Waves, currents and sea level variations along the Letipea – Sillamäe coastal section of the southern Gulf of Finland*

OCEANOLOGIA, 52 (3), 2010.
pp. 391–416.

KEYWORDS
Wave hindcast
Upwelling
Coastal jets
Climate change
RDCP
Baltic Sea

Ülo Suursaar

Estonian Marine Institute,
University of Tartu,
Mäealuse 14, EE–12618 Tallinn, Estonia;

e-mail: ulo.suursaar@ut.ee

Received 17 February 2010, revised 7 June 2010, accepted 21 June 2010.

Abstract

Variations in the hydrodynamic conditions were studied on the basis of 336 days of measurements with a Doppler current profiler. With wave data as a calibration reference, a semi-empirical hindcast of wave parameters is presented in the fetch-limited near-shore area for the period 1966–2008. A resultant 4–6 cm s^{-1} westward current dominated along the coast. Occasional fast sub-surface westward currents under modest wind forcing, as well as asymmetrical vertical profiles for westward and eastward currents indicated the influence of upwelling-related baroclinic coastal jets. The average frequency of upwelling was estimated at 17%; some of the events were identified in near-homothermic winter conditions on the basis of salinity and multi-layer flow records. While the mean sea level trend at Narva-Jõesuu roughly approximated the global estimates for 1899–2009, the annual maximum sea level increase was 5–8 mm yr^{-1}. Both mean and maximum wave heights declined as a result of decreasing winds from the north.

* The study was partially supported by the Estonian target financed project 0104s08, ESF grant project 7609, as well as by Kunda EstCell and Port of Sillamäe monitoring contracts.

The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

A number of new review articles and books have recently been published, summarizing updates on physical oceanography in the Gulf of Finland (Soomere et al. 2008, 2009, Leppäranta & Myrberg 2009). However, the authors of these rather ambitious publications also stated that large spatial differences continue to exist in the Gulf, encompassing a wide range of physical processes at different scales, some of which are still poorly understood. These are, for example, vertical mixing processes, as well as the overlapping of horizontal circulation patterns at different scales and various aspects of climate change. There are still some uncertainties and disagreements regarding the different assessments of wave climates in the northern Baltic Sea (e.g. Räämet et al. 2009, 2010), and at present there is a shortage of long-term wave hindcasts of any kind.

The Gulf of Finland has an area of 29 500 km^2 and an average depth of 37 m with maximum values reaching 121 m in the westernmost part and up to 60–70 m in the eastern half of the Gulf. It receives a relatively large freshwater input from rivers (Neva, Narva, Kymijoki), as well as a pollution load from industries and municipalities. Our study focuses mainly on the south-eastern part of the Gulf of Finland, where the broad Narva Bay defines a roughly 100 km long, relatively straight coastal section between the mouth

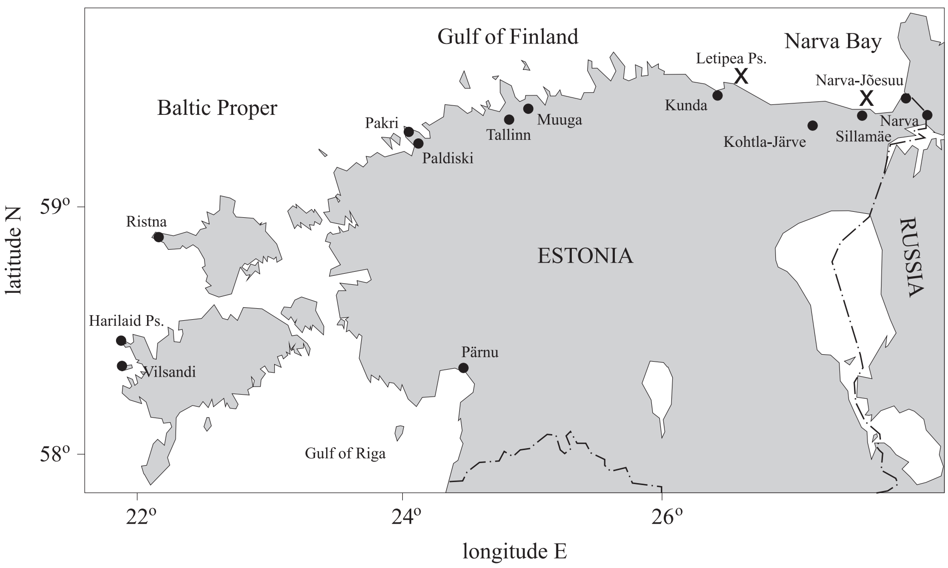

Figure 1. Map of the study area with the RDCP mooring locations near Mahu and Sillamäe indicated by 'x'

of the Narva in the east and the Kunda Bay – Letipea Peninsula area in the west.

Hydrodynamically, Narva Bay (Figure 1) seems to be a less challenging marine area, for example, than the Väinameri Sea of western Estonia (Otsmann et al. 2001). Rather than process-addressed hydrophysical considerations, work on different environmental issues has advanced marine studies in this vulnerable area. For instance, eutrophication processes have recently been studied in Narva Bay (e.g. Laanearu & Lips 2003, Lessin et al. 2007), and anthropogenic pollution and environmental recovery issues were investigated, e.g. by Suursaar et al. (2008, 2009). In the heavily industrialized north-eastern part of Estonia, the oil shale industry near Kohtla-Järve, power plants near Narva, the Kunda cement factory and a depository of radioactive wastes near Sillamäe (Figure 1) have seriously impacted virtually every component of the environment. Although the water quality in the southern Gulf of Finland has improved as a result of the reduced pollution load and self-purification (Suursaar et al. 2009), the new or reconstructed ports at Paldiski, Muuga, Kunda and Sillamäe, the increased oil transit with the accompanying greater risk of shipping accidents (e.g. Wang et al. 2008) and the new pulp mill at Kunda have introduced some new hazards. Finally, the north Estonian coast, or more precisely, Pakri, Letipea and Sillamäe, are possible construction sites for the first nuclear power plant in Estonia. Thus, a wide range of environmental and oceanographic studies, including those of hydrodynamics and mixing conditions, is of great practical importance.

This paper stems mainly from a series of oceanographic measurements performed using a bottom-mounted Recording Doppler Current Profiler (RDCP) at sites near the Letipea Peninsula and Sillamäe in 2006–2009. The first two expeditions (Table 1) were initially planned as applied studies on mixing conditions for Kunda pulp mill effluents (Suursaar et al. 2008). Occasionally, distinct upwelling events occurred along the north Estonian coast during these measurements (Suursaar & Aps 2007, Myrberg et al. 2008), and the coastal section turned out to be an extremely interesting study area per se, where a subsequent set of process-oriented field campaigns were entirely justified.

The aims of this paper are: (1) to give an overview of the hydrodynamic conditions along the coastal section studied, (2) to reconstruct time series of wave parameters using a simple fetch-based wave model and digitized 3-hourly wind data over the period 1966–2009, and (3) to discuss decadal changes in sea level and wave conditions together with variations in the wind climate.

Table 1. RDCP measurements near Letipea Peninsula (expeditions A, B, C, D) and Sillamäe (E). Number of flow records (Rec), significant and maximum wave heights (H_s/H_m), maximum sustained wind speed (Wind, m s^{-1}), maximum current speed (Curr, cm s^{-1}), salinity (Sal) and temperature (Temp) ranges

Exp.	Period	Days	Depth	Rec	H_s/H_m	Wind	Curr	Sal	Temp
A	10.08.06 –14.09.06	34.9	10.9–12.0	5023	2.0/3.1	8.7	59	4.0–7.6	3.3–15.6
B	16.10.06 –25.11.06*	38.9*	10.8–11.9	1179	3.1/4.7	13.4	48	4.4–7.1	4.0–12.9
C	13.08.08 –17.09.08	34.8	10.4–11.0	1677	1.9/3.1	10.9	75	4.2–6.5	4.5–17.0
D	15.11.08 –09.06.09	206.6	10.8–11.9**	4959	3.7/5.8	18.4	45	3.9–6.3	0-11.7
E	29.07.09 –10.09.09	43.0	11.5–12.2	1033	1.3/2.1	8.8	22	3.5–4.4	14.8–19.0

* Flow measurements until 01.11.2006 (16.4 days only).
** Sensor jammed on 11.12.2008, 26.3 days left for the depth measurements.

