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CRITICAL ANALYSIS OF SATELLITE DATA OF NSIDC, NOAA NESDIS IN DETERMINING THE SPATIAL DISTRIBUTION OF ICE ON LAKES

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Abstract

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The process of formation and rotting of ice on lakes is an integral part of the hydrological cycle of many lakes. The conditions of the ice regime significantly influence the ecological system of lakes. The article includes calculation and analysis of errors in the determination of the spatial ice distribution (spatial resolution of 4–6 km) on Lake Onego, Lake Ladoga, Lake Segozero and Lake Vigozero within the period of 2006–2017 according to National Snow and Ice Data Center (NSIDC), National Oceanic and Atmospheric Administration National Environmental Satellite, Data, and Information Service (NOAA NESDIS) data with regard to reliable Moderate Resolution Imaging Spectroradiometer (MODIS) data (spatial resolution of 500 m). It was established that within the monitoring period, NSIDC data have the minimum mean values of errors in determining the spatial distribution of ice on lakes (3–10%) compared to NOAA NESDIS data (11–19%) and are also of more practical interest in estimating the ice coverage of lakes. The dependence of the mean value of errors that occur in the determination of the spatial distribution of ice (according to NSIDC, NOAA and NESDIS data) on the actual value of ice coverage (according to MODIS) was revealed. The results show that the NSIDC data allow estimating adequately the phases of the ice regime; however, the formation of a daily time series of ice coverage during freeze-up and break-up phases is possible only with a significant error (mean value of absolute deviations according to MODIS data is up to 35%).

Key words: NSIDC, NOAA NESDIS, MODIS, spatial distribution of ice, ice coverage, lakes.

Introduction

The formation of the ice cover of lakes depends on a large number of factors both those that influence in the short term (water temperature, air temperature, wind, etc.) and those that affect long before the onset of winter (thermal capacity of the lake). Therefore, ice is a sensitive indicator reacting on changes in these factors (Adrian et al., 2009; Karetnikov, Naumenko, 2008).

In this regard, studies of the annual recurring ice regime of lakes are necessary for solving an important environmental objective that is the establishment of trends in global and regional climate change (Magnuson, 2000).

In addition, the formation and rotting of ice on lakes directly affects the aquatic ecosystem of lakes. In particular, the ice coverage on lake reduces the sunlight penetration, reduces the air–water heat transfer to the atmosphere and stops the kinetic wind to water energy transfer. These factors form ecological system of lakes in winter (Karetnikov, Naumenko, 2008; Filatov, 2012).

Studying the nature of the course of ice regime of lakes comes down to an assessment of the dependence of ice coverage of lakes (parts of the aquatic area covered with ice) on time.

At present, satellite data are widely used to obtain the information on the condition of the earth's surface as well as on the ice coverage of lakes. During the past few years (10–25 years), satellite sensors (MODIS, Visible Infrared Imaging Radiometer Suite (VIIRS), Atmospheric Infrared Sounder (AIRS), Multi-angle Imaging SpectroRadiometer (MISR) and many others) daily perform multi-zone observation of the area in different ranges of electromagnetic wave (visible, infrared and microwave) (Abd Rahman et al., 2016, 2017; Baklagin, 2017).

It is possible to calculate ice coverage of lakes with high accuracy by means of visual expert evaluation based on satellite images of the MODIS sensor made in the visible range (synthesised RGB images (is an additive color model in which Red, Green and Blue light are added together in various ways to reproduce a broad array of colors) or true color images) with high spatial resolution (up to 250 m in open access: https://earthdata.nasa.gov/earth-observation-data).

