5	21.6	59.1	43.83	0.38	50.04	0.99	4	8
18.10.1967	124	250	968.3	11.8	57.0	86.64	0.26	53.90	0.99	8	5
02.11.1969	105	191	963.8	22.0	59.8	49.16	−0.26	66.28	0.84	11	3
06.10.1975	109	156	958.5	27.1	60.9	74.79	−0.24	67.13	0.98	8	9
31.12.1975	105		980.8	29.1	62.8	33.18	−0.02	64.28	0.01	18	7
23.11.1978		153	965.0	21.3	64.6	52.31	0.11	61.25	0.81	3	2
12.09.1978		181	974.5	26.6	60.2	40.00	0.32	53.09	0.84	9	6
27.11.1979		169	974.0	24.3	59.2	26.52	−0.26	65.01	0.69	9	7
24.11.1981	102	170	963.5	14.9	58.8	37.37	−0.09	60.88	0.73	18	11
14.01.1983	100		986.9	20.7	63.9	37.75	−0.06	65.02	0.90	10	8
01.11.1983	104									6	7
30.12.1983		157	967.0	25.4	60.5	37.03	−0.26	67.38	0.94	13	6

Table 1. (*continued*)

Date of storm surge	Sea level height [cm]		Deepest phase of cyclone				Linear interpolation coefficients			$N60\_c$	$N60\_b$
	Tallinn	Pärnu	Pressure [hPa]	Long. E	Lat. N	Velocity [km h^{-1}]	a	b	r^2		
04.01.1984	116		961.2	20.6	61.7	59.02	0.15	58.38	0.98	12	9
06.12.1986	114	161	972.9	21.8	61.4	37.50	−0.07	62.02	0.41	8	3
26.01.1990	116		977.4	28.5	63.7	33.79	0.62	45.45	0.83	10	8
27.02.1990		184	941.4	20.1	61.0	34.35	0.24	56.05	0.92	10	11
06.03.1990		154	972.6	10.8	57.9	84.38	−0.16	60.16	0.89	10	12
10.03.1990	116		985.6	22.7	58.8	37.95	−0.18	63.24	0.96	10	12
11.01.1991	125	155	993.5	23.0	61.1	126.15	0.12	58.27	0.94	5	6
03.01.1992		152	993.9	15.2	56.5	48.44	−0.72	67.08	0.98	7	9
22.01.1993	119	172	966.6	23.8	65.6	68.62	0.04	64.57	0.60	6	4
15.11.2001	129	159	970.4	17.9	66.6	73.64	−0.38	73.03	0.96	7	8
09.03.2002	106		970.5	27.2	62.5	42.73	0.06	60.96	0.76	10	12
29.12.2003	108		969.7	22.2	71.1	16.82	0.03	70.08	0.03	12	10
09.01.2005	155	275	957.4	18.9	61.2	52.75	0.07	58.87	0.63	9	9
14.01.2007	122	162	970.7	11.8	60.8	60.13	0.10	61.63	0.81	15	8

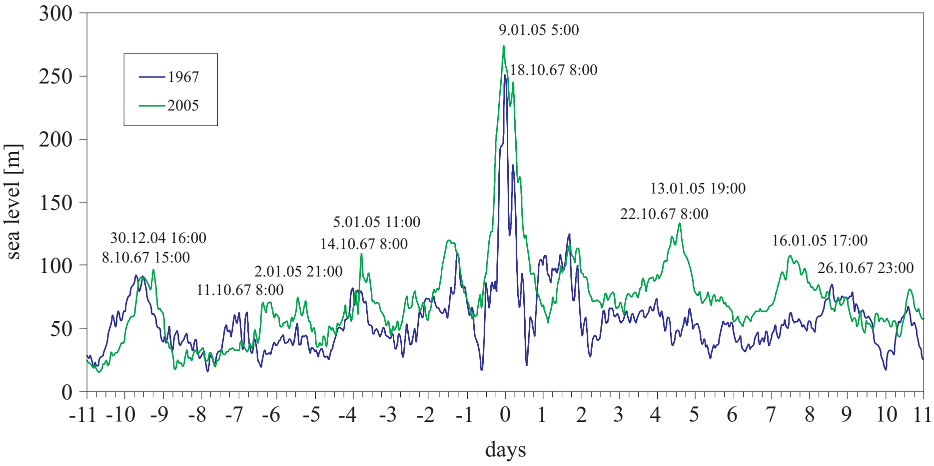

Figure 1. Two cases of extreme sea level maxima recorded at the Pärnu coastal station on 17 October 1967, 08 GMT +250 cm and 9 January 2005, 07 GMT +275 cm. The horizontal axis shows time in days before and after the highest water level in Pärnu