2. Material and methods

2.1. RDCP measurements

Process-oriented studies on hydrodynamic conditions were carried out near the Letipea Peninsula and Sillamäe during five measuring periods in 2006–2009. Four moorings (A–D, Table 1) were performed at the Letipea site (59°33.7′N; 26°40.3′E) and one (E) at the Sillamäe site (59°24.9′N; 27°47.7′E), 60 km to the east (Figure 1). Both sites are about 1.5 km offshore. The coastal section between the sites is relatively straight, so the hydrodynamics can be described on the basis of these two mooring sites. Our hydrodynamic measurements are not representative beyond Narva-Jõesuu, where the coast turns north. The broad curvature of the bay may influence the circulation by introducing some non-persistent wind-dependent gyres. According to our estimates (e.g. Suursaar & Kullas 2006), the influence of the River Narva (average discharge 385 m^3 s^{-1}) on the hydrodynamics is still quite local and does not extend even as far as Sillamäe. There is some influence on salinity along with much the larger (2600 m^3 s^{-1}), but also more distant River Neva. Nevertheless, the salinity never dropped below 3.5 at Sillamäe and 3.9 at Letipea (Table 1).

The measurements were carried out using the oceanographic measuring complex RDCP-600 (AADI Aanderaa). The upward looking instrument was deployed on the seabed by divers from a speed boat of the Estonian Marine Institute or a pilot's launch from the port of Sillamäe. Mainly because of the battery capacity, the recording interval varied with the mooring: it was 10 min at mooring A, 20 min at B, 30 min at C, and 60 min at D and E. In the seasonal cycle, every calendar month was covered to a greater or lesser extent.

The RDCP-data was used in three ways in this study. Firstly, the total of 335.7 days of multi-layer flow measurements probably forms the most extensive data set of its kind in Estonia, allowing us to present quite a representative statistical description of the hydrodynamic conditions. Secondly, the wave measurements served as both calibration and validation references for the wave model, which was then used for long-term wave hindcasts. Finally, the full set of recorded parameters was used for studying some incidental hydrodynamic phenomena, such as upwelling events and coastal jets.

The vertical column set-up for flow measurements included a 2 m cell size with 50% overlap, so the '4 m depth' actually represented the 3–5 m depth interval, '5 m' represented 4–6 m etc. Beginning with the seabed, there was a 2 m blank distance between the instrument and the lowest measurable cell. Also, within the 1–3 uppermost metres, depending on sea level variations and wave height, the measurements were 'contaminated' and discarded because of high standard deviations and some contradictions in the acoustic beam data. Thus, a mooring depth of 10.4–12.1 m (Table 1) enabled 6–7 depth layers to be monitored.

In addition to Doppler effect-based current measurements, the RDCP-600 was equipped with temperature, oxygen, turbidity and conductivity sensors, which sampled the near-bottom layer in contact with the instrument. The high accuracy quartz-based pressure sensor (resolution 0.001% of full scale) enabled measurement of wave parameters.

2.2. Data on wind forcing and sea level

The Estonian Meteorological and Hydrological Institute (EMHI) currently runs 6 weather stations along the northern coast of Estonia. We used data from the Kunda station for the meteorological description of the mooring periods in 2006–2009 (Table 1) and to force the wave model. The Kunda station is the closest to the Letipea measuring site, just 10 km to the west (Figure 1). For wind measurements, the site is somewhat sheltered by land from southerly directions, so the marine wind regimes are from northerly sectors. There is another weather station closer to Sillamäe, at Narva-Jõesuu, but it is ca 80 km distant from Letipea. Moreover, the location of the station changed from Narva to Narva-Jõesuu in 2000, so continuity with older data is disrupted.

Kunda has been operational since 1901, but this study is limited to the digitized 10 minutes sustained wind speed data since 1966. Wind speed was measured with a wind vane of Wild's design during 1966–1976, a recording anemometer during 1976–2003, and the MILOS-520 automatic weather station since September 2003 (Keevallik et al. 2007). While the automatic weather station provides hourly data, the data from January 1966 to August 2003 have a time interval of 3 hours. The data from 1966–1976 have been corrected slightly for homogeneity following the procedure described in Suursaar & Kullas (2009). Basically, it slightly reduces strong winds over 10 m s^{-1}. For example, a wind speed of 11 m s^{-1} corresponds to the previous 12 m s^{-1}, and 20 m s^{-1} is equivalent to the previous 23 m s^{-1}. The value step for the wind speed is 1 m s^{-1} from 1966 until September 2003, and 0.1 m s^{-1} thereafter. Wind directions for 1966–1976 are given in the 16-rhumb system, while the directional resolution is 10° until 2003 and the MILOS-520 weather station provides 1° resolution output. For statistical purposes we also calculated the u and v components of the wind velocity vector. The positive direction is east for u and north for v, which applies to both air (wind) and water (current) movements. The completeness of the data sets is practically 100%: there were hardly any missing values in the database for Kunda.

Data from the tide gauges at Narva-Jõesuu and Tallinn were used to describe the long-term sea level regime. These are the two longest and the most complete sea level series in Estonia. Our study area is located roughly between these two stations, the Narva-Jõesuu gauge being the closest to both the Sillamäe and the Letipea mooring sites. Nearly continuous data sets for Tallinn are available from 1842, but the measurements were discontinued in 1996 owing to construction work at the Port of Tallinn. Thereafter, the station was moved to the Port of Muuga, but continuity was technically lost. Measurements at Narva-Jõesuu have been carried out since 1899.

The data represent the relative sea level with regard to the Baltic Sea Height System (or Kronstadt datum). The Kronstadt 'zero' was defined as the average sea level of 1825–1840, and it approximates the present mean sea level of Estonian tide gauges (Suursaar & Sooäär 2007). Measurements of local relative sea level are confounded by the influence of isostatic movement, which needs to be removed if we wish to isolate the 'eustatic' component of the sea level trend. Information on land uplift at the studied stations was taken from a map compiled on the basis of precise levelling in 1933–1943, 1956–1970 and 1977–1985 (Vallner et al. 1988). The radial crustal movements in Estonia are influenced mainly by regional

Fennoscandian postglacial rebound, and the uplift rate at Narva-Jõesuu is about 0.5 mm yr^{-1}.

2.3. Wave modelling

The SMB-model, also called the significant wave method, is based on the fetch-limited equations of Sverdrup, Munk and Bretschneider, where the significant wave height (H_s) is a function of wind speed, fetch length and depth (e.g. CERC 1984, Massel 2010). For the exact shallow water equations that we used, see Suursaar & Kullas (2009). Our previous effort near Saaremaa Island in 1966–2006 was based on Vilsandi wind data and RDCP calibration data of waves near the Harilaid Peninsula in winter 2006–2007 (Suursaar & Kullas 2009). A comparison between the SMB model and the 3rd generation WAM model showed that such SMB-type models could be used for site-specific long-term hindcasts, despite their limitations regarding mainly spatial coverage (Räämet et al. 2009).

