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Highlights of the physical oceanography of the Gulf of Finland reflecting potential climate changes

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We review highlights of the studies of physical oceanography of the Gulf of Finland, the Baltic Sea, in 1997–2007 that serve, or can be interpreted, as evidence of shifts or changes in the local climate. Also, several findings that can be used as a starting point for studies of climatic changes are described. This time interval starts from the Estonian–Finnish–Russian Year of the Gulf of Finland in 1996, a milestone of joint studies of this area that has separated two worlds since the 1940s. The studies include extensive analyses of historical and recently collected data sets, numerical modelling, and introduction of new theoretical concepts, and cover all basic disciplines of physical oceanography: hydrography, marine optics, marine meteorology, circulation, sea level, waves, and ice conditions. Their output eventually contributed to another milestone — the declaration of the Baltic Sea as a particularly sensitive sea area by the International Maritime Organization in 2005.

Introduction

The Gulf of Finland (hereafter denoted as the GoF) is an elongated basin with a mean depth of 37 m. It is located at the northeastern extremity of the Baltic Sea. Although it is frequently treated as a prolongation of the River Neva estuary, its physics and dynamics are extremely complex and extend far beyond the typical features of estuary circulation. Its waters belong to a specific subclass of multicomponental turbid oceanic coastal waters (Arst 2003). Pronounced salinity gradients and rich mesoscale dynamics distinguish this basin from large lakes and create a certain similarity of its basic processes with those occurring in the Baltic Sea Proper and in the open ocean (Alenius *et al*. 1998). Many hydrophysical features are highly variable in both space and time (Alenius *et al*. 2003). The regular presence of sea ice plays a considerable role in functioning of the gulf (Kawamura *et al*. 2001, Granskog *et al*. 2004). Marine meteorological conditions of the gulf reveal remarkable anisotropy and non-homogenous patterns of air temperature due to the highly variable surface roughness and air–sea heat exchange (Myrberg 1997, Soomere and Keevallik 2003). Dangerous variations of sea level occur here: the total range of historical extremes is the largest in the Baltic Sea area, from about –1 m to +4.21 m. Extremely intense fast ferry traffic crosses the central part of the gulf. Ship wakes form a considerable part of the total wave activity in its certain sub-basins (Soomere 2005b).

The relatively small size and the combination of complexity and interactions of various processes suggest that this region can be interpreted as a unique test area for identification of climate changes and/or shifts of the climatic regime. The small size of the water body is the basis of its high susceptibility with respect to the external forcing factors. For example, changes in river discharge caused by variations of precipitation are usually not measurable in many coastal areas of the ocean but can be easily identified in the GoF. The reasonable size of the gulf permits basin-wide studies within a reasonable budget and drawing conclusions about the whole gulf with confidence.

Numerous changes in the forcing conditions [such as an increase in the average wind speed along the northern coast of the GoF (Soomere and Keevallik 2003) or rapid decrease in the length of the ice season (Sooäär and Jaagus 2007)] and in the reaction of the water masses of the GoF [such as an increase in the variability of sea level (Johansson *et al*. 2001)] were identified during the latter decade (*see* BACC 2008 for more examples). The trends of the average and of extreme values of certain properties are different. This feature has been recently identified, among other processes, for wave conditions. Both instrumental wave data from Almagrundet (Broman *et al*. 2006) and visual wave data from Vilsandi (Soomere and Zaitseva 2007) suggest that during the 1980s there was an increase in the annual mean wave height in the northern Baltic Proper but a drastic decrease in the wave activity has occurred since 1997. At the same time in December 1999 (Kahma *et al*. 2003) and at the turn of 2004/2005 (Soomere *et al*. 2008) extremely rough seas occurred. Such contradicting trends apparently reflect specific patterns of changes in meteorological, oceanographic and hydrological characteristics. Their further analysis evidently reveals many features of climate change.

We review the recent highlights of the studies of physical oceanography of the GoF that serve (or can be interpreted) as an evidence of shifts or changes in the local climate. Several findings that can be used as a starting point of the studies of climatic changes are described as well. The paper is mostly based on publications in international peer-reviewed journals. A thorough overview of earlier publications is available in Alenius *et al*. (1998). Only updates in the knowledge of this gulf during 1997–2007 are considered, with a minimum reference to studies of other basins of the Baltic Sea. This time interval starts from the trilateral Estonian–Finnish–Russian Year of the Gulf of Finland in 1996, a milestone of joint studies of this area that has separated two worlds since the 1940s, and ends with the declaration of the Baltic Sea as a particularly sensitive sea area by the International Maritime Organization at the end of 2005, the status becoming effective from July 2006.

Water body: hydrography and optics

It is commonly anticipated that one of the basic features of the future climate in the Baltic Sea region is the increased air temperature. This feature evidently will be reflected in the sea water temperature. Although the recent studies (Fonselius and Valderrama 2003, Rönkkönen *et al*. 2003, Siegel *et al*. 2006) disagree to a certain extent in their estimates, they all agree that the sea-surface temperature of the GoF has risen by about 0.5–0.8 °C during the last 15–40 years along with the air temperature.