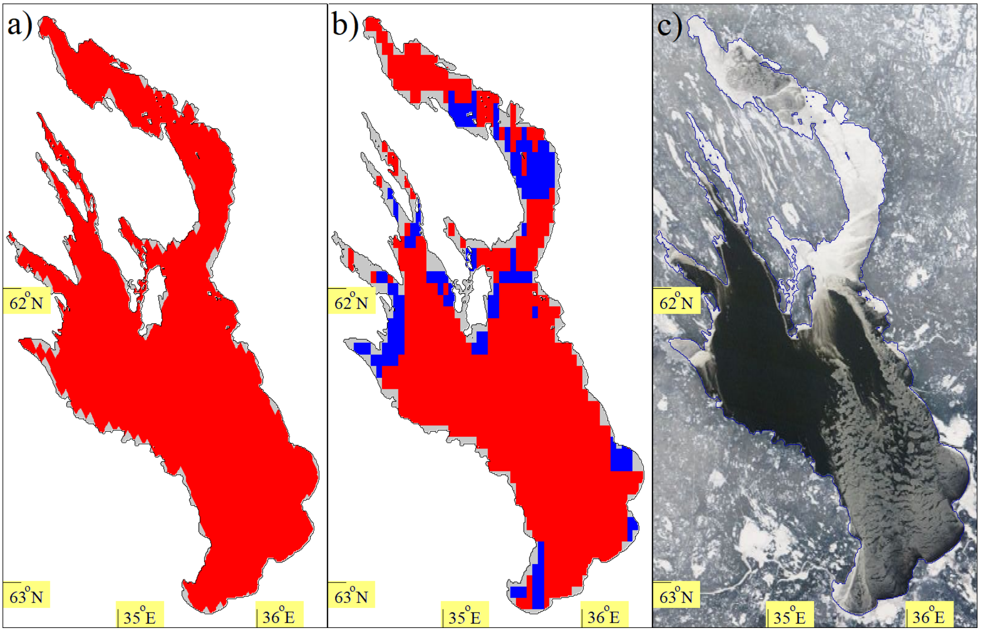

Fig. 1. Visualisation of satellite data on the state of ice coverage of Lake Onego dated 25 January 2012: (a) according to NSIDC data; (b) according to NOAA NESDIS data and (c) according to the MODIS sensor. Red colour represents ice and blue water (a, b).

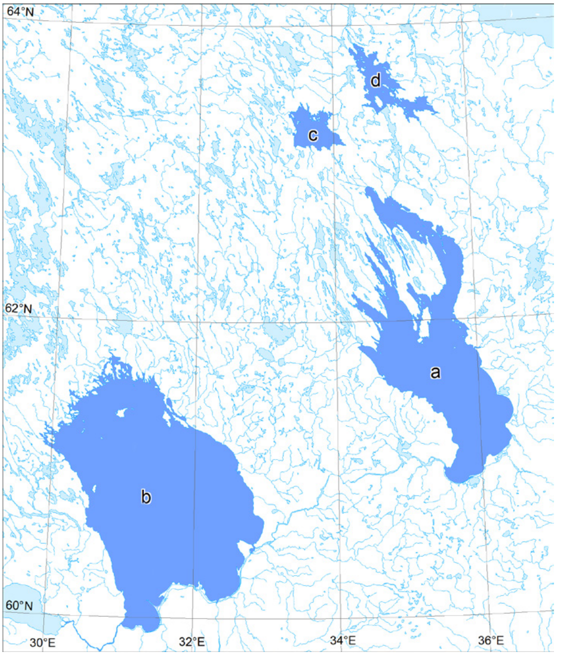

Fig. 2. The lakes in the Mercator projection (the aquatic surface area): (a) Lake Onego (9720 km²), (b) Lake Ladoga (17 700 km²), (c) – Segozero (815 km²) and (d) Vigozero (1250 km²).

However, in most cases, it is not possible to calculate the ice coverage of lakes according to satellite images of the visible range because of the clouds. For example, during the observation period of 2006–2017, 648 satellite images were taken to estimate the state of the ice cover of Lake Onego and 447 images were taken to estimate the state of the ice coverage of Lake Ladoga because of the greater aquatic area (the larger the aquatic area of the lake, the lesser is the likelihood of aquatic area to be completely free from clouds). Therefore, it is not possible to form a continuous series of values of ice coverage of lakes using only these images.

However, there are multi-sensor microwave radiometers that can perform multi-zone observation in the microwave range (Advanced Microwave Sounding Unit (ASMU-A), Advanced Technology Microwave Sounder (ATMS), Advanced Very-High-Resolution Radiometer (AVHHR), MODIS, VIIRS and others) that allows recording the scene daily regardless of the clouds. Automatic mapping of multi-zonal images of these systems results in obtaining the data on snow and ice coverage of the planet. This data is presented by the National Snow and Ice Data Center (NSIDC) and the NOAA NESDIS Center for Satellite Applications and Research (ftp portal in the public domain: ftp://sidads.colorado.edu/DATASETS/NOAA/G02156/ and ftp://ftp.star.nesdis.noaa.gov/pub/smcd/emb/snow/binary/multisensor/global/). Despite the modest spatial resolution of 4–6 km, the data are suitable for ice coverage calculation of many lakes.

