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Statistical characterization of the sea ice extent during different winter scenarios in the Gulf of Riga (Baltic Sea) using optical remote-sensing imagery

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ABSTRACT
This study focuses on the statistical characterization of ice conditions (extent, sea ice occurrence probability (SIOP), and length of ice season) in the Gulf of Riga, Baltic Sea, using remote-sensing data. The optical remote-sensing data with 250 m resolution acquired by a Moderate Resolution Imaging Spectroradiometer (MODIS) during 2002–2011 were used for statistical characterization of sea ice. A method based on bimodal histogram analysis of remote-sensing reflectance data was developed to discriminate ice from water. In general, ice extent information obtained from MODIS data agrees with the official ice chart data (synthetic aperture radar (SAR) and in situ measurements) and multi-sensor product containing data from microwave and infrared instruments ($R^2 >0.83$). However, in case of severe winters and extremely mild winters there are differences in the dates when maximum ice extent is registered. MODIS data can be used for detailed analysis of ice extent in specific basins of Baltic Sea. Depending on the year, the ice season length in the Gulf of Riga ranged from 68 to 146 days, and the maximum ice extent varied greatly from 329 to 15,350 km$^2$. SIOP and number of ice days increased significantly in areas where the depth is less than 15 m. Based on negative-degree days and ice cover characteristics (SIOP and ice season length), three winter scenarios were defined: severe (2003, 2006, 2010, and 2011), medium (2004 and 2005), and mild (2007, 2008, and 2009).

1. Introduction
Sea ice coverage is an important parameter for safe winter navigation and climate research. In addition, statistical sea ice coverage information (i.e. ice extent, sea ice occurrence probability (SIOP)) is crucial for planning of coastal and offshore construction (including planning of the service activities during operations): wind farms, oil platforms, ports, etc. (Eik 2011; Gu et al. 2013). Statistical spatial maps containing information about ice season length and SIOP can be retrieved with high spatial resolution from remote-sensing imagery (Rajak et al. 2015). The Baltic Sea, located in Northern Europe, is one of the world’s largest brackish water basins with seasonal ice...
Ice conditions of the Baltic Sea are very dynamic and vary considerably, depending on the region. This study is focused on ice conditions in the Gulf of Riga, located in the eastern part of the Baltic Sea (Figure 1). The area of the Gulf of Riga is about 18,000 km², with a mean depth of 23 m (Leppäranta and Myrberg 2009). The extent of the ice cover and duration of the ice season are important for winter navigation, marine offshore and coastal planning and climatological and ecological studies, therefore, monitoring and statistical analysis of these variables is necessary. Winter navigation in the Baltic Sea is very active, and vessels need ice-breaker assistance for 3–6 months each winter, although in the mildest winters this need is restricted to the Gulf of Riga, Gulf of Bothnia and Gulf of Finland (Vihma and Haapala 2009).

Previous studies have shown that the ice conditions in the Gulf of Riga can vary significantly from year to year, depending on the weather conditions (Jevrejeva and Leppäranta 2002; Jevrejeva et al. 2004). According to the coastal observations over 100 year period the probability of ice occurrence in the Gulf of Riga was around 80% (Jevrejeva et al. 2004). The first ice usually formed between late November and early January. The length of the ice season, which can last until late April, is in the range of 3–5 months. Ice conditions in the Gulf of Riga are very variable and heavily depend on the severity of winter. Even minor changes in the air temperature can lead to significant changes in the ice extent (Vihma and Haapala 2009). In addition to variations of air temperature the changes in wind conditions can also cause accumulation and redistribution of the sea ice and impact its concentration even if temperatures are normal (Pavlova, Pavlov, and Gerland 2014; Kimura and Wakatsuchi 2000; Wang, Leppäranta, and Köuts 2006). In addition to inter-annual ice cover variations, there are significant spatial variations between the different regions of the Gulf of Riga. As soon as the first negative temperatures occur, the ice starts to form in the shallow bays. For example, in Pärnu Bay ice starts to form earlier due to the river input of fresh water, the sheltering
Baltic Sea ice conditions have been studied for decades (Granskog et al. 2006), and several studies have been carried out near the Estonian coast. Jevrejeva and Leppäranta (2002) have analysed long-term time series of freezing, fast ice formation, disappearance of fast ice, break-up, and ice thickness relying on observations in eight stations situated along the Estonian coast. Jevrejeva et al. (2004) examined the evolution of ice seasons and sea ice occurrence probability in the Baltic Sea during the twentieth century based on a set of 37 time series from the coastal observation stations. Jaagus (2006) has also studied changes in the sea ice regime near the Estonian coast in 1949/1950–2003/2004 and analysed the freezing and break-up dates. Haapala and Leppäranta (1996) have used a model to simulate future ice seasons in the Baltic Sea. Recently, several studies have focused on ice extent scenarios in the Baltic as whole and in the Gulf of Bothnia specifically (Vihma et al. 2014; Karpechko et al. 2015; Uotila, Vihma, and Haapala 2015). Hindcast modelling and in situ measurements have shown that the inter-annual variability of ice cover extent in the Baltic Sea and in its sub-basin (Gulf of Bothnia) is strongly influenced by large scale atmospheric circulation (Vihma et al. 2014; Karpechko et al. 2015). Moreover, Uotila, Vihma, and Haapala (2015) suggested that winters with extremely low ice extent can become the new normality during twenty-first century in the Gulf of Bothnia. However, relatively few studies have focused specifically on the ice extent during different winter scenarios in the Gulf of Riga.