In this study, the wind data from Kunda were used to run the wave model. The data obtained by the RDCP between 16 October and 24 November 2008 (period B, Table 1) served to calibrate the model. The calibration was done by prescribing fetch distances for different wind directions with a step of 10° and searching for the appropriate depth. As the SMB model assumes the basin has a constant depth, it should consider both the depth of the actual mooring (i.e. 11–12 m) and the average depth of the Gulf of Finland (37 m). Our set of calibration parameters included the depth of 31 m. Increasing the depth also increases wave heights, but especially in high wind speed conditions, whereas lengthening fetches influences wave heights more uniformly (Figure 2). Determining the directional distributions of fetches was more complicated. As good

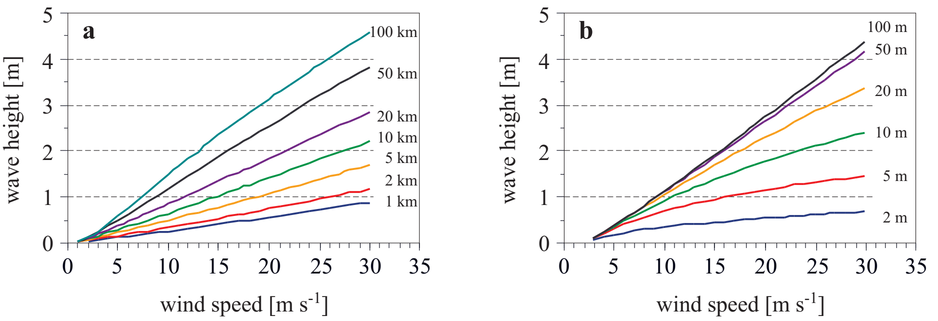

Figure 2. Modelled dependences of significant wave heights from wind speeds and fetches for a 30 m depth (a), and from wind speeds and depths for a 50 km fetch (b)

calibration data are rarely available, the fetch is measured as the headwind distance from the nearest shore for that wind direction, and a procedure for taking into account basin properties in a wider wind sector is applied (see e.g. Massel (2010) for an overview). For the Letipea location the geographical fetch distance varies between 1.5 (S, SW) and about 140 km (NE). However, to compensate for the wind impediment of the southerly directions at Kunda, we had to modify the fetches from W, S, and E directions. The calibration was done iteratively, in an attempt to keep the maximum and average wave heights equal in the modelled and reference series, to maximize the correlation coefficient and to minimize the root mean square error. For the hourly-based 39-day calibration, we obtained the same mean wave height over the period (0.50 m), a nearly equal maximum wave height (2.91 m measured vs. 2.86 m modelled), a correlation coefficient of 0.92 and an RMSE of 0.22 m (Figure 3). The calibration scheme applied here differed from our procedure for the Harilaid-Vilsandi waves (Suursaar & Kullas 2009), and no final correction of the model output was needed.

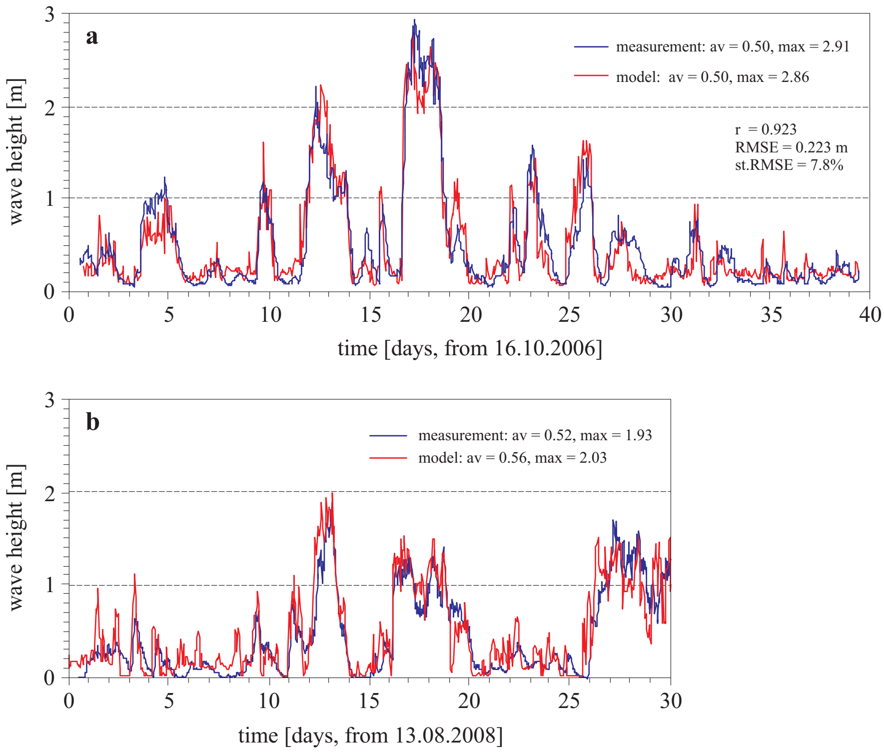

Figure 3. Comparison between the measured and the modelled wave series during the final calibration run (a), and the subsequent validation run (b)

Even so, the correlation was slightly better than in the Vilsandi-Harilaid case (r = 0.88), the RMSE was also better (compared to 0.23), but the standardized RMSE was slightly higher (7.8% vs. 7.4%) owing to the smaller variability range at Letipea.

We also carried out a validation run of the model, where the wave parameters were calculated for the period C using the same settings as in B, and the agreement was still reasonably good (Figure 3b). The calibrated and validated model was then used for multi-year (1 January 1966–31 October 2009) wave hindcasts at a 3 h interval. At the time of writing of the manuscript, the wind data for 2009 were incomplete, so the summary statistics end with 2008. Although forced by Kunda wind and calibrated by waves measured at Letipea, this series is assumed to represent the wave climate of the whole coastal section between Letipea and Sillamäe. The wind climate is shaped mainly by regional meteorological conditions, whereas the relatively unimportant mild wind conditions are mostly generated locally.

The statistical analysis, including the mean, maxima and different percentiles, was carried out in relation to significant wave height (H_s). No wave periods are considered here. The RDCP, having a cut-off period of about 4 seconds for our mooring depth, could not provide proper calibration data for wave periods, i.e. the RDCP and wave models represent slightly different aspects of the wave spectrum. Also, as the Gulf of Finland has a relatively semi-enclosed shape and the role of mixed wave types (e.g. wind waves, swell, ship waves) is small, the empirical relationship (joint distribution) between wave heights and periods has a relatively small scatter (see e.g. Soomere & Zaitseva 2007, Räämet et al. 2010).

Taking into account sea ice conditions was not an important issue in the Vilsandi-Harilaid hindcast, but it is an important issue here. The mean duration of fast ice at Narva-Jõesuu is about 70 days (Sooäär & Jaagus 2007). Depending on the winter, the period can be anything between 0 and 150 days. Thus, in addition to the continuous hindcast, a version of the calculations with an 'ice mask' was produced. We used published data on ice conditions in the Gulf of Finland (Seinä & Peltola 1991, Sooäär & Jaagus 2007), as well as ice data obtained at the Narva-Jõesuu station (by EMHI) and ice maps from the website of the Swedish Meteorological and Hydrological Institute. We estimated the periods with ice cover at the study site and eliminated the wave heights during these periods. Thereafter, we calculated a new set of annual wave statistics. We admit that we encountered some problems, e.g. due to possible miscalculation of actual fetches in the periods when the Gulf was partly covered by ice.

3. Results and discussion

3.1. Changes in sea level regime

Being part of the semi-enclosed and practically tideless Baltic Sea, the coastal waters of Estonia exhibit mainly meteorologically forced sea level variations. The sea level fluctuates mostly around the mean state, and very high or very low values are rare. Owing to the limited water exchange capacity through the Danish Straits, there is firstly a slowly changing regional component due to changes in the Baltic water volume as a whole (Stigebrandt & Gustafsson 2003). On top of that, there is a mainly wind-driven local sea level component (e.g. Suursaar & Kullas 2006, Soomere et al. 2008). In the Gulf of Finland, sea level variability increases from west to east towards St. Petersburg, which has the highest recorded sea levels in the Baltic Sea (up to 423 cm above the mean). Also, Narva-Jõesuu has a larger historical sea level variability range (315 cm, Figure 4) than Tallinn (220 cm); the conditions near Letipea can be interpolated between these two values. The RDCP variability was 110 cm at moorings A, B and D (Table 1).