However, it was established that in some cases, automatic interpretation of satellite data generates significant differences in the determination of the spatial distribution of ice on lakes. All this leads to errors in the calculation of the ice coverage of lakes. For example, according to NSIDC and NOAA NESDIS, some aquatic areas of lakes can be covered with ice (Fig. 1a and b), whereas in reality, there is no ice in these areas (Fig. 1c).

In this regard, the purpose of this article is to verify the adequacy of the use of NSIDC and NOAA NESDIS data to determine the spatial distribution of ice on lakes as well as to calculate the ice coverage of lakes. The study includes the following stages:

1. Collection and analysis of satellite data of NSIDC and NOAA NESDIS on the state of the ice coverage of lakes for the period of 2006–2017.

2. Calculation and analysis of satellite data errors of NSIDC and NOAA NESDIS arising while determining the spatial distribution of ice on lakes as well as while calculating the ice coverage of lakes when reliable data is available.

Material and methods

The lakes located in the Republic of Karelia of the Russian Federation were selected for the purposes of conduction critical analysis of NSIDC and NOAA NESDIS satellite data when determining the spatial distribution of ice. Lake Onego and Lake Ladoga are the largest European lakes located in this geographical region; small lakes that are suitable for the analysis of the ice cover with a spatial resolution of 4–6 km can also be found in this region; they are Lake Segozero and Lake Vigozero (Fig. 2). The lakes are covered with ice completely or partially yearly, which is a necessary prerequisite for carrying out this study.

This made it possible to determine the discrepancy between the NSIDC and NOAA NESDIS satellite data in determining the spatial distribution of ice and calculating the ice coverage of lakes that are approximately of the same size and those that are different in the same climatic conditions.

The time interval of satellite data used in the study corresponds to 2006–2017. At this time interval, data from all the sources are available.

MODIS data with a spatial resolution of 500 m were used in this study as reliable data, whilst NSIDC and NOAA NESDIS data have a spatial resolution of 4–6 km. Therefore, a comparative analysis of the spatial distribution of ice in the aquatic area of lakes has features stipulated by the comparison of data of different spatial resolution.

According to MODIS data, homogeneous parts of aquatic area of lakes $A_{small\ 1}, A_{small\ 2}, \dots, A_{small\ i}, \dots, A_{small\ n}$ correspondingly have an area of $S_{small\ 1}, S_{small\ 2}, \dots, S_{small\ i}, \dots, S_{small\ n}$. According to NSIDC and NOAA NESDIS data, homogeneous parts of aquatic area of lakes $A_{large\ 1}, A_{large\ 2}, \dots, A_{large\ j}, \dots, A_{large\ m}$ correspondingly have an area of $S_{large\ 1}, S_{large\ 2}, \dots, S_{large\ j}, \dots, S_{large\ m}$; $A_{large\ j} = \{{}^{water}_{j}A_{small}, {}^{ice}_{j}A_{small}, {}^{land}_{j}A_{small}\}$.

${}^{water}_{j}A_{small} = \{{}^{water}_{j}A_{small\ 1}, {}^{water}_{j}A_{small\ 2}, \dots, {}^{water}_{j}A_{small\ w}, \dots, {}^{water}_{j}A_{small\ w\_count}\}$.

According to the MODIS data, whilst lots of homogeneous parts corresponding to the area $A_{large\ j}$ in geographical coordinates are the aquatic area of the lake, it is not ice.

${}^{ice}_{j}A_{small} = \{{}^{ice}_{j}A_{small\ 1}, {}^{ice}_{j}A_{small\ 2}, \dots, {}^{ice}_{j}A_{small\ ic}, \dots, {}^{ice}_{j}A_{small\ ic\_count}\}$.

Also, lots of homogeneous parts corresponding to the area $A_{large\ j}$ in geographical coordinates are the aquatic area of the lake and it is ice.

${}^{land}_{j}A_{small} = \{{}^{land}_{j}A_{small\ 1}, {}^{land}_{j}A_{small\ 2}, \dots, {}^{land}_{j}A_{small\ l}, \dots, {}^{land}_{j}A_{small\ l\_count}\}$.

In addition, lots of parts corresponding to the area $A_{large\ j}$ in geographical coordinates are not the aquatic area of the lake.

