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The Ladoga ringed seal (*Pusa hispida ladogensis*) under changing climatic conditions

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ABSTRACT. The Ladoga ringed seal is a Red listed subspecies of ringed seal, which most critical life cycle stages are closely related to ice presence on the lake. Climatic changes which are observed globally have their impact on local marine mammal populations resulting in shifts in distribution, abundance, migration pattern, disease occurrence, reproductive success. We considered trends in various ice related parameters on the Lake Ladoga since mid-XX century in relation to possible consequences to the Ladoga seal population. Analysis of the probability of winter with 100% ice coverage of the lake showed a statistically significant negative trend. Similarly, negative, though rather weak, trends were observed for sum of negative temperatures in the region and average ice thickness. The total duration of the ice period on the lake has reduced by 13.7% during the second part of the XX century. Maintenance of such trends, though non-significant on short term scale, can cause stress reactions in the Ladoga ringed seal living at the very southern edge of the species global range.

KEY WORDS: Ladoga ringed seal, climate change, ice conditions.

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Ладожская кольчатая нерпа (*Pusa hispida ladogensis*) в условиях изменяющегося климата

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РЕЗЮМЕ: Ладожская кольчатая нерпа — охраняемый подвид кольчатой нерпы, наиболее критические фазы жизненного цикла которого связаны с наличием ледового покрова. Климатические изменения, наблюдаемые в глобальном масштабе, отражаются также на локальных популяциях морских млекопитающих, приводя к изменениям в распространении, обилии и миграциях, подверженности болезням, репродуктивном успехе. Мы рассмотрели тенденции в различных параметрах ледовых условий на Ладожском озере, начиная с середины XX века, во взаимосвязи с возможными последствиями для популяции ладожской нерпы. Анализ вероятности наступления зимы со стопроцентным ледовым покрытием озера показал наличие статистически значимого отрицательного тренда. Сходным образом, отрицательные, хотя довольно слабые, тенденции наблюдались в величине суммы отрицательных температур в регионе и средней толщине льда. Общая продолжительность ледового периода на озере сократилась на 13,7% во второй половине XX века. Сохранение подобных тенденций, несмотря на их незначительность в краткосрочных периодах, может вызвать стрессовые реакции у ладожской кольчатой нерпы, живущей на крайней южной границе ареала вида.

КЛЮЧЕВЫЕ СЛОВА: ладожская кольчатая нерпа, изменение климата, ледовые условия.

Introduction

The issue of climate change and associated reduction of the ice period in the northern hemisphere has been widely discussed at the international level (e.g., Ferguson *et al*., 2005; Laidre *et al*., 2008). Climatic conditions are globally changing faster than it was expected based on the work of expert groups and intergovernmental commissions (IPCC, 2007; Stroeve *et al*., 2007). Numerous studies on the influence of climate change on marine mammals (e.g., Ferguson *et al*., 2005; MacLeod *et al*., 2005; Kovacs & Lydersen, 2008), have shown that they may alter their geographical range or migration patterns (IPCC, 2001) in response to changes in climate. The effect of increasing temperature on marine mammal prey species can, in turn, cause changes in the distribution, abundance and migration patterns, exposure to pollutants and diseases, and reproductive success of these marine predators (Villegas-Amtmann *et al*., 2011).

During the breeding season, the ice on which pinnipeds haul out must be thick enough and persist long enough to complete critical stages of parturition, lactation, and, in many cases, annual moult (Burns, 2002). Early ice break-up in spring combined with a lower depth of snow and insufficient ice thickness can lead to a decrease in seal pup survival that has been confirmed by a number of researchers (Hall *et al.*, 2001; Ferguson *et al.*, 2005; Giles *et al.*, 2008). Poor ice conditions correlate with low indices of fatness in the ringed seal and in extreme years can result in 50% decline of ovulation rate according to Harwood *et al*. (2000).