The characteristics of real cyclones are taken from the database of cyclones described by Gulev et al. (2001). We used data regarding geographical coordinates, time, velocity and sea level pressures (SLP) of low pressure centres from the period 1948–2010. This database consists of the cyclone tracking output of the 6-hourly NCEP/NCAR reanalysis (Kalnay et al. 1996) of SLP fields using the software of Grigoriev et al. (2000).

First, we separated cyclones lasting at least 48 hours that attained the minimum air pressure (< 1000 hPa) in the region under scrutiny: 10°E–30°E, 50°N–70°N. Then we approximated the trajectories of these cyclones with a straight line in the longitudinal belt from 0°E until 6 h after the lowest pressure was attained. Truncating the cyclone track at both ends offered us a better estimate of the cyclone's direction in the area of interest, as the cyclone often turned sharply immediately after the instant of maximum depth had been achieved. By using this linear approximation it was easier to make comparisons and group the cyclone tracks.

As the NCEP/NCAR reanalysis has quite a coarse resolution in space ($2.5° \times 2.5°$) and time (6 h), some regional details and cyclones could be missing. Therefore, for the wind-field snapshots during the maximum sea levels at Pärnu we have chosen the regional reanalysis Baltan65+ (Luhamaa et al. 2011), with a spatial resolution of 0.1°.

Table 2. The same characteristics as in Table 1, but averaged over the 20 most dangerous cyclones for the Pärnu and Tallinn sea levels, compared to AV2010 modelled values

Date of storm surge	Sea level height	Deepest phase of cyclone				Linear interpolation coefficients			$N60\_c$	$N60\_b$
	[cm]	Pressure [hPa]	Long. E	Lat. N	Velocity [km h^{-1}]	a	b	r^2		
Tallinn average	114	973.1	19.9	61.7	52.54	−0.06	62.18	0.69	10	8
AV2010			24.8	61.3	54.83	0.22	55.77			
Pärnu average	173	968.6	19.5	60.4	55.59	−0.02	60.90	0.79	9	7
AV2010			24.8	59.5	59.30	0.30	51.96			

3. Properties of cyclones associated with high sea level events at Pärnu and Tallinn

We looked for deep cyclones that might cause high sea level events at Pärnu (above +150 cm) and Tallinn (above +100 cm): for only one case out of 31 was it not possible to detect the corresponding cyclone (1 November 1983, see Table 1). All the high sea level events listed in Table 1 took place during the storm season, i.e. from September to March. Extreme sea levels were not always observed at both stations on the same days, however, as this depends on the cyclone's exact position, lifecycle phase and velocity; but in really extreme cases, sea levels were high over a larger area of the sea along the entire Estonian coast. The cyclones that passed over the Baltic Sea and caused these 31 extreme events in 1948–2010 were not exclusively deep, and there was no obvious correlation between the minimum air pressure of the cyclones and the extreme sea level. Table 2 presents, separately for Tallinn and Pärnu, the average values of the cyclone characteristics for extreme sea level events. The atmospheric pressure at sea level at their centre is lower than the average value in the northern Baltic region – 985 hPa (Link & Post 2007).

We counted the number of cyclones in the research area during 60-day periods to test the hypothesis about the series of cyclones causing these high water events. Here we used two options: either the extreme event was in the middle of the counting period ($N60\_c$) or we counted the cyclones that preceded the storm surge ($N60\_b$). The number of cyclones was higher if the high sea level event was in the middle of the counting period (see Table 2). The same result is supported by Figure 1, where the secondary maximum sea levels are of the same magnitude before and after the main event.