Calculation of the satellite data error (NSIDC and NOAA NESDIS) in determining the spatial distribution of ice on lakes for each time point was carried out according to the formula:

$$\delta = \frac{\sum_{e=1}^{r} {}^{error}S_{large\ e}}{S_{total}} \cdot 100\%$$

where $S_{large\ e}$ is the area of the homogeneous part ${}^{error}A_{large\ e}$ of the set $\{{}^{error}A_{large\ 1}, {}^{error}A_{large\ 2}, \dots, {}^{error}A_{large\ 1}, {}^{error}A_{large\ r}\}$ that are inconsistent with the MODIS data; S_{total} is the number of homogeneous parts that are inconsistent with MODIS data; is the total area of the lake's aquatic area stipulated by the spatial resolution of the satellite data $S_{total} = \sum_{j=1}^{m} S_{large\ j}$.

The discrepancy in data of each part of the aquatic area of lake $A_{large\ j}$ with MODIS data was considered if the following restriction is fulfilled:

$$\left(A_{large\ j} = ice \wedge \sum_{w=1}^{w\_count} {}^{water}_{j}S_{small\ w} > \sum_{ic=1}^{ic\_count} {}^{ice}_{j}S_{small\ ic}\right)$$

$$\vee \left(A_{large\ j} \neq ice \wedge \sum_{w=1}^{w\_count} {}^{water}_{j}S_{small\ w} \leq \sum_{ic=1}^{ic\_count} {}^{ice}_{j}S_{small\ ic}\right)$$

If the restriction is met, the area of lake's aquatic area $A_{large\ j}$ is included in the set ${}^{error}A_{large\ e}$.

Calculations of δ for lakes were performed at time points at which at least one of the data sources (NSIDC, NOAA NESDIS and MODIS) showed ice formations on the lake. Then the mean value of errors $\overline{\delta}$ was calculated for each lake for all the time points.

Results

For the period of 2006–2017, the number of MODIS sensor images (without clouds) showing ice formation of the within the periods of ice phenomena on the lakes amounted to 648 satellite images of Lake Onego, 447 satellite images of Lake Ladoga, 644 satellite images of Lake Segozero and 584 satellite images of Lake Vigozero. These images were used to calculate the data errors of NSIDC and NOAA NESDIS (for each time point at which there is an image).

The mean values of errors in the determination of the spatial distribution of ice on lakes and the mean values of the absolute deviations of satellite data NSIDC and NOAA NESDIS on ice coverage of lakes as regard to the actual ice coverage data (according to MODIS) $\overline{\mathrm{MAD}}_{\mathrm{ice}}$ are presented in Table 1.

T a b l e 1. Mean values of errors of satellite data of NSIDC and NOAA NESDIS in the determination of the spatial distribution of ice on lakes and the mean absolute deviations of ice coverage of lake .

Lakes	(%)		(%)	
	NSIDC	NOAA NESDIS	NSIDC	NOAA NESDIS
Lake Onego	6.1	18.5	4.9	16.1
Lake Ladoga	9.6	10.6	8.2	7.2
Lake Segozero	3.2	12.6	3.1	12.3
Lake Vigozero	5.8	11.5	5.4	11.1

The results show that NSIDC data have lower $\bar{\delta}$ values than NOAA NESDIS data $(\bar{\delta}_{NSIDC}<\bar{\delta}_{NESDIS})$.

At the same time, the following is true for all lakes except for Lake Ladoga $\bar{\delta}_{NSIDC}<7\%$.

The ice coverage not only characterises the areas of ice formations on lakes but does not characterise their location so the following equation is correct: $\overline{MAD}_{ice}<\bar{\delta}$. Ice coverage on lakes is of great practical importance in determining the timing and duration of the ice regime phases. NSIDC data allow performing calculation of ice coverage of lakes with a smaller value than $\overline{MAD}_{ice}$ NOAA NESDIS data for all lakes other than Lake Ladoga ($\overline{MAD}_{iceNSIDC}$=8.2%).

According to the satellite data of NSIDC and NOAA NESDIS, the daily series of ice coverage values of lakes are formed: Lake Onego, Lake Ladoga, Lake Segozero and Lake Vigozero for the period of 2006–2017. Graphs of dependence of ice coverage of lakes on time are shown in Figure 3.