Particularly vulnerable to the ice cover reduction may be seal species that are confined to inland seas and lakes, such as the Caspian seal (*Pusa caspica*), the Baikal seal (*Pusa sibirica*), and subspecies of the ringed seal (*Pusa hispida lagodensis* and *P.h. saimensis*) inhabiting lakes Saimaa and Ladoga because they are limited in their ability to follow the retreating ice cover (Harwood, 2001).

The Ladoga ringed seal is a pagophilic seal for which the most critical stages of the life cycle depend on stable ice cover in winter and spring. Parturition and lactation of these animals take place in the snow lairs or under snow drifts along the coastlines of the rocky islands in the Northern part of Lake Ladoga (Kunnasranta, 2001; Agafonova *et al.*, 2007). The literature does not provide any information on the climate change at the regional level in relation to its impact on the population of the Ladoga ringed seal. Regular registration of ice related parameters, i.e. thickness, coverage, dates of establishment and break-up, were performed by Northwestern State Hydrological Institute and the Institute of Limnology, which used to issue annual newsletters devoted to the monitoring of Lake Ladoga (Usachev *et al.*, 1985). Based on those data and the analysis of satellite images the current trends in ice conditions on the lake were analysed and signs of a shorter ice period reported (Karetnikov & Naumenko, 2008). According to expert opinion, the snow cover in the region of Lake Ladoga is also reducing and by mid-XXI century is expected to fall by 10–30% (Kuusisto, 2005). Freezing of the lake usually begins in November and ice cover lasts from November to May (mean 172 ± 3 days). In March, an average ice thickness reaches 50–60 cm and in the middle of the month ice break-up (Naumenko *et al.,* 2007).

Due to seal winter surveys carried out by Soviet researchers (Antoniuk, 1975; Philatov, 1990), there are some reports available on the specifics of the Ladoga ringed seal use of ice habitat. It was indicated that in severe winters breeding females were distributed in the central part of the lake, while in milder winters animals tend to concentrate in the coastal areas, on fast ice. A map of ringed seal lairs location, provided by Zubov (1965), suggests a rather extensive use of the available ice cover by the seals in both central zone and fast ice area of the lake. However, there is no information available on the fluctuations in the level of seal fertility and survival of offspring in relation to varying ice conditions from year to year. It remains unclear how the ringed seal population would react to further reduction of the ice cover on the lake (if this should continue).

In the current paper we intend to analyze existing trends in various ice related parameters on Lake Ladoga and discuss our findings in the context of the Ladoga ringed seal population status. We consider specifics of the subspecies' environment, its known ecological requirements and habitat utilization aspects in order to reveal the Ladoga ringed seal level of sensitivity to observing climatic changes and conclude on further possible development of the situation.

Material and methods

Assessment of ice conditions was conducted on a number of key features that are significant in terms of reproductive success of the ringed seal in any given season: date of formation of the ice cover (the first date of observation records, or the first clear satellite image when the percentage of lake area covered with ice exceeds 5%), the date of ice complete melt (the first available date, when the percentage of the lake area covered with ice declines to 5% or less), total duration of ice period (in days) and the maximum ice extent over a season (percentage of the area of the lake covered with ice); sum of the average effective (negative) temperatures (SET) for the season (according to data from meteorological stations Sviritsa and Sortavala), the mean ice thickness (cm), maximum ice covered area available per one breeding female (km^2).

The analysis of ice conditions from 1947 to 1982 was performed using the summary tables compiled by Northwestern State Hydrological Institute based on data obtained from 373 regular ice surveys over Lake Ladoga until 1970 and after 1971 from data from the Meteor satellite (Usachev *et al.*, 1985). Data on ice conditions from 2003 to 2012 were obtained by processing satellite images NASA Modis Aqua (http://modis.gsfc.nasa.gov/), the ice coverage of the lake was calculated by ice outlining using Google Earth Pro (2007) software. In total 219 satellite images, which analysis was possible due to low level of cloudiness, were selected and processed.