In addition, remote-sensing data especially synthetic aperture radar (SAR) images have been used for ice studies over the Baltic Sea (Leppäranta, Kuittinen, and Kemppainen 1989; Uiboupin, Sipelgas, and Raudsepp 2009; Karvonen 2015). In addition to SAR images, Uiboupin, Sipelgas, and Raudsepp (2009) have demonstrated the value of optical images acquired by Moderate Resolution Imaging Spectroradiometer (MODIS) for sea ice characterization in the Gulf of Riga. Although during the past years, the emphasis in ice remote sensing has been on exploiting the capabilities and advantages of active sensors (e.g. SAR) for operational sea ice monitoring, the optical imagery can provide valuable information as well. In addition to SAR-based ice charts the daily sea ice concentration products over the Baltic Sea have been provided since 1982 using multi-sensor data from microwave and infrared instruments (CMEMS - Copernicus Marine Environment Monitoring Service 2016, http://marine.copernicus.eu/; Hoyer, Le Borgne, and Eastwood 2014). Previous studies in the Baltic Sea region and globally have shown that visible range MODIS imagery can be used for determining the ice extent and classification of sea ice (Riggs, Hall, and Ackerman 1999; Zhou and Li 2003; Arst and Sipelgas 2004; Hall et al. 2004; Fraser, Massom, and Michael 2010; Uiboupin et al. 2010; Shi and Wang 2012; Su et al. 2013). However, currently there is no statistical ice cover analysis based on high resolution optical satellite remote sensing available for the Gulf of Riga.

The objectives of this study were: (1) to assess the (dis)similarities between ice information obtained from optical satellite data, classical ice charts (which are based on radar data and in situ measurements) and multi-sensor product containing data from microwave and infrared instruments; (2) to obtain accurate high-resolution statistical information about ice conditions in the Gulf of Riga; (3) to characterize
the ice cover extent and ice season length during different winter scenarios using optical remote-sensing imagery; and (4) to estimate how optical satellite data can contribute to monitoring of ice occurrence statistics.

2. Data and methods

2.1. Data

2.1.1. Satellite imagery

Optical remote-sensing imagery from the MODIS, onboard Terra, and Aqua polar orbiting satellites were acquired. In this study, 250 m resolution images in the visible and near infra-red range channels of the spectrum were used: 620–670 nm (band 1) and 841–876 nm (band 2). In total, 366 images from 2002 to 2011 were used for ice extent detection. The main problem with the optical data was the large number of scenes with significant cloud cover. The clouds were masked manually using supervised thresholding. One hundred seven of the collected images were totally cloud free and covered the entire study area. Two hundred fifty nine of them were partially contaminated by clouds, but at least 50% of the study area was cloud free. The number of sufficiently cloud-free images obtained for each winter is shown in Table 1.

The MODIS ice extent retrievals were compared with the official ice chart data (SAR and in situ measurements) and multi-sensor product containing data from microwave and infrared instruments. The daily ice charts with 1 km spatial resolution from winters 2009/2010 to 2010/2011 were obtained from Copernicus Marine Environment Monitoring Service database (CMEMS - Copernicus Marine Environment Monitoring Service 2016). The multi-sensor products with spatial resolution of 0.03º × 0.03º from years 2002/2003/to 2007/2008 were obtained from Copernicus Marine Environment Monitoring Service. The ice area was retrieved from ice concentration products. The grid cell was defined as ice if the ice concentration was at least 10%.

2.1.2. Meteorological and bathymetry data

For analysis of meteorological conditions the air temperature data recorded at Kihnu meteorological station was used. As the Kihnu meteorological station is located in the

Table 1. Number of satellite images used during the study period and indication of cloudiness: slightly cloudy – at least 50% of the study area is cloud free, cloud free – 100% of the study area is cloud free.

<table>
<thead>
<tr>
<th>Winter</th>
<th>Total number of images</th>
<th>Cloud free</th>
<th>Slightly cloudy</th>
<th>December analysis</th>
<th>January analysis</th>
<th>February analysis</th>
<th>March analysis</th>
<th>April analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002/2003</td>
<td>48</td>
<td>18</td>
<td>30</td>
<td>9</td>
<td>7</td>
<td>10</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>2003/2004</td>
<td>38</td>
<td>16</td>
<td>22</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>2004/2005</td>
<td>42</td>
<td>9</td>
<td>33</td>
<td>3</td>
<td>7</td>
<td>12</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2005/2006</td>
<td>51</td>
<td>15</td>
<td>36</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>2006/2007</td>
<td>34</td>
<td>8</td>
<td>26</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>2007/2008</td>
<td>28</td>
<td>7</td>
<td>21</td>
<td>_</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>2008/2009</td>
<td>33</td>
<td>7</td>
<td>26</td>
<td>2</td>
<td>7</td>
<td>4</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>2009/2010</td>
<td>42</td>
<td>8</td>
<td>34</td>
<td>2</td>
<td>10</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>2010/2011</td>
<td>50</td>
<td>19</td>
<td>31</td>
<td>5</td>
<td>7</td>
<td>15</td>
<td>9</td>
<td>14</td>
</tr>
<tr>
<td>All winters</td>
<td>366</td>
<td>107</td>
<td>259</td>
<td>34</td>
<td>65</td>
<td>82</td>
<td>99</td>
<td>87</td>
</tr>
</tbody>
</table>
open part of the Gulf of Riga, it represents the air temperature over the entire Gulf of Riga (Figure 1). Daily average air temperature was calculated from measured data (1 h resolution). Air temperature data were used to calculate the sum of negative-degree days graph according to Jevrejeva (2001). Negative-degree days are defined as the sum of the mean daily air temperature below 0°C. The sum of the negative-degrees days graph is calculated as a sum of daily negative air temperatures during the winter period from the beginning of December to the end of April. Bathymetry data from the Baltic Sea Bathymetry Database were used for analysing the effect of topography on the spatial distribution of ice cover (Baltic Sea Hydrographic Commission 2013).