The mean absolute deviations of ice coverage values obtained from the NSIDC data from the ice coverage values obtained from NOAA NESDIS data are 18.9% for Lake Onego, 11.7% for Lake Ladoga, 19.3% for Lake Segozero and 12.9% for Lake Vigozero.

According to the NSIDC data, the dates of beginning and ending as well as the duration of ice phenomena on lakes are illustrated in Figure 4 in the form of diagrams.

The determination of the dates of beginning and ending of ice phenomena on lakes according to NOAA NESDIS data is complicated by the fact that in some years, ice phenomena also occur in summer. For example, according to NOAA NESDIS data, in 2013, in August and September, ice formations were observed on Lake Ladoga, whilst in July and October,

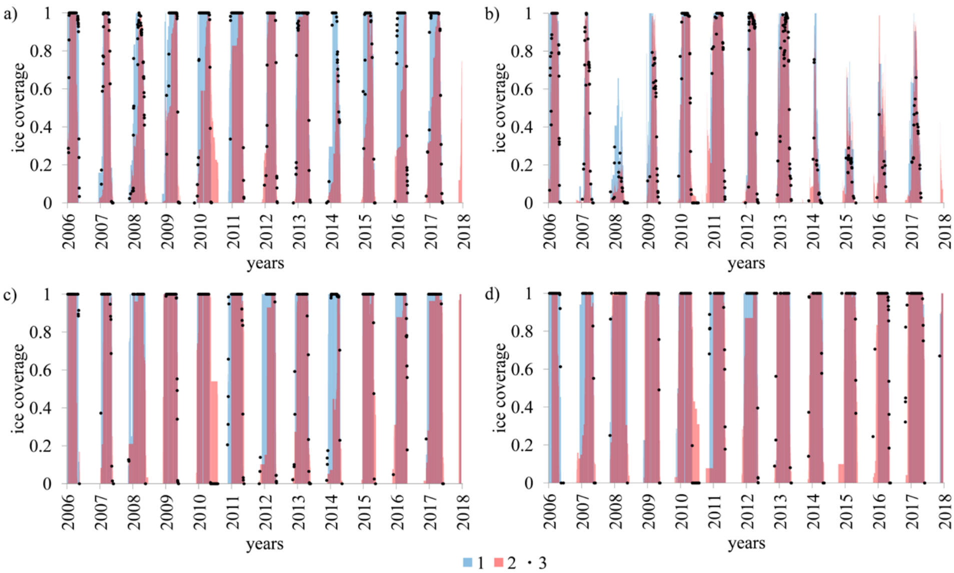

Fig. 3. Graphs of dependence of ice coverage on time: (a) Lake Onego, (b) Lake Ladoga, (c) Lake Segozero and (d) Lake Vigozero. Notation: (1) according to NSIDC, (2) according to NOAA NESDIS and (3) according to MODIS.