We have developed and fitted a model of polynomial regression of SET from 1946 to 1982 and from 2003 to 2012 in relation to year. We tested different types of relation — linear, quadratic or cubic, and then using the Akaike's information criterion (Burnham & Anderson, 2002), we selected the best fitted model which we used further for prediction of ice coverage of the Lake from 1983 to 2002. In the years when there were no empirical data available on average thickness of the ice (from 1983 to 2002), it was calculated based on SET using the formula proposed by B.D. Zaikov (1955).

Changes in SET, ice cover and ice thickness from 1947 to 2012 were described with regression models to determine the statistical significance of downtrends. Hypotheses about the statistical significance of the changes in these indicators were tested by analysis of variance (F-test) or using the nonparametric Mann-Whitney U test. The probability of having 100% ice coverage on the Lake was tested by fitting a logistic regression and using Chi-test for trend assessment. We

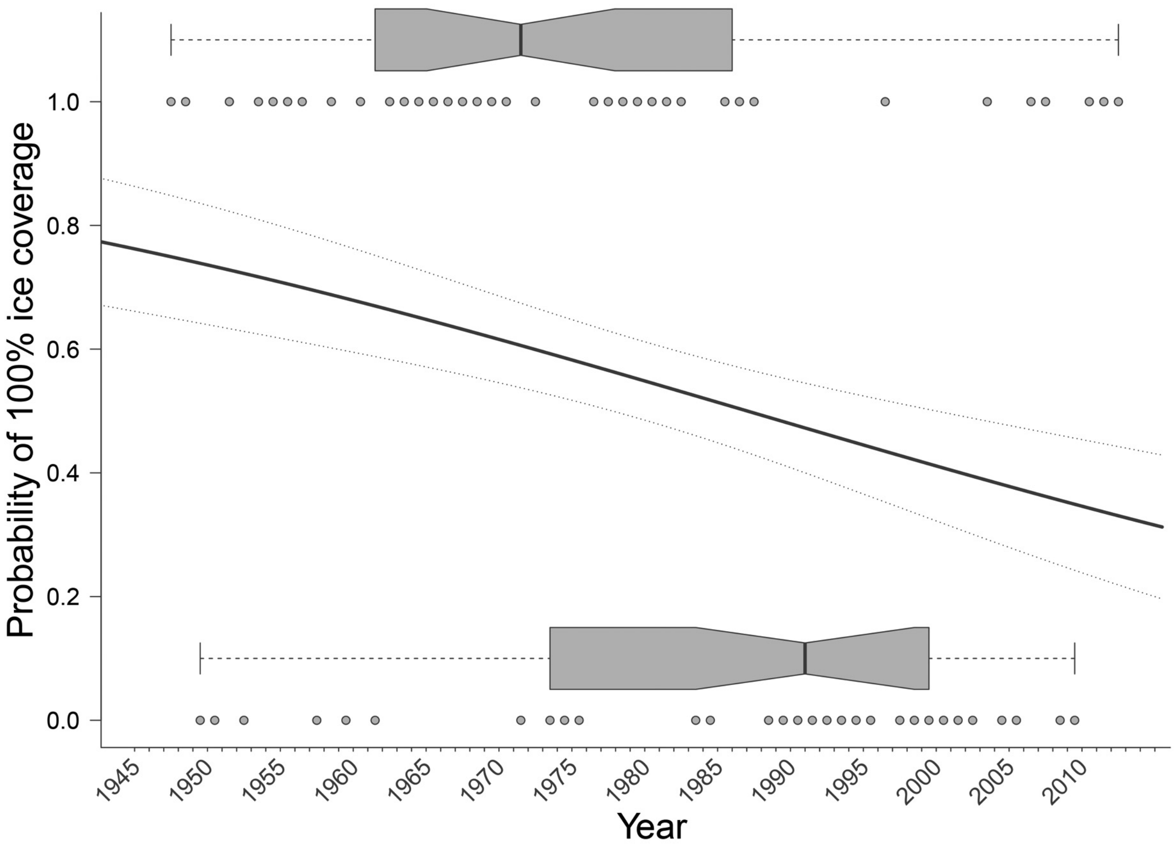

Figure 1. Probability of having a winter with 100% ice coverage. Dots represent empirical values of indicative function I (I = 1 if ice coverage is 100% in a given year, I = 0 if ice coverage is less than 100%); horizontal boxes — distribution of empirical data; bold line — predicted probability trend; dotted lines — confidential intervals.