The water salinity shows a clear decreasing trend in the upper layers of the GoF. This trend apparently reflects changes in the balance between the influence of the Baltic Proper water masses at the western end of the GoF and the fresh water inflow that is mostly concentrated in the eastern part of the gulf. The nature of the long-term changes in the salinity of the entire Baltic Sea is not well understood; for example the present salinity in the Baltic is about the same as at the beginning of the 1900s (Winsor *et al*. 2001). Climate models generally forecast an increase in precipitation in the northeastern section of the Baltic Sea catchment area and the consequent increase in the river runoff into the GoF (Graham 2004). Therefore, a further decrease in the surface-layer salinity of the GoF is probable.

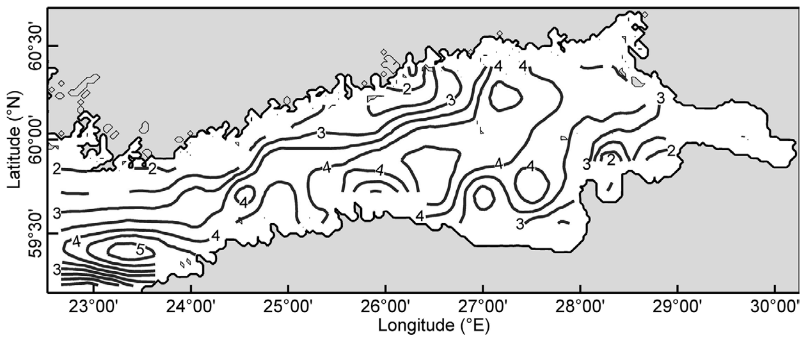

Fig. 1. Spatial variability of the baroclinic (internal) Rossby radius R_1 (km) in the Gulf of Finland in June–July 1996. Adapted from fig. 7 in Alenius *et al*. 2003.

These changes have a large influence on certain dynamical features of the GoF. The interplay of the salt- and freshwater inflow combined with the complex geometry of the gulf results in a strong east–west salinity gradient and in a high spatio-temporal variation of stratification. The baroclinic Rossby radius R_1 (that governs the typical scale of mesoscale current patterns) is quite small (mostly about $R_1 \approx 2$–4 km, Fig. 1; in the eastern part of the gulf R_1 is even smaller) in the gulf and exhibits considerable spatial and temporal variability in shallow coastal regions (Alenius *et al*. 2003). The largest values of R_1 occur in summer in deep parts of the gulf. The potential increase in the temperature and decrease in salinity of the upper layers further decreases R_1.

In order to properly resolve mesoscale features the horizontal grid size must not exceed $0.3R_1 - 0.6R_1$. This request was met in the 1990s when three-dimensional models were implemented with a horizontal resolution down to 1 nautical mile (n.m.) for the whole GoF. Owing to the limitations of computational power, nested-grid approaches are the most popular (Neelov *et al*. 2003, Korpinen *et al*. 2004). The key features of the hydrography such as the vertical salinity and temperature distribution are modelled with a reasonable accuracy (Andrejev *et al*. 2004a, 2004b); however abrupt changes e.g. due to upwelling are still a challenge (Myrberg and Andrejev 2003). A partly open question is whether the use of non-hydrostatic models in the simulations of the GoF dynamics would improve the results (e.g., Zalesnyi *et al*. 2004).

An essential feature of sea water is its optical properties. They determine the transfer of sunlight into the water body, depth of visibility or the Secchi depth, and the euphotic depth, which is about 2.5 times the Secchi depth. In Jerlov's classification, the waters of the GoF are classified as turbid coastal waters (Arst 2003). The light transfer is jointly influenced by the yellow substance, chlorophyll and suspended matter. This feature makes the modelling and interpretation of optical signals difficult. The relevant information has mostly been extracted from *in situ* measurements and from the analysis of water samples. Out from the near-shore zone, the Secchi depth is presently 4–7 m. During the last 100 years its average has decreased from 8 m down to 5 m (Fleming-Lehtinen *et al*. 2007). This change reflects the ever increasing anthropogenic pressure. Direct irradiance measurements have been made mainly at coastal sites in GoF (Leppäranta *et al*. 2003) where the transparency is < 5 m due to the larger amount of suspended matter. The attenuation coefficient is about 1 m^{-1} for total light and as large as 2–3 m^{-1} at 380 nm wavelength owing to the high level of yellow substance.

Optical remote sensing methods have been recently employed to map the quality of the GoF waters (e.g., Zhang 2005). The optical complexity and limited transparency of the waters, in particular the joint influence of yellow substance and suspended matter, severely limit the possibilities of the identification of optically active substances from remote sensing data. These methods have been successful mainly in identifying algae blooms due to their strong signal. Although remote sensing techniques have future promises for identifying different types of water in the basin, it is not clear how to separate the signal of climatic changes from the effect of (potential changes in) the local anthropogenic loads.