The average values of the real cyclone characteristics compared to the values modelled by Averkiev & Klevannyy (2010) are presented in Table 2 and Figure 2. The dangerous cyclones for Tallinn and Pärnu sea levels are slightly different: for Tallinn the position of the deepest phase of the cyclone should be shifted to the north by about two degrees, but the longitudes are considered to be the same. The ideal Pärnu cyclone has a stronger meridional track component (the slope of the trajectory is 0.304 instead of 0.223). On average, the most accurately predicted characteristic of a dangerous cyclone is the latitude of the deepest state; at both sites this coincides with the modelled value within one degree. In fact, the cyclones propagate somewhat more slowly than predicted and therefore their minimum pressure also occurs some 4–5 degrees farther to the west than predicted. The same conclusions are valid for the cyclones that caused these two extreme sea level events in 1967 and 2005: they tended to have a smaller meridional velocity component than that proposed by the AV2010

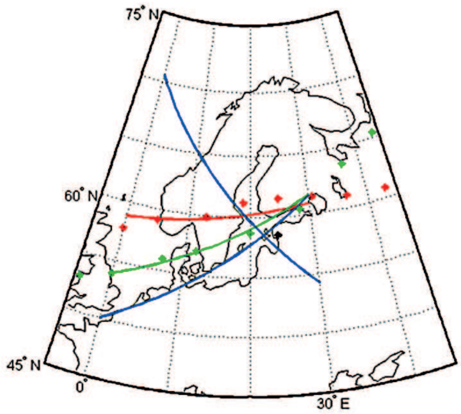

Figure 2. Truncated trajectories of cyclones associated with the most extreme sea levels at Pärnu: 18 October 1967 (green crosses and line) and 9 January 2005 (red crosses and line). The two blue lines encompass the sector for the trajectories of all other cyclones that caused at least +150 cm sea levels at Pärnu

conceptual model. In fact, the tracks of the dangerous cyclones in the research area are not always very straight and they also come from a rather large sector – from the SW to NW (Figure 2). The directions offered by AV2010 have a larger meridional track component than the average of all the real cases.

4. Analysis of the cyclone series during the two most extreme storm surges at Tallinn and Pärnu

At both sites, Pärnu and Tallinn, the highest historical sea levels were registered on 8–9 January 2005, at Pärnu since 1923 and at Tallinn since as far back as 1842. From the viewpoint of atmospheric pressure minima, this was only the twelfth cyclone (with minimum pressure of 957.4 hPa) in the 1948–2010 period in this region. On the other hand, Erwin/Gudrun could be called an explosive cyclone or bomb, according to Bergeron's definition (Roebber 1984), with a maximum Normalised Deepening Rate (NDP) of -24.5 hPa/24 h during its first day of existence. The second highest storm surge in the area, from 18 October 1967, was caused by a much longer cyclone, with a minimum pressure of 968.3 hPa. For the October 1967 cyclone, NDP was -20.9 hPa/24 h – also a very high value.

We presumed that the extreme sea levels during the 8–9 January 2005 event were actually caused not so much by certain parameters of a single cyclone as by the properties of a sequence of cyclones crossing the Baltic Sea that had certain (to some extent similar) trajectories with a certain periodicity over a given time span. In Figure 1 one can follow how an extreme sea level was built up by six progressive secondary sea level maxima, easily detectable over approximately 10 consecutive days before the occurrence of the most extreme sea level, and with a very similar periodicity in both the 1967 and 2005 cases. Looking at the trajectories of the cyclones (Figure 3)