2.2. Image processing

All available MODIS satellite images were geo-referenced and projected onto the same grid in L-EST97 projection. L-EST97 is a Lambert Conformal Conic Projection in Geodetic Reference System ETRS89 with GRS80 reference ellipsoid. Standard parallels of L-EST97 projection are at 58°00' and 59°20' and central meridian is at 24°00'. To distinguish ice from open water, the threshold value was found for each image using bimodal histogram analysis (Sahoo and Arora 2004; Uiboupin et al. 2010). For ice/water discrimination a subset from each MODIS image was chosen where a wide range of reflectance values were representing different ice concentrations/types (from fast ice to open water). Histogram was calculated from all reflectance values within the subset (Figure 2). Bimodal histogram obtained from MODIS wintertime imagery over the sea has two obvious relative modes or data peaks representing reflectance from water (Max 1) and from ice (Max 2) (Uiboupin, Sipelgas, and Raudsepp 2009) (Figure 2). The threshold value was set to distinguish ice from water. The minimum value between the two maxima was used as the threshold value for the entire image (Figure 2). All pixels on each image were classified by applying the image-specific threshold value obtained from bimodal histogram.

![Figure 2](image.png)

**Figure 2.** Example of bimodal histogram that is used for setting threshold reflectance value. Max 1 and Max 2 at 0.06 and 0.20 represent the two data peaks associated to ‘pure’ water and ice correspondingly. Threshold value at 0.13 is located the same distance (0.07) from both maxima.
After processing all of the 366 images the mean ice cover maps (length of ice season, sea ice occurrence probability) for each year were calculated. The mean maps were calculated to provide information about ice formation and melt, as well as about ice dynamics. The SIOP maps show the percentage of times that a pixel was classified as sea ice on MODIS imagery during the period from December to April (i.e. 151 days). SIOP was calculated for each pixel \((i,j)\) as follows:

\[
\text{SIOP}(i,j) = \frac{100 \times n(i,j)}{(Y(i,j) - N(i,j))},
\]

where \(Y(i,j)\) is the total possible number of observations during the winter (in our case total number of MODIS daily observations during one season – 151), \(n(i,j)\) is the number of times the pixel was classified as ice, and \(N(i,j)\) is the number of times that data is not available due to clouds in grid point \((i,j)\) (Rajak et al. 2015). In addition, the maps indicating the ice season length at each grid point were calculated. These maps showed the number of days between first and last ice detection at each pixel location. The same maps were compiled for the entire study period (2002–2011).

### 2.3. Comparison method of different ice extent products

The daily MODIS ice extent maps were compared with ice chart data (CMEMS - Copernicus Marine Environment Monitoring Service 2016) and multi-sensor products (CMEMS - Copernicus Marine Environment Monitoring Service 2016). The coefficient of determination \((R^2)\) and mean bias between different data sources were calculated for each winter using the data from days when MODIS imagery was available.

It was analysed whether the annual maximum ice extent in the Gulf of Riga behaves according to the general pattern in the entire Baltic Sea. To quantify the differences between two data sources, the ice cover area and occurrence dates of MODIS-based annual maximum ice extent maps for the Gulf of Riga were compared with corresponding information obtained from Baltic Marine Environment Protection Commission – Helsinki Commission’s (HELCOM’s) Baltic Sea ice charts provided by Finnish Meteorological Institute (FMI), which are based on SAR data and ground truth observations (http://en.ilmatieteenlaitos.fi/baltic-sea-ice-winters).

### 3. Results

#### 3.1. Validation of MODIS ice extent product

The comparison of seasonal course of ice extent observed from MODIS imagery and multi-sensor product showed that the two datasets coincide rather well with systematically higher values observed in case of multi-sensor data (Figure 3). The coefficient of determination during different winters was between 0.56 and 0.90 while mean bias was in the range from 124 to \(-3037\) km². In case of comparison of multi-sensor and MODIS ice extent products (period from 2002/2003 to 2008/2009) the coefficient of determination was 0.85 and mean bias was \(-2023\) km² (approximately 12.5% of the gulf area). For the SAR-based ice chart and MODIS data (2009/2010 and 2010/2011) the corresponding values were 0.83 and \(-169\) km² (approximately 1% of the gulf area).
3.2. Ice season length

Depending on the year, the ice cover season starts between late November and early January. The length of the ice season, which can last until late April, is in the range of 3–5 months. There was good agreement between the date of first appearance of sea ice and the number of days with sea ice (Table 2). The earlier the first ice cover formed the longer was the ice season. In Table 2, winter mean temperatures (November–April) and the length of ice season (from satellite imagery) is shown. During the study period, the length of the ice season ranged from 68 to 146 days. Winter average air temperatures were in the range of 2.6°C to −3.53°C.