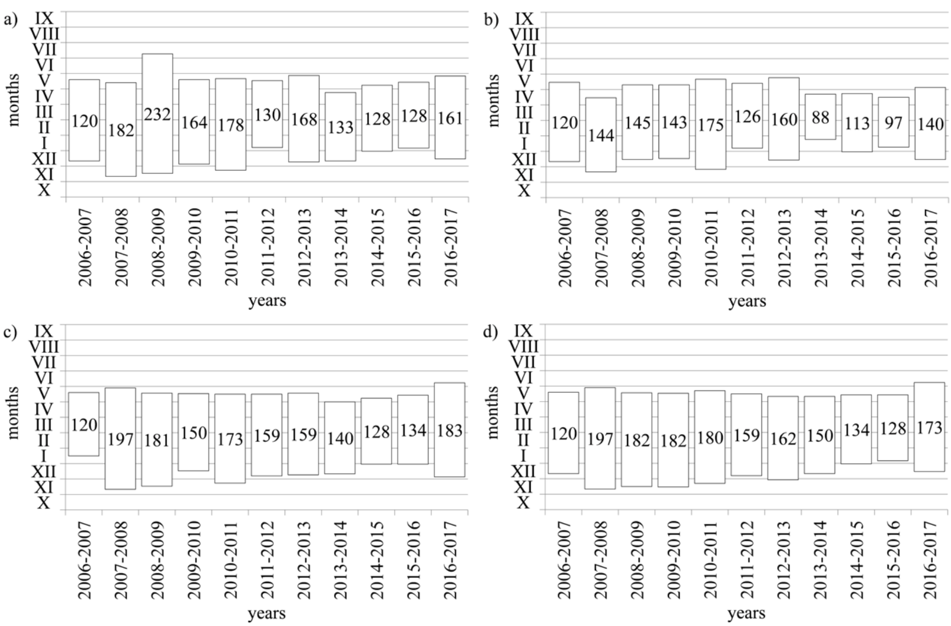

Fig. 4. The dates of beginning and ending of ice phenomena (with an indication of duration) according to NSIDC data for the lakes: (a) Lake Onego, (b) Lake Ladoga, (c) Lake Segozero and (d) Lake Vigozero.

they were not. This is not true for these lakes, which in summer are always completely free of ice. It is impossible to determine the boundaries of beginning and ending of two adjacent periods of ice phenomena. Therefore, it was not possible to compare the dates of beginning and ending of ice phenomena according to NSIDC and NOAA NESDIS data.

According to the NSIDC and NOAA NESDIS data, the number of days the ice phenomena were observed on the lakes during the period of 2006–2017 is correspondingly 1877 and 2294 days for Lake Onego (relative deviation, $\varepsilon = 20.0\%$); 1566 and 2190 days for Lake Ladoga ($\varepsilon = 33.2\%$); 1853 and 2159 days for Lake Segozero ($\varepsilon = 15.3\%$) and 1972 and 2378 days for Lake Vigozero ($\varepsilon = 18.7\%$).

Discussion

Values of $\bar{\delta}_{NSIDC}$ are satisfactory (<7%) when determining the spatial distribution of ice of all lakes, except for Lake Ladoga (9.6%). Therefore, NSIDC data are of greater interest in the determination of the spatial distribution of ice and also in the calculation of ice coverage than NOAA NESDIS data. However, the $\bar{\delta}_{NSIDC}$ value in the determination of the spatial distribution of ice on Lake Ladoga is almost twice as much as that of other lakes. In this regard, a detailed analysis of the errors that occur whilst determining the spatial distribution of ice on lakes in accordance with NSIDC and NOAA NESDIS data was carried out and the dependence of the mean error value in determining the spatial distribution of ice on lakes on the actual ice coverage of the lakes $\bar{\delta}(ice)$ was deduced.

Also the dependence $\overline{MAD}_{ice}(ice)$ characterising the distribution $\overline{MAD}_{ice}$ of actual values of ice coverage (according to MODIS data) was determined.

It was found out that the dependence $\bar{\delta}(ice)_{NSIDC}$ increases steadily whilst actual ice coverage (according to MODIS data) reaching a peak ($\bar{\delta}(0.3\text{-}0.4)_{NSIDC} = 39.2\%$) with ice coverage value of 0.3–0.4, then the error decreases steadily to the minimum value ($\bar{\delta}(1)_{NSIDC} = 0.7\%$) complete freeze-up phase). The graph of the dependence $\bar{\delta}(ice)_{NSIDC}$ is shown in Figure 5.

It should be noted that 70–80% of the satellite images (MODIS) taken for analysis shows lakes that are completely covered with ice, except Lake Ladoga (only 30% of all images). This is explained by the fact that small lakes, Lake Segozero, Lake Vigozero as well as Lake Onego, are completely covered with ice for a considerable time interval of 80–120 days yearly. Lake Ladoga is not always completely covered with ice (Fig. 3b). In 2008–2009 and 2014–2017, there are no MODIS images free from clouds where Lake Ladoga is completely covered with ice. All this explains relatively large value of (9.6%) for Lake Ladoga comparing to other lakes.

It should also be noted that NSIDC data with a small value $\bar{\delta}(0)_{NSIDC}$ (3.9%) make it possible to record the total absence of ice on lake (Fig. 5). Thus thanks to NSIDC data, it is possible to determine sufficiently the dates of beginning and ending of the periods when the lake is completely or partially covered with ice and completely free from ice; at the same time, significant value $\overline{MAD}_{ice\ NSIDC}(0\text{–}1)$ (up to 36%) of freeze-up and break-up phases does not affect the calculation of these dates.