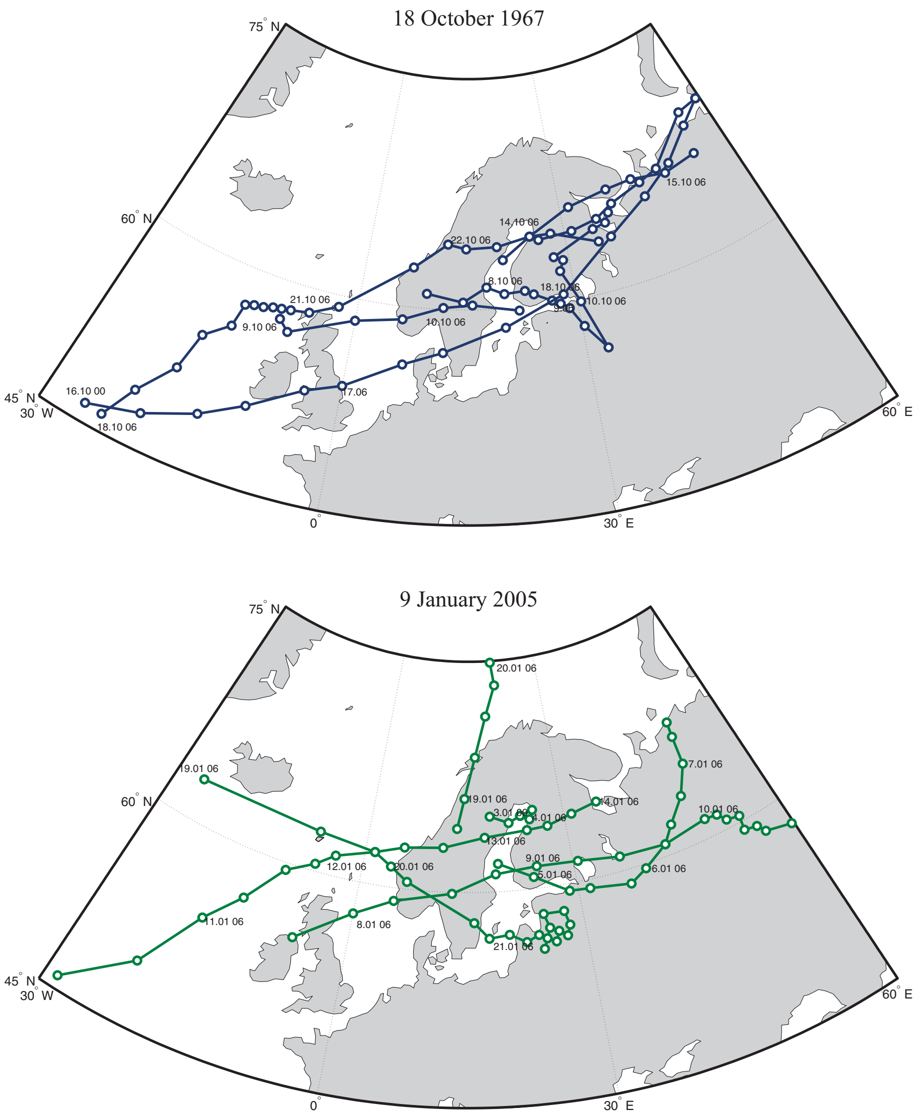

Figure 3. Trajectories of cyclones causing extreme sea levels at Pärnu: 18 October 1967 (upper panel) and 9 January 2005 (lower panel). Six tracks from the same cluster are shown for both periods; the longest ones are truncated at both ends. The numbers on the lines show the date and time of the cyclone's position