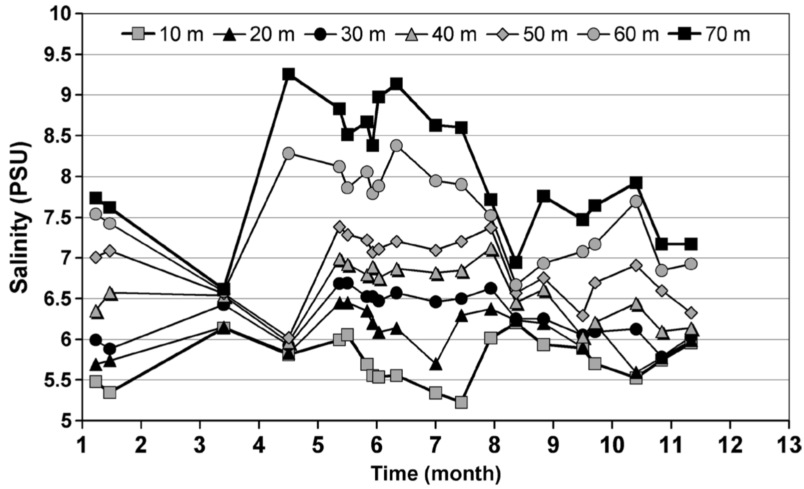

Fig. 2. Time series of salinity on the levels from 10 to 70 m at the monitoring station F3 (59°50.5N, 24°50.3E) in the western part of the Gulf of Finland in 1998 (Elken *et al.* 2003: fig. 6a; reproduced with permission from Elsevier).

Forcing: water balance, marine meteorology and air-sea interaction

The GoF receives river water 112 km^3 a^{-1} (about 10% of the volume of the basin) mostly in its eastern part from the rivers Neva, Narva and Kymijoki. The atmospheric net contribution is very small [about 7.6% from the total net contribution into this area; *see* Omstedt and Axell (2003: table 2)]. Much larger volumes are transported into and out of the gulf through its western entrance. Already Rolf Witting estimated the magnitude of the in- and outflow across the Hanko–Osmussaar line as 480 and 600 km^{-3} a^{-1}, respectively (Alenius *et al.* 1998). Numerical simulations (Myrberg and Andrejev 2003, Andrejev *et al.* 2004a, 2004b) indicate that the outflow in a specific sub-surface layer slightly north of the axis of the gulf is highly persistent as well as the inflow adjacent to the Estonian coast. A noticeable transport into the gulf takes place at the Finnish side in a thin surface layer. The magnitudes of the in- and outflow strongly depend on the averaging period since mesoscale circulation plays a particularly large role in this area and may be responsible for the bulk annual in- and outflows of about 2000 km^{-3} a^{-1} (Andrejev *et al.* 2004a).

This circulation system and its persistence are as important for the functioning of the GoF ecosystem as the salt water inflows for the whole Baltic Sea. A highly interesting phenomenon of the reversal of the classical estuarine deep-water transport pattern (the events when the salt wedge is exported from the gulf) may occur for some sequences of wind events (Elken *et al.* 2003, Elken 2006). The near-bottom layers of the GoF therefore rather actively react to the wind forcing, a reasoning which considerably modifies the traditional concept of the partially decoupled lower layer dynamics for this area.

In particular, long-lasting SW winds may create intense transport of salty bottom water out of the gulf. This process weakens stratification at the entrance to the gulf (Fig. 2) and may serve as a key element of a hypothetical large-scale circulation pattern in the entire Baltic Sea that resembles the conveyor belt in the oceans. Namely, a sort of “chimney” of extensive upwelling may exist at the entrance to the GoF (Fig. 3) in the otherwise strongly stratified Baltic Sea (Elken 2006, Elken *et al.* 2006, Elken and Matthäus 2008). It may be interpreted as an inverse analogue to the Labrador Sea where cold and salty waters downwell to the ocean floor. The susceptibility of the circulation scheme of the GoF entrance area with respect to the wind forcing suggests that changes in wind patterns may have drastic influence on the entire Baltic Sea system.

The basic features of marine winds in the GoF area reflect the large-scale air circulation pattern in the entire Baltic Sea region. The storminess was relatively high in this area during about 1881–1910, decreased at the middle of this century until around 1965 and then increased to

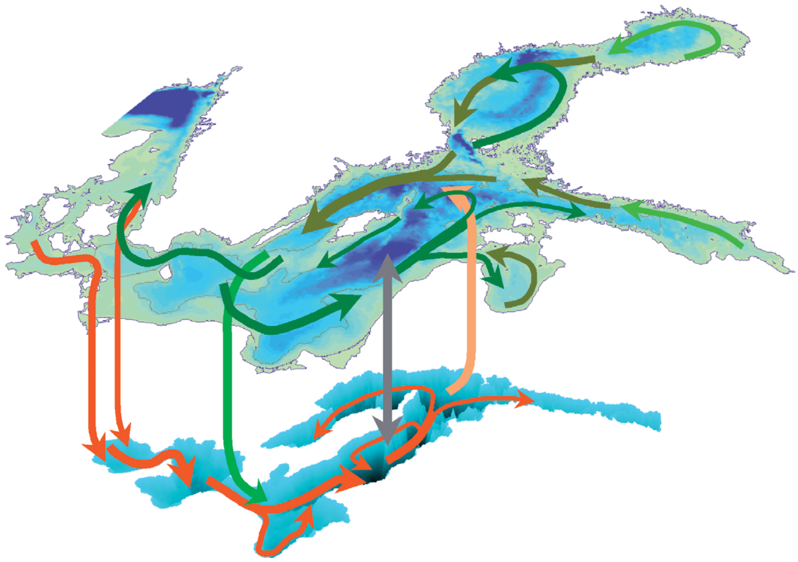

Fig. 3. Scheme of the Baltic Sea internal water cycle). The deep layer below the halocline is given in the lower panel. Green and red arrows denote the surface and bottom layer circulation, respectively. Light green and beige arrows show entrainment. Grey arrow denotes diffusion. Reproduced from BACC (2008: fig. 1.3 (p. 5); fig. A.7 (p. 386) by J. Elken). Copyright (2008), with permission from Springer and J. Elken.