According to the Narva-Jõesuu tide gauge, 90% of the sea level data fell within the –30 to +60 cm interval. The annually expected maximum sea level did not exceed 85 cm (Figure 4), although the return value was about 170 cm for 10 years and about 200 cm for 100 years (Figure 4b). Although the mean sea level included a seasonal cycle ranging between −11.3 (in May) and 11.2 cm (September and December), both extremely high and low sea level events most probably occur during the autumn and winter months (Figure 4a).

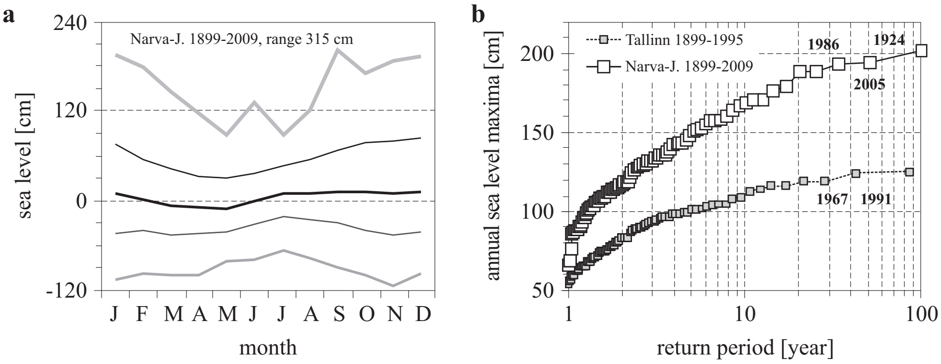

Figure 4. Seasonal variations in monthly sea level statistics – lines from top: absolute maximum, average maximum, mean, average minimum, absolute minimum (a); empirical return periods based on annual sea level maxima at Tallinn and Narva-Jõesuu (b)

The average sea level at Narva-Jõesuu was 3.7 cm over the period 1899–2009, and −0.8 cm at Tallinn in 1899–1996, indicating a quasi-permanent (statistical) Baltic Sea level slope. The relative mean sea level data showed a slightly increasing sea level trend at Narva-Jõesuu and a more or less stable state at Tallinn (Figure 5a). In view of the land uplift rates (0.5 mm yr^{-1} at Narva-Jõesuu and 1.8 mm yr^{-1} at Tallinn), both series indicated a 'climatological' sea level rise of 1.1–1.5 mm yr^{-1} over the period since 1899. This is close to the global sea level rise estimates (IPCC 2007, BACC 2008) for similar periods. However, the rise was not constant in time. It has included both quasi-periodic cycles and probably also an accelerating component since the 1950s (Meier et al. 2004, Church & White 2006). The 30–40 year cycles with amplitudes of about 5 cm showed co-variations

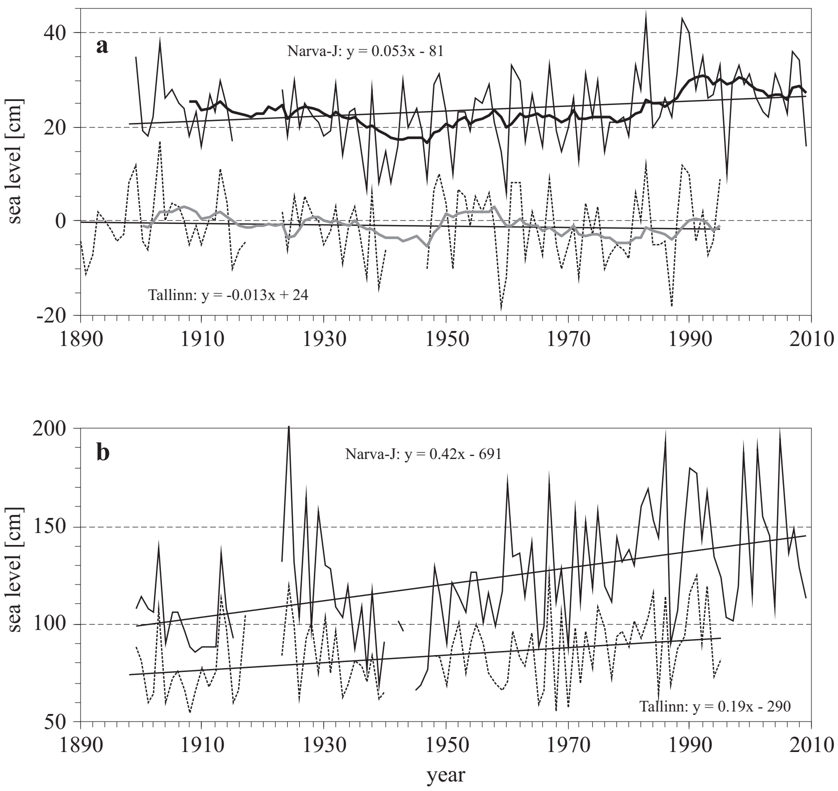

Figure 5. Decadal variations in annual mean relative sea levels together with 11-year moving averages and linear trendlines at Narva-Jõesuu (until 2009) and Tallinn (discontinued in 1996), shifted in relation to each other for 20 cm (a). Decadal changes in annual maximum sea levels (b). The series are not corrected with the land uplift rate, which is about 0.5 mm yr^{-1} at Narva-Jõesuu and 1.8 mm yr^{-1} at Tallinn

with large-scale forcing indices (such as NAO-index and storminess data; Suursaar & Sooäär 2007, Jaagus et al. 2008), and influenced linear trend estimates, which depended largely on the terminal points and the periods chosen. For instance, the linear sea level trend corrected for land uplift was 2.2 mm yr^{-1} over the period 1939–2009 and even 2.3 mm yr^{-1} at Narva-Jõesuu in 1976–2008.

Rising sea level trends in annual time series appeared to reflect greater rises in the winter (December to March) sea level, whereas summer trends were markedly less steep or even declined slightly. Moreover, the trend estimates for annual maximum sea levels were much higher and varied between 5 and 8 mm yr^{-1} for different periods at Narva-Jõesuu and 3–6 mm yr^{-1} at Tallinn (Figure 5b). This was probably due to the increased intensity of westerlies in winter, as also indicated by the NAO-index (Suursaar & Sooäär 2007, BACC 2008).

According to both hourly data from the Narva-Jõesuu tide gauge and the relative sea level variations given by the RDCP, easterly winds lower the sea level in Narva Bay, whereas westerly winds raise it. This applies to both short-time variations, as well as to low-frequency variations through corresponding changes in the Baltic seawater volume. High sea level events in Narva Bay are associated mainly with north European cyclonic storms, which bypass Estonia to the north over the Scandinavian Peninsula, as the strongest winds within a travelling cyclone occur a few hundred kilometres to the right of the cyclone track. In Estonia, such cyclones cause westerly winds that approach unobstructed over the sea surface, which has a smaller friction than land. Also, the elongated shape of the Baltic Sea together with the Gulf of Finland provides a distance for the surge wave to increase towards the east, as the depth also diminishes and the gulf becomes narrower.