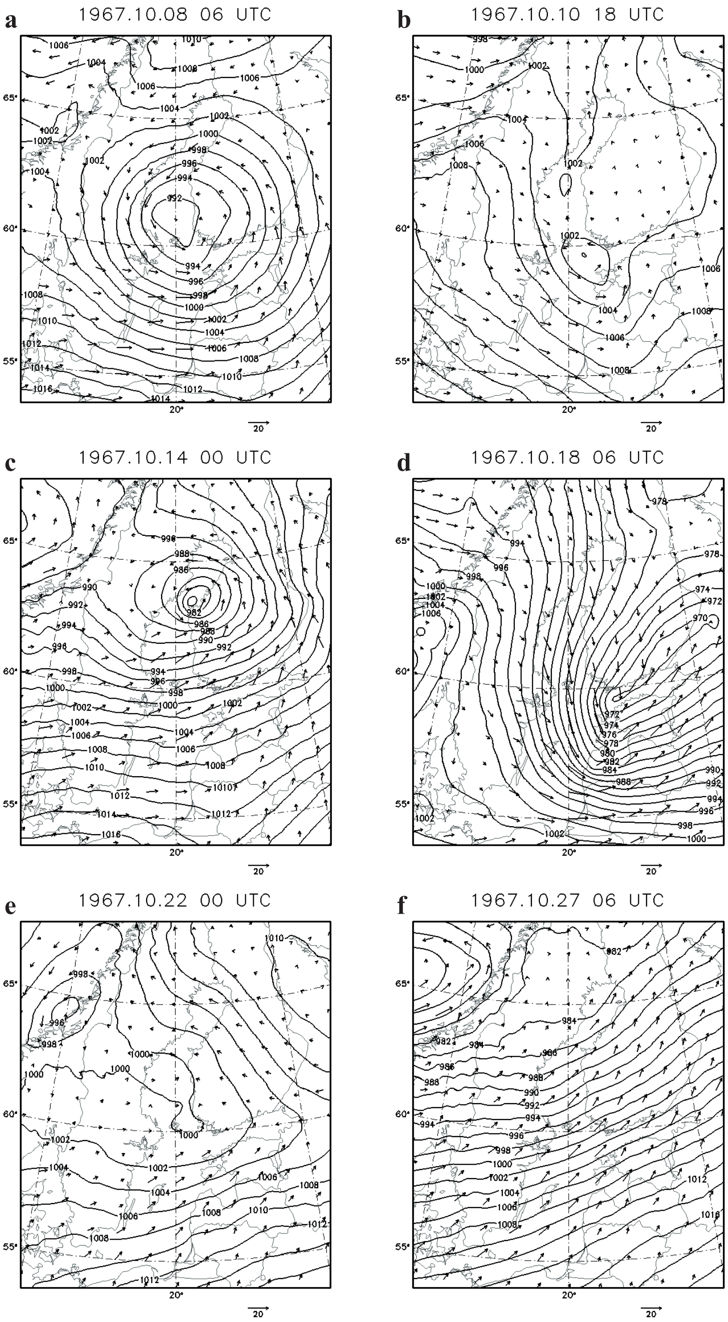

Figure 4. Mean sea level pressure charts with the wind-field arrows from Baltan65+ regional reanalysis for the northern Baltic area during the October 1967 high sea level period at Pärnu. The dates of the charts were selected for the sea level maxima from Figure 1. The arrow drawn below is equal to 20 m s^{-1}