the original level at the 1980s–1990s (Alexandersson *et al*. 1998). These changes eventually are responsible for many features of the GoF area such as an apparent change in the long-term trend of the relative mean sea level along the Finnish coast or the increase in the annual maxima of the sea level. The major progress in understanding the meteorological conditions in the GoF has become possible due to the availability of data from Kalbådagrund, a caisson lighthouse in the central part of the gulf (59°58´N, 25°37´E). This is the only site of regular wind measurements in the GoF that is practically not affected by the presence of the coast. Wind speeds on the open sea are considerably higher than those estimated from the coastal data or from the older lighthouse data (Niros *et al*. 2002).

The marine wind regime is highly anisotropic in the GoF basin (Fig. 4). It is formed as a superposition of SW and N to NW winds dominating in the northern Baltic Proper, and more local W and E winds blowing along the gulf (Soomere and Keevallik 2003). Unlike the wind regime in the Baltic Proper, the directional distribution of strong winds in the GoF often poorly agrees with that of all winds. The frequent and relatively strong afternoon surface winds along the GoF coasts during summer may reflect downstream meanders of the geostrophic flow caused by its interplay with sea breeze and the geometry of the gulf (Savijärvi *et al*. 2005). The surface heat balance (in terms of monthly mean heat fluxes on the open sea) is dominated by the radiation balance, which is normally positive in April–September and peaks to 200–250 W m^{-2} in the summer months. In winter, the high albedo of the ice and snow lowers the incoming solar radiation. Sensible and latent heat fluxes are important in autumn and winter when the winds are strong and stratification of the atmospheric surface layer is unstable. From November until ice formation the turbulent losses are together at –100 W m^{-2}, that is, even larger than the net radiation losses (Niros *et al*. 2002).

Water dynamics

A traditional, but idealized, view of the GoF circulation stemming from Witting's time is that it is generally cyclonic with an average velocity of a few cm s^{-1} (Alenius *et al*. 1998). One can expect that the circulation is intrinsically baroclinic whereas at shorter time scales wind stress plays a dominant role. Eddy-resolving simulations of the GoF circulation (Andrejev *et al*. 2004a) revealed that the generally discernible cyclonic circulation overlaps with numerous quasi-permanent mesoscale features (eddies, fronts and local jets) and possesses a nontrivial vertical structure. The radius of eddies typically exceeds the internal Rossby radius. This is consistent with the rare observation of an eddy with a diameter of about 15–20 km (about $4R_1$) that was formed after rapid splitting of an eastward downwelling jet to an offshore cyclonic and an inshore anticyclonic branch at the entrance of the GoF (Pavelson 2005).

The surface-layer flow pattern is characterized mainly by the Ekman-type drift. Strong currents in the easternmost part of the gulf are caused by the voluminous runoff from the River Neva. A relatively persistent flow along the whole gulf towards the Baltic Proper exists in a certain subsurface layer northwards from the gulf axis (Fig. 5). Multi-layer flows have also been detected in several bays at the southern coast of the GoF (Raudsepp 1998). The stability of the flow patterns with respect to changing climatic conditions and the potential of the subsurface current (Fig. 6) as a prospective location of the major fairway (Soomere and Quak 2007) are important issues for further studies.

The distribution of the water age mostly depends on the water inflow and exchange patterns, and on the scheme of currents, and has a pronounced horizontal variability. The smallest values of the water residence time are found in the inflow regions and at river mouths. The highest water ages were encountered in the outflow regions (Andrejev *et al*. 2004b).

The complex-shaped coastline of Finland is generally favourable for upwelling that occurs as frequently as 30%–50% along certain parts of the coast (Fig. 7). The typical extent of a single upwelling event is 10–20 km offshore (major effects are observed in a 5–10 km broad zone) and about 100 km alongshore, and from several days up to several weeks. Usually it is caused by a wind event with duration of more than 60 h. The temperature difference between the upwelled and surrounding surface water can be up to 10 °C. The horizontal gradient may reach 1 °C km^{-1} (Myrberg and Andrejev 2003). For the description of the dynamics of the upwelling filaments the 1-n.m. resolution models are still too coarse (Zhurbas *et al*. 2007).

Upwelling events are particularly important in development of late-summer cyanobacterial blooms although the direct influence of the drop of the surface temperature leads to the decrease of the filamentous cyanobacteria biomass. *Nodularia spumigena* is more severely affected due to its strong buoyancy and vertical displacement near to surface (Vahtera *et al*. 2005). Owing to

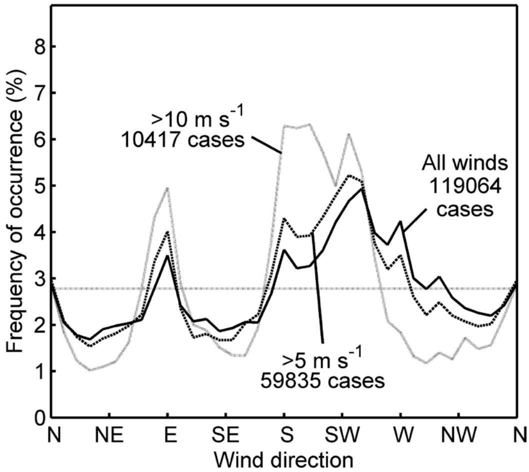

Fig. 4. Directional distribution of all winds (solid line), winds > 5 m s^{-1} (dashed line) and strong winds (> 10 m s^{-1}, dotted line) at Hanko 1961–2001, with the angular resolution of 10° (Soomere and Keevallik 2003: fig. 4b). The horisontal line corresponds to an equidistribution of wind directions. Reproduced with permission from The Estonian Academy Publishers.