assumed a value to be statistically significant at a rate of $\alpha = 0.05$. For the entire process of the analysis, i.e. modeling and hypothesis testing, we used the R programming environment (R Development Core Team, 2011).

Results

Our primary goal was to analyze the changes in ice conditions on Lake Ladoga in the past 66 years. When considering the available data on the dependence of the ice cover on SET, it became clear that even if SET is as low as –671°C (as, for example, in 2012), the lake can still freeze up completely. The critical value of SET which guarantees full ice coverage of the lake is –976°C. Upon reaching this value by SET in all of the cases considered the ice coverage reached 100%.

Based on the fitted cubic model (determination R^2 criterion 70.1%) describing the relation between SET and ice coverage, we predicted the values of lake ice coverage for the years in which SET did not exceed –976°C between 1982 and 2002. For the rest of the years of that period, we have assumed 100% ice coverage.

From these data, the average date of the beginning of ice formation on the lake has shifted, on average, for 2 weeks, from December 2 to December 17, over the period 1947–2012. The date of ice complete melt shifted, on average, for 13 days back, from May 14 to May 1. The total duration of the ice period has therefore significantly reduced by 13.7%. In the first half of the period 1947–2012 mean ice coverage was 94.57% (SD = 4.02), in the second — 86.89% (SD = 6.32). Criterion for significance of differences (Mann-Whitney U test) was $U_{emp} = 362.5$ ($p = 0.011$), which allowed us to conclude that difference in the ice extent on Lake Ladoga in these two periods is statistically significant. In the first half of the reporting period, the percentage of winters, when the lake was completely covered with ice, was 69.7%; in the second half — only 33.4%. Analysis of the probability of winter with 100% ice coverage of the lake showed a statistically significant ($p = 0.038$) negative trend ($\beta = -0.028$) in the second half of the twentieth century (Fig. 1).

Each year SET from 1947 till 2012 has been decreasing on average by 5.56°C, and during the whole period has significantly reduced by 35.2%. However,