3.2. Statistics of observed currents

According to the traditional but idealized views on the Baltic circulation stemming from Witting's and Palmen's times nearly a century ago, the generally cyclonic scheme with an average velocity of a few cm s^{-1} continues to prevail (e.g. Voipio 1981, Leppäranta & Myrberg 2009). A hindcast with realistic wind forcing of the Gulf of Finland circulation using an eddy-resolving model (Andrejev et al. 2004) has revealed a series of quasi-permanent topographically modified mesoscale gyres in the Gulf, and interestingly, from the point of view of this paper, a resultant westward current along the coast between Narva-Jõesuu and Kunda (Soomere et al. 2008, 2009). This branch seems to contradict both previous circulation schemes as well as local prevailing wind statistics. However, our in situ measurements carried out over a period of 336 days confirm that scheme (Table 2). Indeed, a resultant NWW current with a speed of 5–6 cm s^{-1} was found in the near-surface layer. At the same time (in 2006, 2008 and 2009), the mean u-component of the wind vector was positive at Kunda. Although the measurements at Sillamäe were not as representative owing to their shorter duration, they did indicate a prevailing westward current as well.

Table 2. Weighted statistics of current velocity components at different depth layers at Letipea (292.7 days) and Sillamäe (43.0 days). The statistics of the main longshore component (u) are given for both W and E directions (frequency in %, average and maximum velocity of the direction, cm s^{-1}), as well as resultant values for both u and v, and average and maximum modulae (i.e., velocity regardless of direction, M_{av}, M_{max})

Depth	W%	W_{av}	W_{max}	E%	E_{av}	E_{max}	u	v	M_{av}	M_{max}
Letipea										
2–4	66	−14.8	−70	34	10.1	46	−6.3	3.1	15.0	76
3–5	65	−13.7	−59	35	9.7	45	−5.4	2.8	13.9	66
4–6	63	−12.2	−50	37	9.2	44	−4.3	2.2	12.6	57
5–7	62	−10.2	−45	38	8.6	44	−3.0	1.5	10.8	48
6–8	58	−7.9	−42	42	7.6	45	−1.4	0.5	8.9	48
7–9	47	−6.1	−38	53	6.7	46	0.7	−0.3	7.4	51
Sillamäe										
2–4	63	−5.2	−21	37	3.2	15	−2.0	−0.4	5.4	22
3–5	67	−4.7	−18	33	3.0	15	−2.2	−0.6	5.1	19
4–6	69	−4.6	−19	31	2.8	14	−2.3	−0.7	5.0	19
5–7	73	−4.7	−17	27	2.8	12	−2.7	−0.8	5.1	18
6–8	76	−4.7	−16	24	2.9	14	−2.8	−0.8	5.2	17
7–9	77	−4.4	−15	23	2.9	14	−2.7	−0.9	5.1	16
8–10	79	−4.3	−13	21	2.8	14	−2.9	−1.4	5.1	15

Because of the proximity to the coast, the measured currents tended to be polarized and modified by the coastline. Most of the velocity readings lay within two narrow directional intervals of 270–310 and 80–120 degrees: the u (W–E) velocity component described 78–88% of the total variability at the Letipea mooring site and 80–93% at Sillamäe. Over most of the water column (down to 8 m depth), the westward flow was both more frequent (58–66%) and faster at Letipea. Only in the near-bottom layer (7–9 m) did a compensatory eastward flow slightly prevail (Table 2, Figure 6).

The most striking feature of the statistics was the different vertical structure of the westward and eastward currents (Figures 6–8). For the westward currents, both averages and extremes were larger in the upper

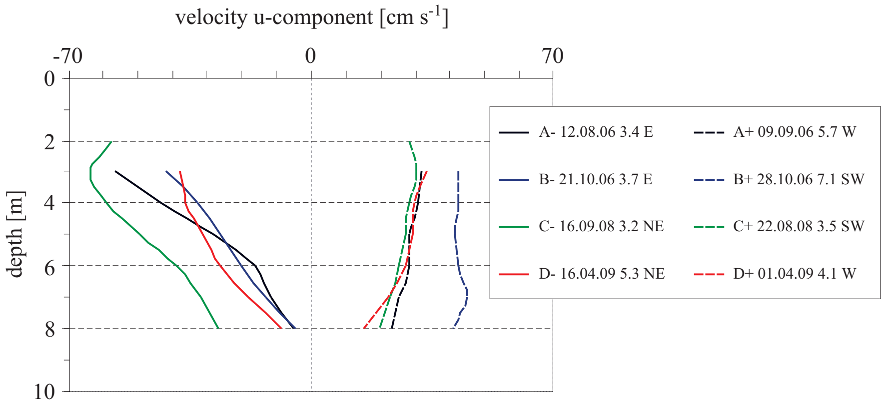

Figure 6. Vertical profiles of some fast east- (+) and westward (−) currents for the moorings near Letipea Peninsula (see also Tables 1 and 2). Assuming each layer to be 2 m thick with a 1 m overlap, the actual sampling depth was 1–9 m at C and 2–9 m during other moorings. The legend also indicates the date of the profile and the corresponding 24 h average wind conditions preceding the event

layers, but considerably smaller in the near-bottom layer. Moreover, the fast westward currents were caused by rather moderate winds, whereas strong W or NW winds were unable to produce equally rapid eastward currents. The maximum sub-surface current (76 cm s^{-1}) was recorded on 16 September 2008, when the sustained wind speed was just 3–4 m s^{-1} at Kunda and the maximum gust wind speed did not exceed 8.2 m s^{-1}. Such current structures, as well as specific findings regarding water temperature and salinity, were indicative of stratification effects and upwellings.

3.3. Upwelling and coastal jets

In the Baltic Sea, upwelling is mainly a mesoscale process, which usually occurs when the wind blows parallel to a coastline on its left. Then, the offshore transport of mass in the surface layer is balanced by an onshore flow in the deep layers and an Ekman pumping of water from those deep layers up to the surface. Basically, upwelling implies a vertical current. According to some estimates and modelling studies, the vertical velocities should be around 0.01–0.1 cm s^{-1} (e.g. Bowden 1983, Lehmann et al. 2002). Although RDCP also measures vertical velocities directly, the results ranging roughly from −2 to +2 cm s^{-1} failed to describe the hydrodynamic processes actually occurring, or their contribution appeared in the record as white noise due to the mismatch between the characteristic scale of the process and our measurement integration (Suursaar 2009). The only detectable low-frequency variations reflected mainly the equilibrium between resuspension and the settling of particles, predominantly forced by wave activity. Thus, apart from thermohaline effects, upwelling is manifested in the RDCP records by a distinctive vertical structure of horizontal currents (Suursaar & Aps 2007) and not by measurable vertical velocities.

Nevertheless, it is quite a frequent phenomenon (up to 20–30% according to Myrberg & Andrejev 2003, Kowalewski & Ostrowski 2005) along straight sections of the coast, but it does require a few days of favourable winds of moderate strength, as the relatively small and practically immeasurable vertical velocities must cause certain detectable changes in thermohaline regime of the surface layer. In general, the time required for the 'evidence' of upwelling to reach the sea surface can be approximated as the ratio of the thickness of the upper mixed layer to the vertical velocity. In practice, the use of sea surface temperature (SST) satellite images has become very common (Bychkova & Viktorov 1987, Suursaar & Aps 2007, Myrberg et al. 2008): such upwelling can be registered when the temperature of the surface layer differs significantly from that of the upwelled waters, which means that the method is necessarily limited to warm seasons and the sea surface. However, in terms of vertical velocities and a rise in the pycnocline, upwelling can occur without influencing the surface layer. Sometimes it is just a transition phase before or after the 'real' upwelling. In thermally more homogeneous situations, in situ salinity measurements or eddy-resolving hydrodynamic modelling (Jankowski 2002, Lehmann et al. 2002, Myrberg & Andrejev 2003) can be used, but neither is as handy as the analysis of satellite imagery.