This makes it possible to solve an important hydrological task – to determine the timing and duration of phases of the ice regime of lakes. However, the formation of a daily series of

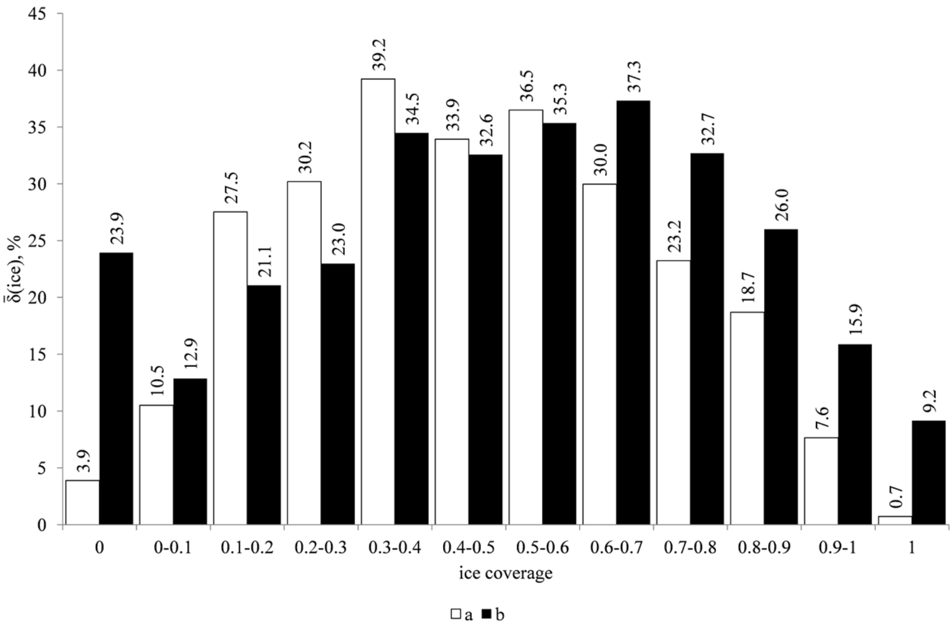

Fig. 5. Graphs of dependence : (a) NSIDC data and (b) NOAA NESDIS data.

values of ice coverage of lakes is impossible with NSIDC data during freeze-up and break-up. To do this, it is necessary to use additional more accurate data.

Dependence $\bar{\delta}(ice)_{NESDIS}$ is similar to dependence $\bar{\delta}(ice)_{NSIDC}$; the maximum value $\bar{\delta}(0.6\text{–}0.7)_{NESDIS}$=37.3% is reached when the ice coverage value is 0.6–0.7 and the minimum value is $\bar{\delta}(1)_{NESDIS}$=9.2% during the complete freeze-up phase (Fig. 5).

The difference between $\bar{\delta}(ice)_{NESDIS}$ and $\bar{\delta}(ice)_{NSIDC}$ dependences is the presence of a significant value $\bar{\delta}(0)_{NESDIS}$=23.9% at the time when lake is completely ice free. Such a value $\bar{\delta}(0)_{NESDIS}$ takes into account the summer periods when according to NOAA NESDIS ice phenomena occur on the lakes, whereas in reality, the lakes are always completely ice free in summer. For the same reason, the number of days within the period of 2006–2017 the ice phenomena were observed on the lakes according to NOAA NESDIS data for all lakes is >15–30% according to NSIDC data.

Conclusion

It was established that comparing to MODIS data, NSIDC data have a smaller value (3–10%) than NOAA NESDIS data (11–19%) for lakes (Lake Onego, Lake Ladoga, Lake Segozero and Lake Vigozero). Therefore, it is advisable to use NSIDC data when determining the spatial distribution of ice on lakes. According to NSIDC (as well as NOAA NESDIS) within the freeze-up and break-up phases, $\bar{\delta}(ice)_{NSIDC}$ can reach an unacceptable value of 40% ($\overline{MAD}_{ice}$

is up to 36%). In this regard, the formation of a detailed time series of ice coverage values within the freeze-up and break-up phases using the NSIDC and NOAA NESDIS satellite data is possible only if it is corrected by more accurate data, for example, MODIS data.

However, the NSIDC data make it possible to calculate the value of the ice coverage of lakes during the complete freeze-up phase and the absence of ice phenomena on the lake with sufficient accuracy ($\overline{MAD}_{ice\ NSIDC}(0)$=3.9% and $\overline{MAD}_{ice\ NSIDC}(1)$=0.7%). This allows us to conclude that the use of NSIDC data is advisable for determining the timing and duration of the ice regime phases.

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