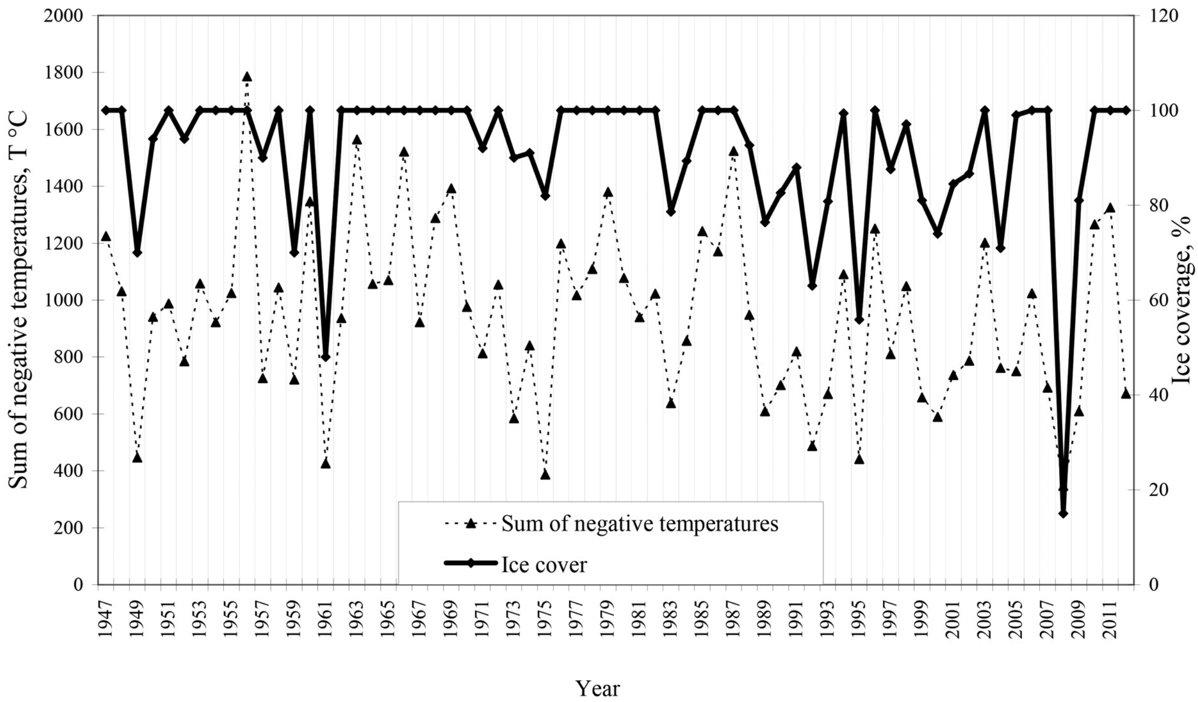

Figure 2. Fluctuation in sum of negative temperatures and maximum ice coverage (partly based on data NASA Modis Aqua (http://modis.gsfc.nasa.gov/) and Usachev *et al.*, 1985; SET values for 1983–2002 are estimations).

the coefficient of determination R^2 criterion is quite low — 6.7%. The mean thickness of the ice on Lake Ladoga has been decreasing during the same period on average by 0.18 cm per year and significantly decreased by 11.88 cm; R^2 criterion is low again — 3.8%. In the short periods of time negative trends in ice conditions on Lake Ladoga are barely noticeable. However, there are significant fluctuations between years, with no evident pattern of recurrence (Fig. 2). In the long term (over 50 years) scale a general warming trend was revealed. Whether this trend is part of longer term climatic variations is not possible to evaluate in this relatively short-term scale and at the local level: it requires a long-term sampling of a complex of climatic parameters and the transition to a larger, regional level.

According to the studies of the Arctic (*P.h. hispida*) and the Baltic ringed seals, an average area of ice which is sufficient for successful reproduction, should be 2.5 km^2 per one breeding female in a case of low density population. In this case, the density of animals or the amount of available food resources is not playing any limiting role in the survival of pups, which achieves its theoretical maximum of 65%, whereas lack of breeding habitat leads to 95% offspring mortality (Sundqvist *et al.*, 2012). Following Sundqvist *et al.* (2012) we assumed a simple linear relation between the area available for the females and pup survival rate expressed by the equation (1) $y = 0.24x + 0.05$, where x — ice area available for one female, y — survival of pups (proportion). We applied this equation to the Ladoga ringed seal and plotted maximum population size (and the corresponding number of breeding females at the rate of 0.25 of the total seal number) against each possible value of the ice coverage on the lake which would provide each breeding female with 2.5 km^2 (Fig. 3).

The graph (Fig. 3) shows that at the current estimated Ladoga seal population size of 5500–8000 individuals (based on the results of aerial survey conducted in 2012, which gave the estimate of the number of seals on ice equal to 5068 individuals; Trukhanova *et al.*, in press), the ice conditions on the lake in ideal situation are not a limiting factor for the seals if the ice coverage exceeds 30%. However, we should keep in mind that not all the ice is suitable for lair construction, breeding and resting and the proportion of areas with hummocks varies from year to year depending on the ice formation pattern (influenced by temperature, wind strength and direction, etc.). Consequently, our calculations represent the minimal sufficient area of ice — in reality the ice covered area must be larger to maintain normal level of survival of offspring. Extreme values of the ice cover over the last 66 years were observed recently, in 2008, when the available ice cover was clearly below the threshold (15% under SET value of 347ºC), which resulted in high mortality of the pups (predicted by (1) mortality rate — 64%) and the numerous strandings of pups which required rehabilitation (Alekseev & Andrievskaya, 2010). In other years the value of ice coverage did not fall below the threshold, if we stick to