In Figure 4, the sum of negative-degree days on Kihnu station during 2002–2011, November to April, is shown. In 2002/2003, 2005/2006, 2009/2010 and 2010/2011 the sum of negative degree days is over 500°C day. In addition, the winter seasons started early, especially 2002/2003 and 2010/2011, when the number of negative-degree days increased faster than usual. Average seasonal air temperatures in these winters were in the range from −1.79°C to −3.53°C. For 2003/2004 and 2004/2005, the sum of negative degree days is about 300°C day, and average air temperatures were slightly below zero. For 2006/2007, 2007/2008, and 2008/2009, the sum of negative degree days is around 200°C day and lower. Average air temperatures were in the range of 0.54–2.60°C. The date of first ice formation ranged from 1 December to 29 January (Figure 4). We can see that ice formed every winter before the sum of negative degree days increased over 75°C day (Figure 4). The last ice detection was in the range from 15 March to 28 April. The last ice was detected approximately 15 days after the mean daily air temperature remained above 0°C day in case of all analysed winters.

The number of ice cover days in different winters can be seen in Figure 5. The maps show the number of days that each pixel (with area of 0.0625 km²) was covered
Table 2. The first and last date of occurrence of ice observed from MODIS imagery, the length of the ice season, winter average air temperature, maximum ice extent observed from MODIS imagery in Gulf of Riga (GOR) and the corresponding date (Julian days), maximum ice extent observed from ice chart in the Baltic Sea (BAL) and the corresponding date during different winters from 2002/2003 to 2010/2011.

<table>
<thead>
<tr>
<th>Winter</th>
<th>First ice</th>
<th>Last ice</th>
<th>Length of the ice season, MODIS/GOR (days)</th>
<th>Winter average air temperature (°C)</th>
<th>Max ice extent, MODIS/GOR (km²)</th>
<th>Max ice extent, ice chart/BAL (km²)</th>
<th>Date of max ice extent, MODIS/GOR (Julian day)</th>
<th>Date of max ice extent – Ice chart/BAL (Julian day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002/2003</td>
<td>6 December 2002</td>
<td>27 April 2003</td>
<td>142</td>
<td>-1.79</td>
<td>15,185/14,033¹</td>
<td>233,000</td>
<td>5/62¹</td>
<td>64</td>
</tr>
<tr>
<td>2003/2004</td>
<td>3 January 2004</td>
<td>8 April 2004</td>
<td>100</td>
<td>-0.12</td>
<td>11,491</td>
<td>153,000</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>2004/2005</td>
<td>12 December 2004</td>
<td>17 April 2005</td>
<td>126</td>
<td>-0.36</td>
<td>14,328</td>
<td>178,000</td>
<td>68</td>
<td>72</td>
</tr>
<tr>
<td>2005/2006</td>
<td>1 December 2005</td>
<td>30 April 2006</td>
<td>139</td>
<td>-2.62</td>
<td>15,148</td>
<td>211,000</td>
<td>66</td>
<td>72</td>
</tr>
<tr>
<td>2006/2007</td>
<td>29 January 2007</td>
<td>7 April 2007</td>
<td>68</td>
<td>1.45</td>
<td>4496</td>
<td>140,000</td>
<td>56</td>
<td>54</td>
</tr>
<tr>
<td>2007/2008</td>
<td>14 January 2008</td>
<td>6 April 2008</td>
<td>83</td>
<td>2.60</td>
<td>328/205¹</td>
<td>49,000</td>
<td>35/87¹</td>
<td>83</td>
</tr>
<tr>
<td>2008/2009</td>
<td>1 January 2009</td>
<td>15 March 2009</td>
<td>73</td>
<td>0.54</td>
<td>1263/1224¹</td>
<td>110,000</td>
<td>34/52¹</td>
<td>51</td>
</tr>
</tbody>
</table>

¹ Denotes area and observation date in case when secondary ice cover maximum was identified.
by ice. In the winters of 2002/2003, 2005/2006, 2009/2010, and 2010/2011 the maximum number of ice cover days was between 135 and 149. During these winters in some regions (mostly the northeastern coastal zone) the ice cover remained almost throughout the entire ice season. The open part of the Gulf of Riga was covered longest by ice in winter 2002/2003, when thick pack ice drifted from the northwestern coastal zone to the central part of the Gulf and remained there until complete melting. In the winters of 2003/2004 and 2004/2005, the maximum number of ice days was in the range of 100–126 days. During these winters ice conditions of the open part of the Gulf of Riga were very dynamic and the ice drift was strongly influenced by wind and current regime. In the winters of 2006/2007, 2007/2008, and 2008/2009, there was no ice in the open part of the Gulf of Riga. The maximum number of ice days was in the range of 68–83. The winter of 2007/2008 was extremely mild, with low average winter air temperature and a low sum of negative-degree days, which resulted in a marginal number of ice cover days in the coastal area.