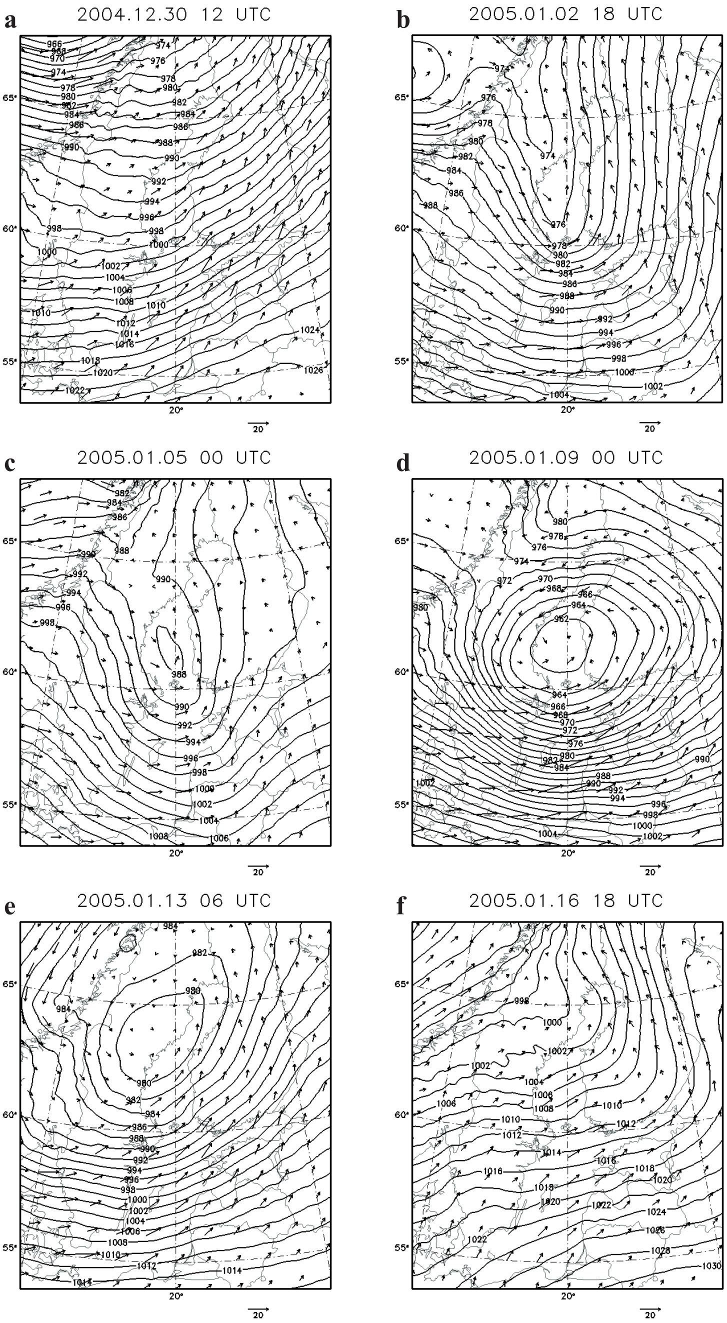

Figure 5. Mean sea level pressure charts with the wind-field arrows from Baltan65+ regional reanalysis for the northern Baltic area during the January 2005 high sea level period at Pärnu. The dates of the charts were selected for the sea level maxima from Figure 1. The arrow drawn below is equal to 20 m s^{-1}

and comparing the sequences of cyclones for these two extreme storm surges, in both cases we can point out 5 cyclones that had the lowest air pressure values in the sector 10°E–30°E, 55°N–67°N. There were four cyclones crossing the area that arose one after another and had very similar directions of propagation. Nevertheless, common to both events were the two very long (in time and space) cyclones generated over the western Atlantic Ocean at latitude ca 40°N. The second of these was generated after the time of the sea level maxima, which indicates the possible serial clustering of cyclones, induced by the time-varying effect of large-scale atmospheric factors on individual cyclone tracks.

Figures 4 and 5 show maps of mean sea level pressure for six dates when a strong SW wind reached Pärnu Bay, and a sea level maximum could be detected at Pärnu in either October 1967 or December 2004/January 2005 (see Figure 1). Some of the synoptic patterns recall the ideally circular cyclone shown in AV2010, especially in the case of the main, strong 2005 cyclone (9.01.2005 0UTC), but also some side cyclones in the 1967 case (9.10.1967 6UTC, 14.10.1967 0UTC). During both main events the horizontal gradient of the air pressure is the largest, which also produces very strong winds with strong wind stress at sea level. What makes these periods exceptional is the strong SW winds after 2 to 5 days, causing secondary sea level maxima in Pärnu Bay. That happened at least 6 times, but not all the maxima in Figure 1 could be associated with strong winds from the 'right' directions.

5. Discussion and conclusions

After studying the properties of 31 cyclones that could be associated with the 20 highest sea levels at Tallinn and Pärnu during the 1948–2010 period, we came to the following conclusions:

1. These cyclones approached the northern Baltic region from the sector bounded by SW and NW directions. As the sector was about 90 degrees wide, the hypothesis of one dangerous cyclone direction for a certain site was not supported. Nevertheless, the AV2010-predicted propagation vectors of cyclones remained well within the sector of the real cyclone tracks (Table 1 and Figure 2). Suursaar et al. (2006, 2009) theoretically discussed the possible trajectories of dangerous cyclones and found a somewhat narrower sector from SW to W. In Table 1, nearly half the cyclone tracks have a negative slope of the linear approximation ($a < 0$), which means directions between W and NW.