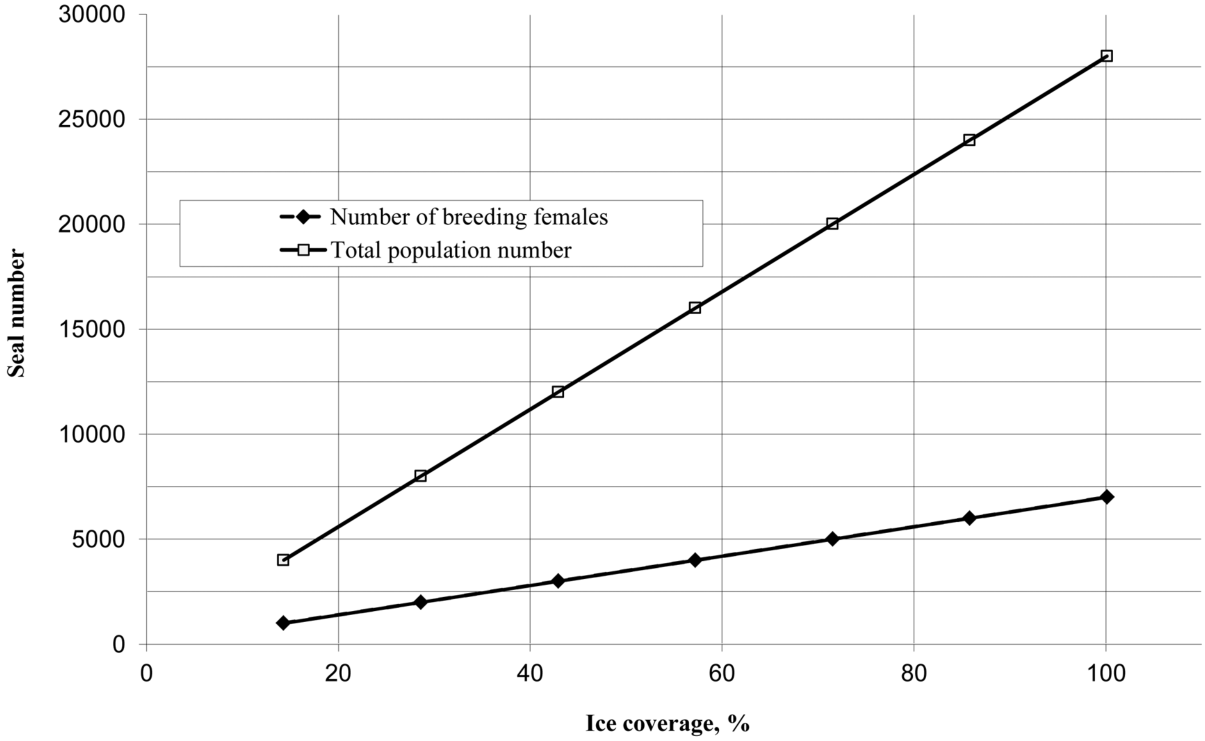

Figure 3. Maximum acceptable Ladoga ringed seal population numbers and corresponding numbers of breeding females ensuring sufficiency of ice covered area per one breeding female at different values of ice coverage.

available published data on the number of animals on the lake as a reference point.