3.3. Seasonal variability of ice coverage

To characterize the ice extent, the ice covered area in square kilometres for every satellite image was found (Figure 6). The maximum ice extent during different winters varied greatly in range, i.e. from 329 to 15,350 km². Usually ice starts to form in December and reaches its maximum extent in February. In the winters of 2002/2003, 2005/2006, 2009/2010, and 2010/11 ice started to form already in December. In winter 2002/2003, the ice cover area reached a peak value of 15,350 km² already in the beginning of January with the secondary maximum (14,033 km²) in the beginning of February.
The ice formation pattern differed from year to year. In the winters of 2003/2004 and 2004/2005 ice started to form in January, reaching its maximum in March, and the respective maximum ice coverage areas were about 11,500 km\(^2\) and 14,300 km\(^2\). In winters when the ice cover was marginal 2006/2007, 2007/2008, and 2008/2009, the ice

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{icePatterns.png}
\end{figure}
formed only in shallow coastal areas and maximum ice coverage areas were less than 5000 km$^2$ (Figure 6). In every ice season, smaller variations in ice cover extent can be identified in Figure 6. These variations are caused by ice melting or ice accumulation due to drift during the ice season. The sea ice drift in the Gulf of Riga is in correlation with wind. The ice drift pattern follows wind with no essential time lag as the currents are weak in Gulf of Riga (Leppäranta 2011).

Spatial variations of ice cover extent during different years were also studied. Seasonal SIOP maps for the winters of 2002–2011 (Figure 7) represent the sea ice occurrence probability (percentage) in every pixel. In the winters of 2002/2003, 2005/2006, 2009/2010, and 2010/2011 the probability of ice occurrence was considerable over the Gulf of Riga, with the SIOP over 30% in the open part of the Gulf of Riga. The SIOP in the southern part of the gulf areas, where the depth of water was up to 15 m, was more than 60%. Based on these maps, we can consider the winter of 2002/2003 as the most severe, when the maximum ice cover probability was over 94%. In the winters of 2003/2004 and 2004/2005 the ice cover probability rose in some places up to 80%, but mostly remained below 50%. Over 50% probability occurred in the areas where the depth of water was below 10 m (Figure 1). In the open part of the Gulf of Riga the SIOP was less than 40%. In the winters of 2006/2007, 2007/2008, and 2008/2009 the open part of the gulf remained absolutely ice free. Ice cover probability did not increase over 70% in any region. The winter of 2007/2008 may be considered as extremely mild; therefore, even in shallow coastal areas the SIOP remained below 20%.

### 3.4. Average SIOP and ice season length maps for the period of 2002–2011

Figures 8 presents the mean SIOP and ice season length maps calculated from ice seasons 2002/2003 to 2010/2011.

The average SIOP map (Figure 8), which includes data from 366 images from 2002 to 2011 shows that the northern part of the study area has ice cover probability over 60%, while the corresponding value for the rest of the area was below 30%.
The average number of ice days map shows that the ice season lasts the longest in the coastal zone of the Pärnu Bay region (up to 114 days) (Figure 8). The average ice season length in the open part of the Gulf of Riga was around 30–40 days.

There is a good agreement between ice maps (Figure 8) and the bathymetry map (Figure 1) (Baltic Sea Hydrographic Commission 2013). SIOP and number of ice days are larger in the areas where the water depth is less than 15 m. The shallowest area, Pärnu Bay, has the highest SIOP and is covered by ice for the longest period.

3.5. Winter scenarios

3.5.1. Definition of winter scenarios

Based on the sum of negative degrees days (Figure 4), winters can be divided into three classes: severe, medium, and mild. This parameter-based division has good correlation with division based on the ice season length and ice coverage obtained from MODIS imagery.

In 2002/2003, 2005/2006, 2009/2010, and 2010/2011 the sum of negative degrees reached the value over 500°C day and negative degree days lasted until mid-April, therefore these winters were classified as severe. For seasons 2003/2004 and 2004/2005, the sum of negative degrees is between 250°C and 350°C day with negative degree days occurring until the beginning of April. These two winters were classified as medium. During the remaining three winters 2006/2007, 2007/2008, and 2008/2009, that were defined as mild, the sum of negative degrees remained below 250°C.

In different winter scenarios, ice freezing and melting dates, ice season length, and average air temperatures are variable (Table 2). Classification of ice seasons relying on negative degree days (Figure 4) was in good agreement with measured winter mean air temperatures and the length of ice season observed from satellite imagery (Table 2). In addition, the winters with more than 130 days with ice cover and average temperature
below −1 degrees are considered to be severe. If there are more than 100 days of ice cover and average air temperature varies from −1ºC to 0ºC, the winter is considered to be medium. In mild winters, average air temperature is over 0ºC, and the number of ice-covered days is less than 100 (Table 2).