We can identify upwelling from temporal variations in the T, S or density graphs of a point measurement, especially if we can also take into account the occurrence of stratified flow regimes, which in the case of a westward current, should indicate an upwelling-accompanied baroclinic coastal jet. Our records included several major upwelling events. A rather prominent one occurred in summer 2006, which was described in more detail by ourselves (Suursaar & Aps 2007), as well as by some other authors (Myrberg et al. 2008, Lips et al. 2009). It lasted from around 1 July until 5 September and had a horizontal extension of about 360 km. The maximum longshore extension is determined largely by the coastline. Where it substantially changes its direction, a particular wind does not favour upwelling. MODIS SST images showed spatial variations from about 5°C (in the upwelling zone) to about 21°C in the unaffected central part of the Gulf of Finland. Simultaneous RDCP measurements showed pronounced temporal variations both in water temperature (between 3.3 and 15.6°C) and salinity (between 7.6 and 4.1; Figure 7c). An upper layer coastal jet with longshore velocities of up to 59 cm s^{-1} was recorded (Figure 7b), whereas

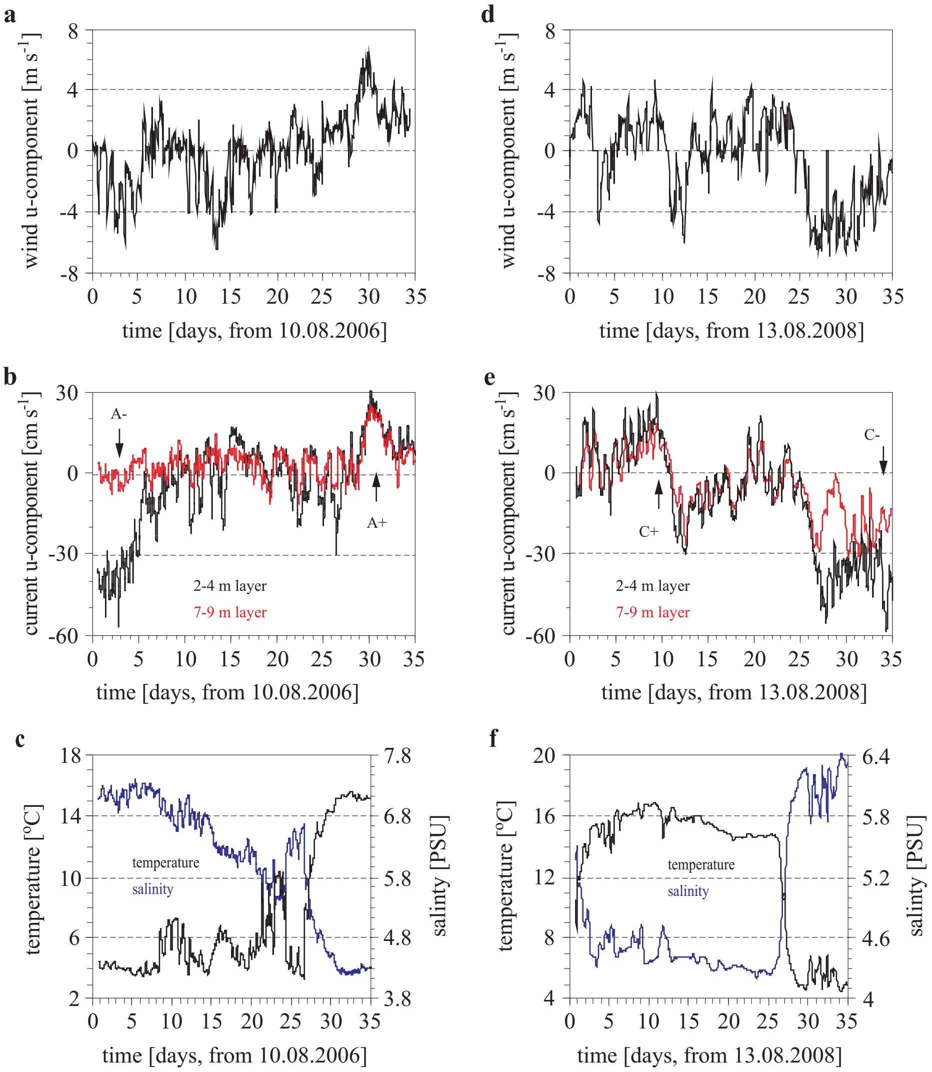

Figure 7. Variations in wind forcing (a, d), longshore current velocities in two depth layers (b, e), and near-bottom water temperature and salinity (c, f) during two moorings, A and C (Table 1). A−, A+, C− and C+ mark the moments for the vertical profiles presented in Figure 6. The upwelling events were identifiable by low temperatures, high salinities and stratified currents

the near-bottom counter-current did not exceed 12 cm s^{-1} at the same time. The typical easterly wind speeds were only 3–6 m s^{-1}, while after the event, westerly winds with sustained speeds of up to 8–14 m s^{-1} were capable of generating a current with a top speed of only 32 cm s^{-1} (Figure 7a–c). Obviously, for generating a current in the relatively thin upper layer of a stratified sea, a much smaller momentum input is needed than in the case of a homogeneous sea (Weisberg et al. 2000). Thus, upwelling-favourable winds seem to produce disproportionately larger responses in near-shore current speeds than downwelling-favourable winds.

According to widespread opinion, the width of the coastal jet can be determined by the value of the internal Rossby radius, which is about 3–4 km in this region of the Baltic Sea (Lehmann et al. 2002, Myrberg et al. 2008). According to Lass & Talpsepp (1992), the offshore scale of the jet exceeded the baroclinic Rossby radius by a factor of two. But it is still less than in the area of low SST derived from satellite images, as the cold water tends to spread and form filaments that may eventually reach the central line of the Gulf of Finland (Suursaar & Aps 2007). Stratification, which enables the baroclinic jet to form, could appear due either to temperature or to salinity differences. Characteristically in our study area, the salinity variation range of 4–7 and the temperature range of 4–23°C both yield roughly the same 2.7 kg m^{-3} density difference. For forming a coastal jet, the summer rise and sharpening of the pycnocline due to the combination of both is probably the most effective.

During the second major upwelling event in the first half of August and then again in September 2008 (Figure 7d–f), the upwelling-induced temperature variations reached about 13°C, while the salinity variation was 2.5 units. Oxygen saturation decreased as a result of upwelling from about 95% to 55% at the 11 m deep near-shore location, and the speed of the upwelling jet was as high as 70 cm s^{-1}, again under modest (3–7 m s^{-1}) wind forcing. We should bear in mind that some surface current data are missing or have been discarded, so the velocities could have been even higher at the sea surface, at the point of momentum input.

The longest record D included several examples of winter upwelling events, manifested mainly in salinity and velocity records. The ones with relatively small density gradients occurred on 27–30 January and 10–15 February 2009. The velocity difference between the sub-surface and near-bottom layers in the case of westward currents was just about 30 versus 15 cm s^{-1}. The more obvious examples included an event with salinity variations of 1.5 units on 26–31 March, an up to 1.9 unit event on 7–17 April (Figure 8), but also a 1.8 unit event on 20–23 May and a 2.3 units case on 6–9 June 2009. Some of these included temperature variations in contrast to the usual warm season upwelling situation, namely, the upwelled water was slightly warmer (3.5–4°C) than the surface water (1.5–2.5°C), the highest-density temperature being ca 3°C for a salinity of 5 units. Out of all the measurements, upwelling was identified on 57 days, so the average upwelling frequency was estimated at 17%. There were no fully developed upwellings at moorings B and E.