Discussion

Various species of marine mammals demonstrate various degrees of dependence on the availability and structure of the ice cover, and the time of its formation and melt. According to the assessment method proposed by Laidre *et al*. (2008), the Ladoga ringed seal should be classed in the category of marine mammals most sensitive to climate-induced habitat degradation. Extending its range is not possible; possibilities for substitutes for the dominant prey species may be more limited than in the open ocean, since the fish fauna of a freshwater lake is less diverse. Reduced availability of ice, caused by its early melt, and aggravated by the presence of fishermen on ice (Trukhanova *et al*., in press), may lead in some areas to an increase in population density achieving the values which are not typical for the ringed seal in general. Distance reduction between breeding females is one of the potential causes of high pup mortality due to the spread of density-dependent infectious diseases (Burek *et al*., 2008) as it was shown for other seal species (e.g., Jüssi *et al*., 2008), lack of suitable habitat and prey stock deficiency for the mothers.

The Ladoga ringed seal is under the high risk in a case of epidemic outbreaks due to the limited range. Change in temperature regime might enhance the development of various viral and bacterial diseases that normally occur in latent forms in populations of marine mammals (Geraci & Lounsbury, 2002; Würsig *et al.,* 2002). For instance, during the last three decades a significant increase in the frequency of mass mortality events associated with outbreaks of diseases caused by morbillivirus (canine distemper virus) has been registered. The outbreaks were detected in the populations of Caspian, common (*Phoca vitulina*) and grey seals (*Halichoerus grypus*) and the Baltic ringed seal (*Pusa hispida botnica*) and the factors which triggered these epizootics are not clear (Harvell *et al*., 1999; Domingo *et al*., 2002; Geraci & Lounsbury, 2002). Observations of Ladoga seal haul-outs on the islands of Valaam Archipelago from 2001 to 2009, about 10–20% of the animals had lesions of the skin — ulcers and patches (ECOS, 2007). In 2011–2012, according to fishermen’s reports (I.S. Trukhanova, pers. comm.), similar marks (concentric pink spots) were found on the skin of the seals stranded dead on the islands. The pathogen that causes skin lesions observed, was not so far reliably identified, however, according to experts’ visual examination results, it might be the pox virus (N.V. Medvedev, pers. comm.). Skin lesions might be related to weakening of immune system and the attention should be played to population health status in terms of circulation of infectious diseases.

Late formation of ice together with shallow snow cover (less than 32 cm; Ferguson *et al*., 2005) can affect the success of construction of pupping lairs which provide protection for the newborn pups from low temperatures, wind chill and predators during lactation (Sipilä, 2003). One study of northern fur seals (Trites & Antonelis, 1994) showed that in years with late ice formation, the seals had additional implantation delay, resulting in later pregnancy and parturition. We suppose that this could be critical for the pups in years where late winter ice was followed by early ice melt. The behavioural response of Ladoga ringed seal females seeking to construct a pupping lair in unfavourable snow and ice conditions is not known. There is one report of a female nursing her pup under a fishing boat lying upside down on one of the islands of Valaam Archipelago in 2007, although in that year the ice conditions were favorable for normal lair construction (E.M. Andrievskaya, pers. comm.).

Early ice break-up can lead to early separation of females and their pups due to habitat fragmentation (storms often lead to the destruction of ice fields, and ice floes can be displaced by wind for a considerable distance), or rapidly melting ice around the lairs. Pups prematurely separated from their mothers usually die either from starvation and hypothermia. It is not known whether the Ladoga ringed seal pups can continue suckling on shore, but our experience suggests that lone preweaning pups stranded on the shore are frequent in mild winters 2007 and 2008 (Alekseev *et al*., 2012).

Lake Ladoga is a typical cold water lake inhabited by a variety of cold water fish species such as trout (*Salmo trutta*), salmon (*Salmo salar*) and several whitefish subspecies (*Coregonus lavaretus*). At the same time this is an oligotrophic water basin with rather low productivity level though its fish stocks are actively used by the fisheries (Naumenko & Karetnikov, 2002). Graduate elevation of water temperature in the lake might eventually cause even further decline of its natural productivity and changes in species composition. Temperature increase can lead to intensification of algae bloom and hence to decline of O_2 concentration in the water which will have its consequences in terms of the total fish biomass values (see, e.g., Camargo & Alonsa, 2005).