In mild winters, 47.8% of the study area was ice free throughout the season (Table 3). There is also almost no area where the ice existed more than 90 days. In medium winters, only 9.8% of the study area was open water throughout the season and 5.5% of study area was covered by ice up to 120 days. In severe winters, there was no area which remains ice free; ice cover existed at least a few days everywhere. About 17.7% of the study area was covered by ice up to 120 days, and there were also areas where ice occurred up to 150 days.

### 3.5.2. SIOP during different winter scenarios

Maps of SIOP and number of ice days in different winter scenarios are shown in Figures 9 and 10.

#### Table 3. Spatiotemporal sea ice coverage in case of different winter scenarios.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Ice coverage (days)</td>
<td>Percentage/square kilometres of the study area (%/km²)</td>
<td>Percentage/square kilometres of the study area (%/km²)</td>
<td>Percentage/square kilometres of the study area (%/km²)</td>
</tr>
<tr>
<td>150</td>
<td>0.0/0</td>
<td>0.0/0</td>
<td>0.0/0</td>
</tr>
<tr>
<td>Up to 150</td>
<td>0.0/0</td>
<td>0.0/0</td>
<td>0.2/30</td>
</tr>
<tr>
<td>Up to 120</td>
<td>0.1/13</td>
<td>5.5/845</td>
<td>17.7/2724</td>
</tr>
<tr>
<td>Up to 90</td>
<td>1.9/294</td>
<td>12.8/1960</td>
<td>65.7/10,091</td>
</tr>
<tr>
<td>Up to 60</td>
<td>9.6/1466</td>
<td>27.9/4276</td>
<td>79.8/12,247</td>
</tr>
<tr>
<td>Up to 30</td>
<td>52.2/8014</td>
<td>90.2/13,845</td>
<td>100.0/15,350</td>
</tr>
<tr>
<td>Water</td>
<td>47.8/7336</td>
<td>9.8/1505</td>
<td>0.0/0</td>
</tr>
</tbody>
</table>

Figure 9. Mean maps showing the sea ice occurrence probability (SIOP) with 250 m spatial resolution during different winter scenarios. (a) Mild winters in 2006/2007, 2007/2008, and 2008/2009; (b) medium winters in 2003/2004 and 2004/2005; (c) severe winters in 2002/2003, 2005/2006, 2009/2010, and 2010/2011. The SIOP maps show the percentage of times that a pixel was classified as sea ice on MODIS imagery during the period from December to April (i.e.151 days).
In mild winters, almost the entire study area was ice free most of the time. Even shallow coastal regions have mean SIOP less than 50%. However, the ice conditions in the coastal zone are very variable and dependent on wind forcing.

In case of winters with medium ice conditions, the ice cover probability of the coastal areas during the ice season was less than 70%. In the open area of the Gulf of Riga, the SIOP is less than 20%. Ice conditions in medium winters are dynamic, and, when ignoring fast ice belts, the ice is almost always in motion. During medium winter, the ice which formed during cold and calm periods can be accumulated in the coastal area during warmer but at the same time windier periods.

During severe winters, almost all of the Gulf of Riga freezes over. Pärnu Bay and other shallow coastal areas have SIOP over 80%, and the open part of the Gulf of Riga has SIOP over 50%. Generally, the ice conditions in severe winters are stable and there are no such wind effects as in case of mild or medium winters.

3.5.3. Ice season duration in case of different winter scenarios
The number of ice days in different winter scenarios are shown in Figure 10. Maps for different winter classes give a good overview of the temporal stability of the ice.

In severe winters, the maximum number of ice days was 136 (4.5 months). The open part of the Gulf of Riga was covered with ice for around 60–80 days. In medium winters, the ice remains longest on the shallow coastal zones but no longer than 113 days. Pärnu Bay was covered by ice over 100 days. In the open part of the Gulf of Riga, the number of ice days varied in a wide range, which is mainly caused by the ice dynamics. The maximum number of ice days in the open part was 60, but it mainly remained between 15 and 30 days. In mild winters, the number of ice days in the open part of the Gulf of Riga was close to zero. There was an area covered by ice in the northern part of the gulf, but no longer than 20 days. The number of ice days in Pärnu Bay was around 80, and the maximum number of ice days in mild winter was 98.
3.6. Annual maximum ice extent in the Gulf of Riga and in the Baltic Sea

The annual maximum ice extent and its occurrence time (date) observed from MODIS imagery in the Gulf of Riga and from ice charts in the Baltic Sea were compared. The analysis showed that annual maximum ice extent in general followed similar pattern in case of both datasets (MODIS and SAR-based ice chart) and the coefficient of determination ($R^2$) between the two datasets was 0.75 (Table 2, Figure 11). In case of MODIS data over Gulf of Riga area, the annual variations are more pronounced. The Gulf of Riga is rather shallow (mean depth 23 m) and less saline basin compared to northern areas of the Baltic Sea (e.g. Gulf of Finland) (Baltic Sea Hydrographic Commission 2013). Therefore, ice extent develops faster (starting in sallow and less saline Pärnu Bay) compared to other regions during medium/severe winters and almost entire Gulf of Riga is covered by ice at one point during the winter. Moreover, it can be reported that during winters when the annual maximum ice extent of the Baltic Sea (ice map) is over 50% the Gulf of Riga is entirely (over 95%) covered by ice (Figure 11). The good agreement between the MODIS data and ice charts is observed when the dates of maximum ice extent are compared. Due to the physical conditions of the Gulf of Riga, the maximum ice extent is achieved usually 2–6 days before the maximum extent is reached in the entire Baltic Sea (Table 2, Figure 11). However, there are some occasions when the freezing up of the Gulf of Riga occurs significantly earlier compared to the date of maximum ice extent in the entire Baltic reported on ice charts.