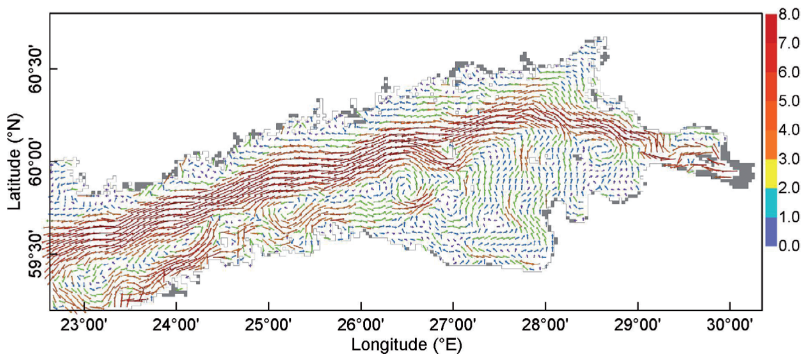

Fig. 5. Simulated mean circulation (cm s^{-1}) in the sub-surface layer between 2.5 and 7.5 m from September 1987 to August 1992. Based on fig. 2 of Andrejev *et al*. (2004b).

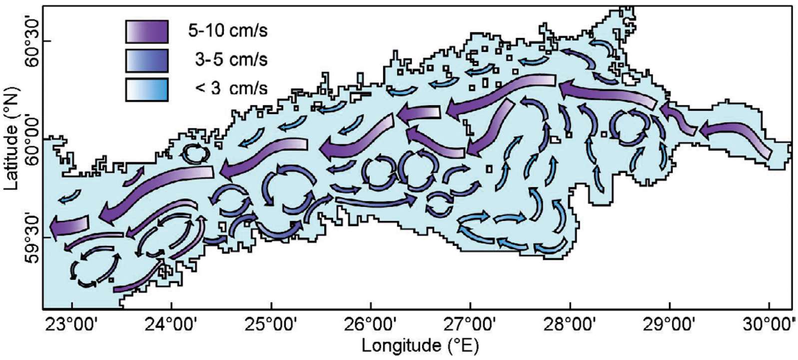

Fig. 6. Schematic representation of simulated mean circulation (cm s^{-1}) in the sub-surface layer between 2.5 and 7.5 m from September 1987 to August 1992. Based on fig. 11 of Andrejev *et al*. (2004a).

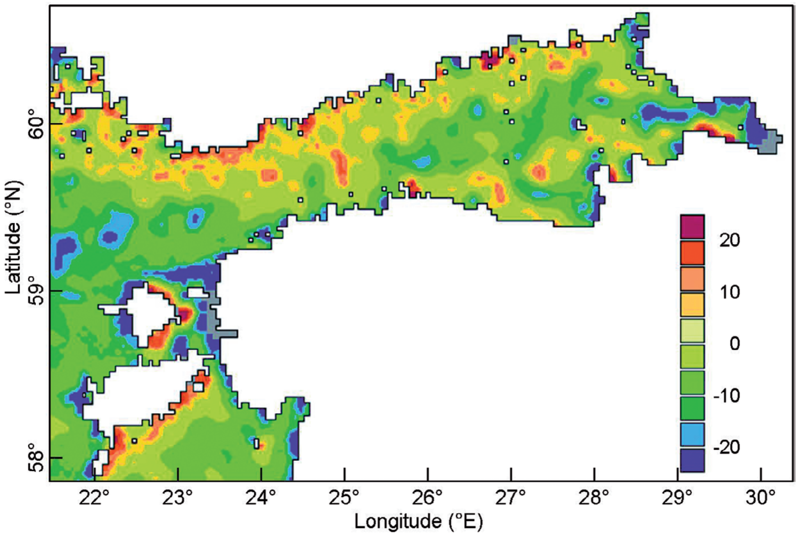

Fig. 7. Upwelling index for the Gulf of Finland. Based on fig. 5 of Myrberg and Andrejev (2003).

the low DIN:DIP ratio of the upwelled water, the nitrogen-fixing *Aphanizomenon flos-aquae* populations located at the top of the thermocline occupy favourable position for exploiting the additional phosphorus. There is a lag of 2–3 weeks between the upwelling and the biomass increase (Vahtera *et al*. 2005).

Since the upwelling patterns reflect the wind anisotropy, potential changes of the directional wind structure owing to, e.g., a shift of the trajectories of cyclones or to changes in the overall air circulation pattern, may substantially affect the existing distribution of upwelling and downwelling areas.