Food deficiency for seals leads to the use of blubber reserves, resulting in the mobilization of the body fat acids and pollutants accumulated there including organochlorines, bromides and polyaromatic acids (Moore, 2008). According to several studies (Medvedev *et al*., 1993, 1997; Kostamo *et al*., 2000a) in the subcutaneous fatty tissue, lymph nodes and some internal organs of Ladoga seal a presence of toxic substances, including hexachlorocyclohexane, a number of metabolites of DDT and aldrin, which affect the general state of the immune system of animals, was found. Some of these compounds were found in high concentrations in surface waters of the lake (Drabkova, 2002) as well as in fish (Kostamo *et al*., 2000b). Medvedev *et al*. (2012) reported high concentrations of heavy metals in the fur of pups and adult animals, which may indicate, in general, the significant intake of pollutants into the waters of the lake. This problem was previously highlighted also by Finnish researchers (Kostamo *et al*., 2000a).

There is plenty of evidence (Sipilä, 1996; Kunnasranta, 2001; Agafonova, 2007) that the Ladoga seals prefer to give birth in fast ice zone, on the border between the primary and secondary ice with lots of hummocks and ridges. In northern areas of the lake the lairs are generally formed in showdrifts on the shorelines of islands and islets. However, the results of our aerial survey (Verevkin *et al*., 2012, Trukhanova *et al*., in press) have shown that plenty of lairs can be also found in the central part of the lake in the event of sufficient level of hummocking and deep snow cover there. We should note, that detection of seals in the central areas of the lake was also reported, for example, in the papers by of Philatov (1978) and Zubov (1965). We can conclude that the ringed seal in the winter demonstrates widespread use of the available ice habitat, even though its distribution is not homogeneous. This means that an incomplete formation of the ice cover in a given breeding season can lead to a significant decrease in the area of ice suitable for pupping, forcing the animals to use coastal zones most affected by the pressure of predators and human disturbance. In the absence of ice in the center of the lake breeding females are likely to concentrate on fast ice which is extensively used by fishermen, making these areas unsuitable for the animals. For example, in winter 2012 the fast ice zone comprised about 44% of the total area covered with ice on Ladoga Lake, and 30% of this zone (approximately 2800 km^2) were used by fishermen, leaving only 4841 km^2 potentially available for the seals (Trukhanova *et al*., in press). Consequently, in the years when the secondary ice does not form at all, the ice area available per one breeding female could be reduced to 2.4 km^2, which implies pup survival rate to be 63% in the best case scenario given the current population size. Climate warming trend in the region along with an increasing intensity of vehicle traffic on the ice will negatively influence reproduction success of the population in the nearest future which has already been demonstrated for other ice associated seal species (see, e.g., Sokolov, 2010).

Our data analysis showed that there is indeed a certain tendency to a decrease in the sum of negative temperatures, which is being a major cause of reduction of ice cover and mean ice thickness on the lake (although the R^2 in both cases is quite low). Maintenance of such trend, though non-significant on short term scale, can cause stress reactions in animals, especially if they live at the extreme upper limit of their thermal tolerance (Lafferty *et al*., 2004), which is highly relevant to the Ladoga ringed seal, the range of which is located at the southern edge of the species distribution, and northward migration of the population is not possible.

Conclusion

The emerging trend of climate warming in recent decades is evident on a global scale, and according our analysis conducted for the region of Lake Ladoga, already has its consequences for freshwater land-locked water basins in temperate latitudes. Therefore, the Ladoga ringed seal in the near future may face the same negative consequences of climate change which has already become real for Arctic species of marine mammals. Given the high degree of sensitivity of this subspecies to climate fluctuations, it is necessary to pay special attention to the development of rapid response measures to be taken in the event of an unforeseen deterioration of climate parameters in the region. The Ladoga ringed seal is a unique freshwater seal subspecies which is endemic to the lake, and extremely vulnerable to stochastic changes in the environment. Beyond all doubts it is important to maintain its high conservation status at national and international levels.

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