During extremely severe winter 2002–2003, the maximum ice extent (15,185 km$^2$) was reached by 5 January. However, shortly after the maximum extent was reached the ice from the central part of the Gulf of Riga drifted to NW part of the gulf due to wind conditions and positive air temperature (Figures 5 and 6). The ice was accumulated to 9000 km$^2$ area by mid-January (Figure 6). By 3 March, the ice extent reached the secondary annual maximum (14,033 km$^2$). The date of secondary annual maximum ice extent observed from MODIS agrees well with the corresponding date of ice charts – 5

![Figure 11](image-url) Inter annual variation of maximum sea ice extent: in the Baltic Sea observed from ice charts (solid line) and in the Gulf of Riga observed from MODIS imagery (dashed line). Date of maximum ice extent in the Baltic Sea observed from ice charts (cross). Primary (circle) and secondary (dash) date of maximum ice extent in the Gulf of Riga observed from MODIS imagery.
March. Similar effect (although less pronounced) was also observed on winter 2009/2010 when the time difference between first and secondary annual maximum ice extent dates was 37 days (Table 2).

A second situation when the date of annual maximum ice extent differed significantly (17–48 days) between the two datasets was during extremely mild winters. During these extremely mild winters (2007/2008 and 2008/2009), the annual maximum ice extent was below 10% of the Gulf of Riga area and the ice thickness was low. Therefore, ice field could have been easily deformed by wind events, which in turn caused larger relative variations of ice extent.

Having explained the cause of the date differences we can replace the first maximum extent dates on some years with the secondary maximum ice extent dates. In case we use only first maximum ice extent date information, the correlation between the dates obtained from two different datasets is nonexistent while in case we also use secondary maximum values, the coefficient of determination is very high ($R^2 = 0.90$) (Figure 11).

4. Discussion

4.1. Seasonal variation of threshold value

The basic techniques used in the snow and ice mapping algorithms are threshold based. Use of the ratio of a short-wave IR channel to a visible channel was determined by Kyle et al. (1978). In our study, the thresholding method (Sahoo and Arora 2004; Uiboupin et al. 2010) was used to distinguish ice from open water. In order to get accurate ice classification results, it was important to determine correct threshold value from the reflectance data. Threshold value is individual for each image, and it depends on light condition and air temperature (affecting the ice surface properties) variation from December to April. An increasing trend of threshold value is observed through the season (Figure 12). In December, values less than 0.02 reflectance units are classified as water, and values larger than 0.02 reflectance units are classified as ice. In March, the average threshold value was 0.12 reflectance units. The increase of threshold value from

![Figure 12. Scatter plot showing the temporal variation of the reflectance threshold value used for classification of sea ice and water.](image-url)
December to March was linear, while at the beginning of April, the threshold value decreased significantly over a short period of time. At the beginning of April, the average threshold value decreased to 0.08 reflectance units and later on at the end of April it increased again to 0.1 reflectance units.

There are number of factors that could influence the variations of threshold value: surface roughness, viewing geometry of the sensor, white caps, snow melt on ice, etc. In case of water and ice discrimination (not different ice type classification) from optical data using robust algorithm, the viewing geometry, whitecaps, and surface roughness play minor role compared to the reflectance changes due to snow cover and melt water on ice. This is also evident from the studies by Zhou and Li (2003) and Shi and Wang (2012), which show that the reflectance difference of water and ice in near-infrared (NIR) part of the spectrum is at least 50%. Indeed, if the aim would be detailed discrimination of different ice types then the effects of surface roughness, atmospheric correction, and viewing geometry would have to be addressed in more detail. However, for robust ice/water discrimination algorithm it is not crucial (and helps to reduce the processing time), which is also confirmed by the high coefficient of determination ($R^2 = 0.83$) between MODIS- and SAR-based products (Figure 3). Therefore, the most significant factor that influences the reflectance threshold value is the variation of ice albedo due to snow melting. The reason for sudden decrease of threshold value could be that in April snow on sea ice melts and less light is reflected from the surface. Thus the threshold value depends on the air temperature values. For example, Notarnicola et al. (2013) used two main thresholds for snow mapping: 283 K for the winter period from November to April, and 290 K for the remaining months. In this study, connection with average air temperature can also be seen. Average temperature during December to March stays below 2°C. In the beginning of April, which can be considered as extensive melting period the average temperature increased over 2°C.