2. The latitudes and longitudes of the cyclones' centres at the moment of lowest air pressure were distributed in a small area compared to the cyclone diameter, and agreed quite well with AV2010.
3. These cyclones had lower deepest air pressures than the cyclones in this region on average, but they were not the deepest during the entire study period, and no obvious correlation was found between the minimum air pressure of the cyclones and the extreme sea level value.
4. The propagation velocities of these cyclones varied strongly, and the higher they were, the easier it was to approximate their vectors with a linear approximation in latitude-longitude coordinates in the study area. The actual velocities of cyclones were lower than predicted by AV2010.

We analysed the two most severe storm surge events separately during the study period. The January 2005 case, the highest historically recorded sea level since 1923 at Pärnu, and since 1842 at Tallinn, was caused by cyclone Erwin/Gudrun, which could be classified as an explosive cyclone or bomb, according to Bergeron's definition (Roebber 1984). The Erwin/Gudrun cyclone was not exclusively deep, nevertheless Suursaar et al. (2010) classify Erwin/Gudrun as the most significant storm since 1966 to have crossed Estonian territory and, in fact, the Baltic Sea. In evaluating the statistical ensemble of the highest observed sea levels, Suursaar et al. (2010) conclude that the two events with the highest sea levels at Pärnu in 1967 and 2005 (+250 cm and +275 cm respectively) appear as outliers or elements of other populations in the ensemble of sea level maxima. This means that the realisation of these two extreme sea levels lies beyond the conventional model, when high sea levels are a consequence of the activity of a single cyclone, as these two most extreme sea level events were not caused by the deepest or fastest cyclones. We have not quantified the horizontal air pressure gradient, which is certainly high in both cases, as can be seen from Figures 4 and 5. That characteristic was not proposed by AV2010 either.

The generalised patterns of cyclone tracks for these two extreme event periods of about 3 weeks (Figure 3) enabled us to concentrate not only on the local to mesoscale processes, where the atmospheric forcings to the sea level are manifested through the local wind field, but also on the larger-scale atmospheric circulation. With longer time periods, larger scales in space are also involved. This means that if we look at events lasting about 3 weeks, then the exceptional regime in the atmosphere is not at the local or meso-scale, but at the planetary scale. Mailier et al. (2006) revealed that the large-scale atmospheric circulation pattern controls the speed and the path of existing cyclones. As the Baltic Sea region lies at the end of the North Atlantic storm track, serial clustering of cyclones in this area is common, but it is also important that the serial clustering of mid-latitude cyclones is particularly associated with strong systems (Mailier et al. 2006, Vitolo & Stephenson 2009). Therefore, we find that the actual cause of the sea level extremes in 1967 and 2005 could be the properties of a series of cyclones crossing the Baltic Sea, rather than the parameters of a single cyclone causing a particular storm surge flooding coastal areas.

The clustering of cyclone tracks in time and space does not have a very high probability, but produces extreme cases that do not belong to the ensemble of high storm surges. In other words, certain (to some extent, similar) trajectories of cyclones with certain periodicities in a given timespan give rise to extreme sea levels that are real outliers in the ensemble of extreme cases. This conclusion is supported by the series of higher-than-normal sea levels oscillating before and after the main extreme event, but also by the fact that there was always more than one deep cyclone during the approximately two-month period that surrounded the highest sea level events.

The exact characteristics and sequence of the cyclones need further research, as the more than just chance clustering of cyclones does not provide sufficient evidence for the causality of the forcing. But at the local scale, the propagation of these cyclones merely generates a wind system that changes in speed and direction, and the estimation of these winds and their evolution, preconditioning and conditioning of sea level extremes also require refining and downscaling of the wind pattern (see Figures 4 and 5). Ensemble hydrodynamic modelling of the sea (using ROMS, HIROMB, HBM, NEMO, etc.) could provide important information about the response of the sea system and would help to define the framework for atmospheric forcing and uncertainty of sea level extremes, as well as the necessary preconditions for sea level extremes. Analysis of two extreme storm surges and the relevant forcing of cyclonic activity permits the definition of the basic parameters of cyclones and their series causing extreme sea levels along northern Baltic coasts.

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