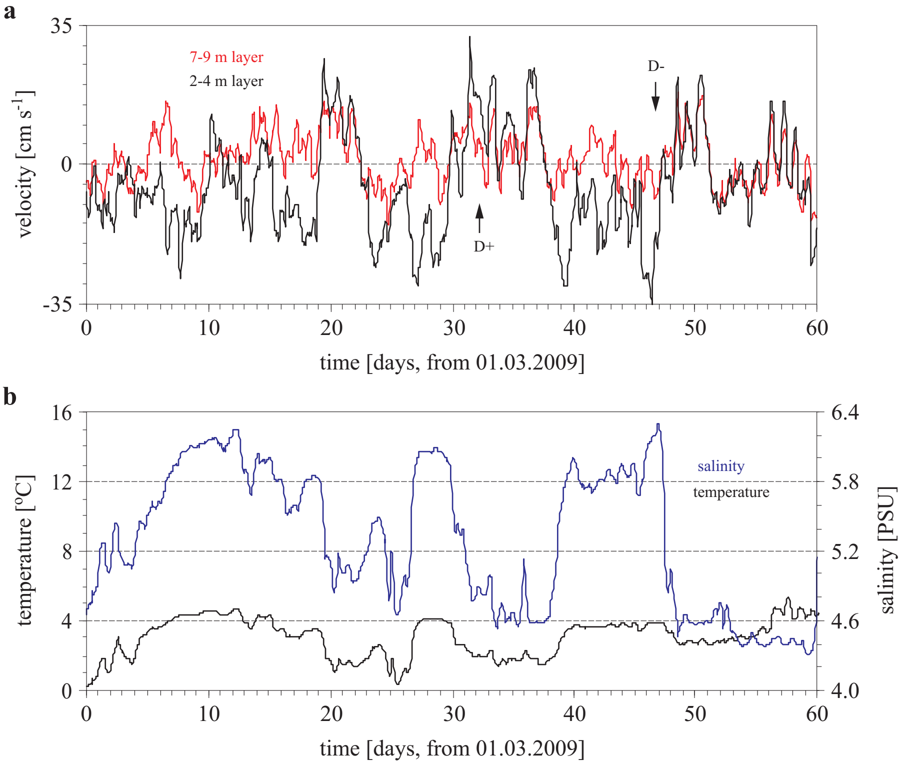

Figure 8. Variations in longshore current velocities at two depth layers (a), and in near-bottom water temperature and salinity (b) during mooring D (extract from 1 March to 29 April 2009). Because of the small temperature variations, the stratification is due mainly to salinity differences, which nonetheless yield stratified westward currents

Being just an 'occasional' mesoscale process, upwelling can still leave a detectable imprint on the long-term spatial thermohaline and flow statistics of the whole Gulf. Indeed, from repeated CTD-castings along cross-sections of the Gulf of Finland, some patches of more saline water were found along the coast, which had probably been formed as a result of repeated upwellings (Talpsepp 2008).

3.4. Wave climate 1966–2008

The hindcast results for the period 1966–2008 (125 648 data points with 3-hour intervals) had a gross average value of 0.52 m (in terms of H_s).

The mean standard deviation was 0.52 with a positively skewed empirical frequency distribution, which is frequently approximated using the Rayleigh distribution (Soomere & Zaitseva 2007, Soomere 2008). The maximum recorded H_s value occurred on 23 November 2008 (D, Table 2). The H_s was 3.7 m and the peak wave period reached 9.3 s in a northerly storm with a sustained wind speed of 18.4 m s^{-1} and a gust wind speed of up to 26 m s^{-1}, as measured at the Kunda station. Wind speeds and wave heights, both maxima and averages, displayed a clear seasonal variability. Wave periods for the most typical waves (0.25–0.75 m) were 2–4 s.

While according to our previous hindcast at Harilaid the trend in mean wave heights was gradually decreasing with an overall rate of –0.001 m per year in 1966–2006 (Suursaar & Kullas 2009), the trend was a steeply decreasing one near Letipea (-0.005 m yr^{-1} in 1966–2008). On the basis of annual series of the 90 and 99 percentiles, as well as annual maxima, the trends were clearly increasing near Harilaid, but still decreasing near Letipea (Figure 9, 10). As with sea level, the trends of wave properties were

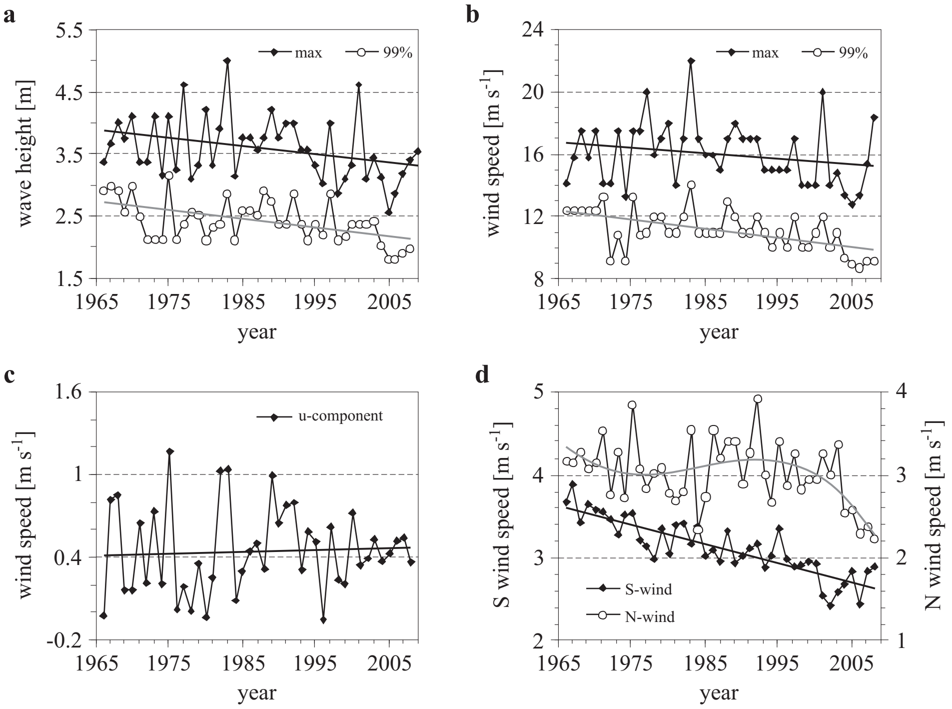

Figure 9. Decadal variations in the annual wind and wave statistics: maxima and 99-percentiles of the hindcast waves (a) and Kunda winds (b), mean zonal wind component values (c), and the northerly and southerly constituents of the meridional wind component, both given as positive values in (d)

different in different months. For instance, even at Letipea, the December to March subset of mean wave heights showed an increasing trend of 0.0017 m per year.

In general, if a wave model is applied to a relatively small, semi-enclosed basin, it should in some way reflect the wind conditions above that basin, as the part played by remotely generated wave fields is negligible. Since the present model is largely fetch-dependent, the decrease in wave heights at Letipea appears to be mainly the result of decreasing northerly winds at Kunda. Decomposition of the v-component showed that both the southerly and northerly components are less (Figure 9d). Although the fate of the southerly component is quite irrelevant for the waves in our study area, the present reduction in the northerly component obviously influences the wave statistics.

Although the average wind speed has probably decreased at both the Vilsandi and the Kunda meteorological stations, the frequency and strength of storm events in recent decades have increased at Vilsandi (Jaagus et al. 2008) but decreased at Kunda (Figure 9b). The westerly component increased at Vilsandi (Suursaar & Kullas 2009) and showed a level or slightly increasing trend at Kunda (Figure 9c). But the westerly direction has relatively small fetches for the Letipea area, and this component could not keep waves high so long as the northerly component was decreasing. On the other hand, increasing regional westerly winds and westerly storms are still capable of producing wind-driven sea level rise at Narva-Jõesuu (Figure 5).

The increasing storminess at Vilsandi and the fewer strong winds at Kunda are probably associated with changes in the atmospheric pressure patterns above northern Europe and the northward shift of cyclone trajectories over recent decades (BACC 2008, Jaagus et al. 2008): there are more cyclones bypassing Estonia to the north, creating strong westerly winds, but fewer cyclones crossing Estonia itself, giving rise to strong northerly winds.