Sea level variations

The strongly anisotropic wind regime is one of the main factors forming the local sea level variations. It may also contribute to long-term changes by creating an eastwards rising surface slope. Long-period sea level variations in the GoF follow the fluctuations of the water surface of the entire Baltic Sea, a large part of which is imported from the North Sea (Vermeer *et al*. 1988). About 50%–80% of the dominant component of the sea level variation — the annual cycle — is imported from the North Sea as well (Samuelsson and Stigebrandt 1996). The variations with periods of 6 months to 10 years have an almost identical geographical pattern and probably a common origin; yet there is a discussion whether the whole Baltic Sea level acts as a quarter-wave-length (with the node at the southern Baltic Sea) or a half-wave-length oscillator for these periods (Samuelsson and Stigebrandt 1996, Ekman 1996). The temporal and spatial fluctuations of water level along the southern coast of the GoF are well correlated. The water level is relatively well predictable: simple stochastic models correctly reproduce > 90% of the sea level variability at the Estonian coast (Raudsepp *et al*. 1999).

This decade brought further evidence for the feature mentioned by Alenius *et al*. (1998) that apparently not only the relative magnitude of the land uplift with respect to the water level along the northern coast of the GoF changed around the year 1960 (Fig. 8; the relative uplift was about 3.3 mm a^{-1} until 1960 and about 1.6 mm a^{-1} since then) but the amplitude of the annual cycle changed as well. The amplitude of the annual range was about 10 cm during the first half of the 20th century, increased rapidly by about 75% in the 1970s–1980s, and decreased to around 13 cm at the end of the century (Johansson *et al*. 2001). These changes only partially match the long-term changes of the wind regime described in (Alexandersson *et al*. 1998).

There have been remarkable changes in the short-time variability of the sea level in the GoF; for example, the seasonal monthly maximum of sea level has shifted from the end of September in the 1950s to the end of October today. The annual standard deviation of the sea level has largely increased in the 1960s–1970s. The annual maximum values of water level have significantly increased at the Finnish coasts during the latter half of the 20th century. It is remarkable that the overall variability of the Baltic Sea water level has increased even more than its local variations, thus large-scale phenomena rather than local storms have caused these changes (Johansson *et al*. 2001).

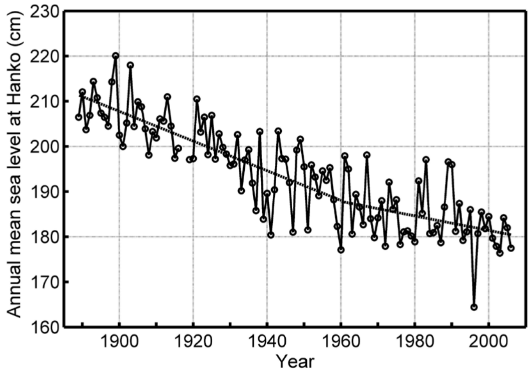

Fig. 8. Annual mean (solid line and circles) and fitted mean sea level (dashed line) at Hanko. Based on (Johansson *et al*. 2004: fig. 9). Data for 2003–2006 kindly provided by Milla Johansson (Finnish Marine Research Institute).

A common feature along the Finnish coast is that the higher sea levels are more probable than the low levels. The closed eastern end of the GoF hosts the largest variation of sea water level in the whole Baltic Sea. The total range of historical extremes exceeds 5 m. The highest storm surge reached 4.21 m in Sankt Petersburg. The January storm in 2005 set new sea level maxima at many sites (Table 1).

Surface waves

The basic advances in surface wave studies in the GoF during the last decade result from (i) the

Table 1. Water level during windstorm Gudrun (8–9 Jan 2005) and historical sea level maxima along the coast of the GoF [Suursaar *et al*. 2006, Johansson *et al*. 2001, data of the FIMR (www.fimr.fi)]. The sites where new records were established in 2005 are indicated in italics.

Location	Maximum (cm) on 09 Jan 2005	Highest prior to 2005		Measurements since
		Maximum (cm)	Date	
Dirhami	134	148	18 Oct 1967	1954
Tallinn	152	135	15 Nov 2001	1842
Kunda	139	157	6 Jan 1975	1958
Toila	160	155	11 Jan 1991	1991
Narva-Jõesuu	194	202	23 Sep 1924	1907
Turku	130	127	9 Jan 1975	1921
Hanko	132	123	9 Jan 1975	1887
Helsinki	151	136	27 Jan 1990	1904
Hamina	197	166	7 Dec 1986	1928

implementation of contemporary spectral wave models, (ii) the improvements of atmospheric models, and (iii) the availability of high-quality marine wind data. Operational wave models are mostly based on the model WAM cycle 4, have a typical spatial resolution of 5–9 n.m. and reasonably forecast wave conditions even in the most extreme storms. Scientific models use resolutions down to 1–2 n.m. in the gulf and a few hundred meters in the nested regime. Owing to relatively short wavelengths in the GoF, the WAM model gives reasonable results until the depth of about 5 m and as close to the coast as 200–300 m in the bays adjacent to the GoF (Soomere 2005a).

Directional wave statistics are available for selected ice-free periods at the beginning of the 1990s and more or less continuously from November 2001 from the central part of the GoF (Pettersson 2001). The maximum significant wave height occurring once in 100 years in the GoF was estimated to be H_s = 3.8 m with a corresponding single wave height of 7.1 m (Alenius *et al*. 1998, Pettersson 2001). Much higher waves (H_s = 5.2 m) were measured on 15 November 2001 off Helsinki (*see* Soomere 2005a). Very long waves (peak periods up to 12 s, H_s > 4 m) occurred in the GoF on 9 January 2005 (Soomere *et al*. 2008). Given the above-discussed rapid decrease in the annual mean wave height in the northern Baltic Proper in 1997–2005, these events suggest that certain nontrivial changes in the forcing patterns apparently have occurred during the latter decade (cf. Keevallik and Rajasalu 2001).