4.2. Advantages of the use of MODIS data in ice extent monitoring

Data from a variety of space-borne sensor has been used for sea ice detection and methods have been developed for microwave-based sensors (SAR, scaterometers, microwave) as well as for visible/thermal infrared sensors (e.g. Shi and Wang 2012; Ivanova et al. 2015; Karvonen 2015; Lindell and Long 2016). Although the poor temporal coverage due to cloud cover is a limiting factor in case of optical satellite data (i.e. MODIS) compared to other sensors (e.g. SAR), it can provide complementary information about ice conditions. The MODIS optical imagery has high spatial resolution (250 m), which is similar to SAR data (around 100 m) and significantly better compared to scaterometers and passive microwave sensors (from 5 to 50 km). Thus, MODIS imagery enables to monitor dynamic ice conditions and ice leads, which is important for discriminating regions with land fast ice and drift ice. The discrimination of fast ice and drift ice regions can be observed also on mean maps of ice season length and SIOP (Figure 8). In the shallow and sheltered northern part of the Gulf of Riga (specially Pärnu Bay), the average SIOP and season length values are rather high and spatially homogenous (around 60% and 70 days correspondingly) indicating the fast ice region, while in the open part of the gulf the corresponding values are lower and more variable (specially mean ice season length) indicating the area of dynamic ice conditions.
In addition to the benefits of high resolution of the MODIS optical data, the accuracy of proposed sea ice detection method is high. Our study demonstrated that MODIS data can be used for ice extent detection in the Baltic Sea, and it agrees with the SAR-based data ($R^2 = 0.80$) (Figure 3). This is also in accordance with the study by Wakabayashi, Mori, and Nakamura (2013) who also demonstrated that sea ice area obtained from MODIS visible and NIR data was equivalent to that derived from L-band SAR data. Moreover, previous studies from around the globe have shown that MODIS imagery can be used for determining the ice extent (e.g. Zhou and Li 2003; Fraser, Massom, and Michael 2010; Shi and Wang 2012; Su et al. 2013).

The advantage of MODIS optical data compared to SAR data is the possibility to classify correctly the ice, which is covered by melt water (melt ponds) (Light et al. 2015). In the Gulf of Riga, the depth of melt water on sea ice is relatively shallow (up to 20 cm) compared to Arctic (where it can reach values over 70 cm) (Lu et al. 2016). However, it is deep enough to enable the formation wind-wave roughened surface that may cause false classification from C-band SAR, which is sensitive to different surface roughness levels (Scharien et al. 2012). According to Lu et al. (2016), apparent optical properties (and albedo) of melt-pond depend more on underlying ice than on pond depth or pond surface roughness. Therefore, the pond covered sea ice can be detected more reliably from optical imagery (Istomina et al. 2015).

5. Conclusions

The aim of this work was to accurately map the ice cover in the Gulf of Riga using optical remote-sensing data. It was shown that the use of optical remote-sensing methods enables monitoring of ice extent, SIOP, and ice season length, which can be the basis for classification and description of different winter scenarios. All available MODIS satellite data (366 sufficiently cloud free images) during the winter periods of 2002–2011 were used for ice and open water classification from bimodal histogram. As a result, high-resolution statistical information about ice conditions from the Gulf of Riga was collected and the ice cover extent and ice season length during different winters was found.

In general MODIS ice extent data over the Gulf of Riga area agrees with the Baltic Sea ice chart data ($R^2 = 0.83$, bias = 1%) and multi-sensor product containing data from microwave and infrared instruments ($R^2 = 0.85$, bias = 12.5%). However, there are occasions (extremely mild and extremely severe winters) when the complementary information from the different data sources enables to improve ice extent mapping in the Gulf of Riga which has specific properties: relatively shallow, lower salinity due to river inflow. MODIS can be used for detailed analysis ice extent of specific basins.

As a result of satellite imagery analysis, maps to indicate SIOP and number of ice days in different winter scenarios were compiled. These maps give a good overview of the temporal stability of the ice and can be used as bases for practical applications (e.g. marine special planning) in the Gulf of Riga.

Depending on the year, the length of the ice season in the Gulf of Riga was in the range of 3–4.5 months. The maximum ice extent ($\text{km}^2$) during different winters varied greatly in a range from 329 to 15,350 $\text{km}^2$. Shallow coastal areas had ice coverage every winter during
In the study period of 2002–2011. In severe winters, open part of the Gulf of Riga had SIOP up to 70%, while in mild the open part of the gulf stayed absolutely ice free.

Based on the length of the ice season, sum of negative-degree days, and ice cover characteristics, three different winter scenarios stand out. The winters of 2006/2007, 2007/2008, and 2008/2009 are classified as mild. In mild winters 47.8% of the study area was ice free through the season. The number of ice days in the open part of the Gulf of Riga was close to zero, and coastal areas were covered by ice less than 40 days, except for Pärnu Bay, where the ice coverage existed around 80 days.

The winters of 2003/2004 and 2004/2005 are classified as medium, and ice conditions in these winters are dynamic, as when ignoring fast ice belts, the ice is almost always in motion. The ice remains longest on the shallow coastal zones, but no longer than 113 days. In the open part of the Gulf of Riga the number of ice days varied in a range 15–30 days.

The winters of 2002/2003, 2005/2006, 2009/2010, and 2010/2011 are classified as severe. In severe winters there was no area, which stays ice free; ice formed at least a few days everywhere. The open part of the Gulf of Riga was covered by ice around 60–80 days. Ice conditions in severe winters are stable, and there were no such drifting ice effects caused by wind, as in the case of mild or medium winters.

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