Our simulated average wave graph for the Letipea Peninsula is quite similar to the one by Soomere et al. (2010) derived from visual observations at Narva-Jõesuu. This means that the two very different methods are capable of revealing the most essential features of the wave fields in Narva Bay.

The average number of days with ice at Narva-Jõesuu was 115 over the period 1949–2004 (Sooäär & Jaagus 2007). According to the linear trend, the ice period has decreased by 12 days at Narva-Jõesuu and by as many as 30–40 days in the open parts of the Gulf of Finland (Leppäranta & Myrberg 2009). The 'ice mask', described in the Material and methods section, included as many as 80–100 ice days in the 1960s, but typically just 20–60 days in recent decades. The mildest winters, without ice cover near the Letipea Peninsula, were 1991/92, 1994/95, 2001/02, 2007/08 and 2008/09.

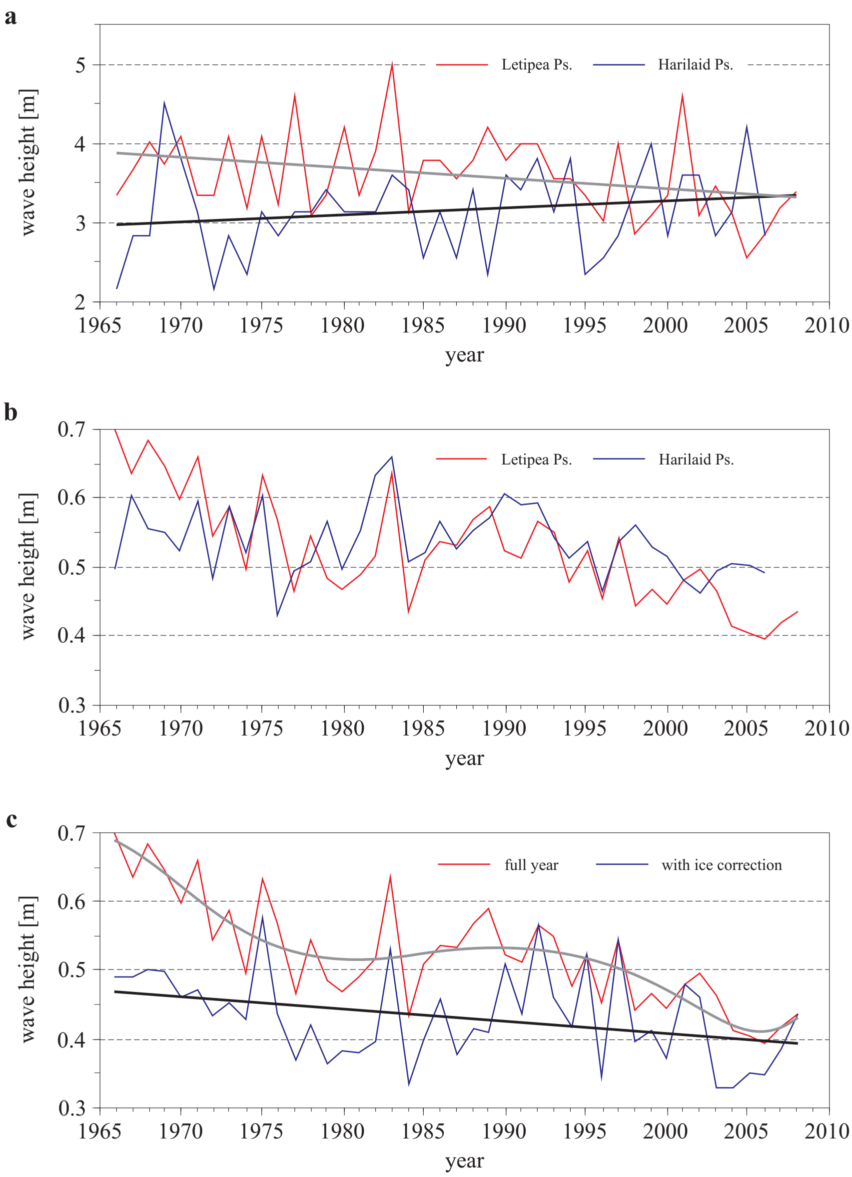

Figure 10. Comparison of hindcast decadal variations in the annual maximum (a) and mean wave heights (b) at Letipea and Harilaid (data for Harilaid according to Suursaar & Kullas 2009). Comparison between the strictly meteorologically forced (full year) hindcast and the hindcast with ice mask applied in winters with real ice cover in the Letipea Peninsula region (c)

Though not as steep as in the original series, the trend corrected for ice (Figure 10c) still decreased by 7 cm over a 43-year period. The ice corrections affected the annual samples slightly with respect to the 90 and 99-percentiles, but the maxima hardly at all. There were only three years – 1987, 1993 and 2004 – when the annual maxima were slightly different, which did not affect the trend (Figure 9c). Apparently, the strongest winds (and waves) occur mainly during cyclonically active and ice free winters, whereas ice cover develops mainly during anticyclonic and relatively calm weather conditions.

Some additional wave studies are still needed, as different hindcasts occasionally reveal different behaviour in the north-eastern Baltic (Soomere et al. 2008, Suursaar & Kullas 2009, Räämet et al. 2009). In semi-enclosed marine areas it is mainly a question of the quality or inherent properties of the wind forcing used, as the models basically reflect winds: there cannot be any hidden mechanisms that prevail over the 'wind's will'. However, the issue may be more complicated in large and complex marine areas (e.g. Weisse & Günther 2007), where local wave properties may appear as a mixture of several wave fields.

4. Conclusions

The relatively straight coastline in north-east Estonia has quite intense hydrodynamic mixing conditions, which are manifested mainly as a result of meteorologically forced sea level variations (with a historical range up to 315 cm), longshore currents, upwelling events and up to 5 m high waves.

The statistics of extensive, 336 day multi-layer flow records show that, though time-variable, the coastal current was directed predominantly (60–66%) westwards, parallel to the shore, with average velocities of 10–15 cm s^{-1} in that direction and resultant values of up to 5–6 cm s^{-1}. The vertical profiles were asymmetrical for westward and eastward currents. Both averages and maxima were larger in the westward sub-surface currents, even with relatively modest wind forcing. The eastward current was vertically rather homogeneous, and even with strong wind forcing the current never reached the magnitude of the westward baroclinic coastal jet. The records of currents and water column properties did indicate upwelling during about 17% of the total mooring period, but there are always some disputable areas in the record. The most pronounced events occurred in August 2006 and 2008. Some winter upwellings were identified on the basis of salinity variations and stratified flow regimes of westward currents in February-March 2009. Considering their relatively frequent occurrence, as well as their profound impact on the thermohaline regime, upwelling events may leave a detectable imprint on the long-term spatial thermohaline and flow statistics.

While the long-term mean sea level trend at Narva-Jõesuu roughly approximates the global sea level rise trends (1.5 mm yr^{-1} for 1899–2009, 2.2 mm yr^{-1} for 1976–2009), the trend estimates for annual sea level maxima were between 5 and 8 mm yr^{-1}, depending on the period in question. This was probably due to changes in large-scale atmospheric pressure systems, which on the windward coasts of western Estonia is manifested by an increase in westerlies and storm winds. Surprisingly, both average and maximum wave heights decreased according to the local Letipea-Sillamäe hindcast for 1966–2008. For this area, which has the longest wave fetches in northerly directions, the changes in westerlies are not as relevant as on the west coast of Estonia. Instead, northerly winds make the greatest contribution to the wave climate, but this is the wind component that decreased over the hindcast period.

Acknowledgements

The author is grateful to the Estonian Meteorological and Hydrological Institute for providing meteorological, sea level and ice data, to Dr. Jaak Jaagus for some additional ice information, to Dr Georg Martin, Kaire Kaljurand and Arno Põllumäe for helping with the RDCP mooring.

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