The strongly anisotropic wind climate of the Baltic Sea is one of the main factors forming temporally and spatially inhomogeneous wave climate in semi-sheltered bays of the GoF (Soomere 2005a). The average wave directions are often concentrated in narrow sectors along the gulf axis although the wind directions are more evenly spread. This phenomenon is attached to the slanting fetch conditions in which the wind direction is oblique to the gulf axis. Shorter waves are usually aligned with the wind, while somewhat longer and higher waves (that often dominate the wave field) propagate along the gulf axis (Pettersson 2004). The ‘memory’ of wave fields is relatively short and the changes in the wind field are fast reflected in the wave pattern. As a consequence, the wave fields in smaller sub-basins (such as Tallinn Bay or Narva Bay) of the GoF mimic the changes of the open-sea winds (Soomere 2005a, Laanearu *et al*. 2007).

The central part of the gulf and Tallinn Bay host extremely intense fast ferry traffic. Fast ferries are defined here as large ships sailing at speeds close to the phase speed of long waves. Their wakes have substantial remote influence and frequently contain highly nonlinear waves (Soomere 2007); for that reason ship-wave-induced near-bottom orbital velocities may be larger than expected from the linear wave theory (Soomere *et al*. 2005). The leading wake waves frequently have the heights about 1 m and periods of 10–15 s (Soomere and Rannat 2003). Such waves occur extremely seldom in natural conditions in Tallinn Bay and may cause unusually high near-bottom velocities at the depths of 10–30 m.

The annual mean energy of ship waves in the coastal area of Tallinn Bay forms about 5%–8% of the total wave energy (6%–12% during the spring and summer seasons) and about 18%–35% (27%–54% during spring and summer season) of the wave energy flux (wave power, Soomere 2005b). The influence of ship wakes has been quantified with the use of optical measurements. It extends to a depth of at least 15 m and usually lasts about 6–15 minutes but is limited to a layer with a thickness of about 1 m near seabed. About 10 000 kg of sediments per metre of the affected sections of the coastline may be brought into motion by ship wakes annually. The total loss of sediments could be several hundred litres per metre of coastline (Erm and Soomere 2004, 2006) and thus is equivalent to quite a strong change in natural wave conditions.

Ice conditions

Sea ice is present in the GoF for 4–5 months each winter, from December to April. In mild winters, only the eastern part freezes but normally the basin becomes fully ice covered. At the beginning of the winter the freezing front progresses from Neva Bay westwards along the northern coast, and consequently the ice season is more severe towards the east and the north of the gulf. On the Estonian coast, the heat inflow owing to the easterly coastal jet from the Baltic Proper, and domination of southerly to southwesterly winds helps to keep the area ice free. The asymmetry of the ice conditions is further enhanced by the coastal morphology supporting a wide fast ice zone along the coast of Finland.

The maximum annual thickness of coastal fast ice is 30–80 cm, increasing towards the east. Congelation ice is the dominant formation type in the stratification of the ice sheet. Snow-ice amounts to 10%–30%, and frazil ice proportion is small but it is not known how small. The brackish ice of the Baltic has a fine scale structure similar to sea ice (Palosuo 1961, Kawamura *et al*. 2001). The ice crystals have irregular boundaries and the brine entrapment is significant, the salinity of the ice being 0.5‰–2‰ in winter. According to observations in the GoF, the fresh water ice type occurs only at river mouths, where the salinity of the water is less than about 1.5‰ (Kawamura *et al*. 2002).

Outside the fast ice zone there is the drift ice zone with a highly nonlinear mechanical behaviour. Ice thinner than about 20 cm normally drifts with the wind and currents. The theoretical free drift speed (2% of the wind speed, Leppäranta 2005) is then a useful approximation. Southerly and northerly winds frequently open wide leads on the lee side. Easterly winds push the ice out of the GoF, while westerly winds pack the ice towards the eastern end. In the presence of compressive drift, pressure ridges form. The largest mapped ridges have been 6–8 m thick (Leppäranta and Hakala 1992), but it is likely that larger ones exist, in particular at the eastern fast ice boundary at Kotka–Vyborg longitudes (Leppäranta and Wang 2002). High rates of ridged ice production may substantially increase the probability of navigation disasters (Palosuo 1975, Pärn *et al*. 2007); since this production rate is sensitive to changes in the properties of ice and meteorological conditions, the relevant climate changes may have a large influence on navigational safety. In addition, the abrupt increase in oil transport along the Gulf of Finland means increasing risk levels which is critical in wintertime, when monitoring, forecasting and combating of oil spills is particularly difficult (Wang *et al*. 2008).

When the ice becomes thicker than 50 cm, as is the case in cold winters such as 1987, the wind forcing can no more overcome the yield stress of the ice, and the GoF ice cover may be stationary during the mid-winter for up to two months (Leppäranta and Wang 2002). When the thickness of ice is within 20–50 cm, it has restricted mobility. Displacements are typically smaller, and the length scale of the motion increases so that islands and shoals lock the drift into the fast ice zone. A good example is Gogland, which locks the more eastern ice pack.

The sea ice has a remarkable influence on the oceanography of the GoF. Ice formation and melting influence the stratification of the waters, in particular the freshening of the surface layer in spring is important. Even more drastic is the nonlinear dynamical behaviour of the drift ice. Thick ice radically reduces the transfer of momentum from the wind to the water body, and the circulation becomes weak as forced only by boundary fluxes at the ice edge (Leppäranta 2005). The specific features of circulation of the subsurface layer (Andrejev *et al*. 2004a) may dominate in quite a thick upper layer of the sea as hypothesized in (Soomere and Quak 2007).

Dynamic-thermodynamic sea ice models have been developed for the GoF (Haapala and Leppäranta 1996, Leppäranta and Wang 2002), both as a part of a full Baltic Sea model and as a local fine resolution model. The evolution of the ice conditions can be rather well predicted, the main problems being the ice mechanics in the near-fast ice boundary zone. Also there is a large change in the quality of ice across the basin, from thin pancake ice in the west to heavily ridged pack ice in the east, which requires good advection schemes from numerical models.

There are long time series available for the coastal ice conditions in the GoF. The longest one (reflecting ice break-up at Helsinki) dates back to 1829. During the 20th century, the variability of the dates of freezing and ice break-up has been about three months, but only the latter one shows significant trend towards shorter ice seasons, as much as 15–20 days per hundred years (Leppäranta and Seinä 1985, Jevrejeva and Leppäranta 2002, Jevrejeva *et al*. 2004). A decreasing trend has been found in the maximum annual ice thickness. The decreasing trend of the

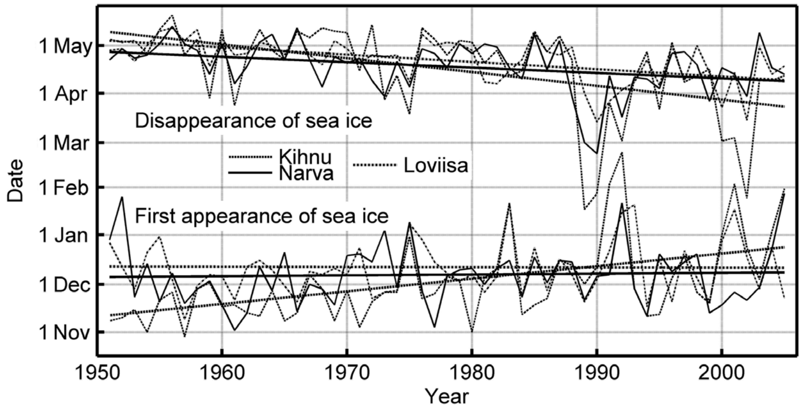

Fig. 9. The dates of first appearance and disappearance of ice at Loviisa (dotted line) and Narva (solid line) in the Gulf of Finland in 1950–2005, and at Kihnu (dashed line) in the Gulf of Riga. Adapted from Sooäär and Jaagus (2007). The data for Loviisa are from the Finnish Institute of Marine Research.

total ice period (understood from the first appearance of ice up to its total disappearance) in the eastern part of the GoF is largely caused by an earlier disappearance of ice (Fig. 9). A possible climate warming would move the climatological ice edge further north and is likely to largely increase the variability of ice seasons.

Foresight studies and discussion

The presented results suggest that several unique features of the Gulf of Finland and the existing patterns of its physical and dynamical processes may be used as indicators of the climatic changes or of the shifts in the climate regimes in the Baltic Sea region. The project FIGARE/FINSKEN developed scenarios up to 2100 of four key environmental attributes (climate, sea level, surface ozone, and sulphur and nitrogen deposition; *see* Carter *et al*. 2004). Although the uncertainties in the scenarios are large, in most cases the rise in water level is expected to balance the land uplift at the northern coast of the GoF, and the past declining trend of the relative sea level is not expected to continue (Johansson *et al*. 2004).

Orviku *et al*. (2003) suggested that the seemingly increasing storminess (expressed as a statistically significant increasing trend of the number of storm days over the last half-century) in the eastern Baltic Sea has already caused extensive erosion and alteration of depositional coasts. The relative water level rise at the southern and eastern coasts of the GoF combined with such an increase of wave activity would cause, for example, extremely large pressure to sandy beaches (Kont *et al*. 2003).

Apart from the listed well-known effects of the future climate, several much more subtle aspects may be changed. The forecast climate changes are likely to affect factors controlling not only the volume of the water body or its mean temperature but also: salt water inflow conditions into the entire Baltic Sea; the overall transport scheme of waters in it; the distribution of upwelling and downwelling patterns; the location areas of the largest wave intensity and wave-induced mixing, and therefore the vertical and horizontal distribution of salinity, temperature, oxygen and nutrient fluxes; and other decisive background constituents of the local ecosystem. For example, the increased sea surface temperature, which may easily happen if the structure of up- and downwellings will change, leads to the reduction in the ice cover area and to the decrease in the ice period in the GoF, and to a manifold of related effects. The wind stress at sea surface evidently increases during winter months. This will lead to enhancing of the extremes in wave and sea-level heights. Timely detection of such changes is a major challenge for scientists. Launching adaptation measures for society is an accompanying challenge for decision makers.

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