Sea ice phenology in the Caspian Sea

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ABSTRACT

To understand the spatial and temporal variations in the extent and timing of sea ice in the Caspian Sea (CS), 15 years of sea ice presence and its phenology (freeze-up, break-up, and duration) were studied in the Northern CS (NCS) for a period from 2004 to 2018. This study indicated that the percentage of sea ice covered area in the CS showed fluctuations ranging from 54.2 % in 2004 to more than 89 % in 2006 and 2008. This study, furthermore, found regional differences within the NCS in sea ice phenological features during 2004 to 2018. Specifically, earlier sea ice formation, later ice melt, and longer ice periods were observed in the eastern than the western NCS. Noticeable interannual changes were also observed in the timing and duration of the NCS ice (2004-2018). However, most parts of the NCS did not show significant trends ($P>0.05$) in the formation, decay, and duration of sea ice and their interannual variability. The observed spatial and temporal patterns in the CS ice can have implications for phytoplankton blooms and higher trophic levels, such as fish and endangered Caspian seal populations and merits further investigation.

INTRODUCTION

The Caspian Sea (CS) is located in Western Asia and Eastern Europe. With a surface area of approximately 370’000 km^2, the CS is considered as the world’s largest enclosed water body (Lattuada *et al*., 2019). Due to its latitudinal extension, the CS crosses multiple climatic zones and encounters a strong north to south gradient in geological, physical, and chemical properties (Barale, 2010). Conventionally, the CS has been divided into three major basins according to water depth and geographical location, namely the Northern, Middle, and Southern CS (Fairbridge, 1966; Ibrayev *et al*., 2010). The Northern Caspian Sea (NCS) is very shallow (with an average depth of less than 5 m and maximum depth of 20 m; Stolberg *et al*., 2006) and is located on the extreme southern boundary of sea ice cover development in the Northern Hemisphere (Kouraev *et al*., 2004). Every year, its surface area freezes during winter, while most of the middle and southern CS stays ice free year-round (Barale, 2010). Thickness of sea ice may reach up to 75 cm in the western and central NCS and 120 cm in the eastern parts of this basin. The cumulative impacts of climate conditions, wind fields, water currents, and sea morphology lead to a significant temporal and spatial variability in the sea ice cover over the CS (Kouraev *et al*., 2004).

To understand spatial and temporal variations in the extent and timing of sea ice in the CS, here, 15 years of the sea ice presence and its phenology (freeze-up, break-up, and duration) in the NCS for a period from 2004 to 2018 were studied. Sea ice data were provided by the Centre for Ice Hydrometeorological Information at the Arctic and Antarctic Research Institute in St. Petersburg (AARI), the Hydrometeorological Centre in Moscow (Hydrometcentre), and local hydrometeorological offices in the Arctic, Far-Eastern Russia, Baltic, Black and Caspian seas, all belonging to the Russian Federal Hydrometeorological Service (Roshydromet). The Roshydromet coastal weather polar stations provide visual and instrumental observations on different features of sea ice such as sea ice concentration and thickness. The centre also employs visible and infrared satellite images from American (NOAA HRPT, EOS TERRA) and Russian (METEOR, OKEAN) satellites for the sea ice monitoring. All the data are processed and utilized for sea ice analysis at the AARI station. The AARI station is compiling weekly sea ice conditions charts for the CS since winter 2002 (WMO, 2006).

METHODS

Caspian Sea ice data are provided by AARI in the shape of lines and polygons data (http://wdc.aari.ru). Weekly binary raster maps of sea ice presence and absence in 0.1×0.1 degree resolution were created in ArcMap environment and were written into Netcdf format for further analyses in Matlab. Several algorithms were developed in Matlab environment to extract different features of the sea ice in the NCS for the period of study (2004-2018). Percentage of sea ice cover over the NCS in each year was computed as the total number of ice-covered pixels in each year divided by the total number of pixels in the NCS. Algorithms were developed for retrieving sea ice phenology metrics, including the time of sea ice freeze-up and break-up, as well as duration of ice-covered sea for each pixel in the NCS for a period from 2004 to 2018. The time of ice formation (week) was set as the time when the sea ice appeared for the first time in a year in a pixel that was ice free in its previous two weeks. This value was negative for the years when the ice formed in the autumn of the previous year. The time of ice break up (week) was set as the time when ice was observed for the last time in a year in a given pixel, while the pixel remained ice-free for at least two subsequent weeks. The duration of ice coverage in a pixel (weeks) was calculated as the difference between the time of ice in and ice out. The existence of a linear trend in the sea ice phenology (start, end, duration) for each pixel during the period of study (2004 to 2018) was analysed using non-parametric Mann-Kendall test (P<0.05). The magnitude of inter-annual variability (iv) in the phenological characteristics of the sea ice (i.e., timing of the ice formation and break-up, and the duration of the sea ice coverage) for each individual grid point in the NCS was computed based on the standardized anomalies in the ice phenology metrics of each pixel in each year. To this aim, the differences between all the grid points for each phenological feature in each year and their climatological averages (2004-2018) were computed and divided by the standard deviation (2004-2018; Soppa *et al*., 2016). Average climatologies of anomalies of the phenological features over the study period (2004-2018) were calculated and the magnitude of their interannual variability were computed as absolute temporal mean of anomalies (2004-2018).

RESULTS AND DISCUSSION

The percentage of sea ice covered area in the CS from 2004 to 2018 ranged between 54.24 (2004) to 89.79 to 89.97% (2008 and 2006, respectively; Fig. 1). The observed oscillation in the sea ice coverage can be explained by changes in the severity of different winters during the period of this study (Kouraev *et al*., 2004). The dependence of the ice regime to the air temperature was also shown in other studies (*e.g.*, Baklagin, 2019). A gradual west/southwards gradience was observed in the time of the sea ice formation in the NCS. The shallow eastern parts of the NCS froze earlier than other parts of the NCS (as early as the second half of December on average (week -2); Fig. 2b). The sea ice later spread out to the west (because of the Volga runoff impact; Kouraev *et al*., 2004), and the latest ice developed in the southern parts of the NCS (in late February and early March; Fig. 2b), where larger depths and increase in the water exchange with the Middle CS limited further development of sea ice cover in this area (Kouraev *et al*., 2004). CS ice (Fig. 2c) decayed earlier in the southern parts of the NCS (from as early as the first half of January; week 2), then in the western parts of this area near the Volga delta, and finally, last CS ice disappeared in the eastern parts of the NCS (as late as April; week 12), where the thickest ice is observed (average of 40-50 cm; Kouraev *et al*., 2004). Expectedly, longest periods of ice coverage are in the eastern NCS (8-18 weeks) and as we go further west and south, sea ice lasted for less time (Fig. 2c). Spatial differences in the sea ice timing have been also reported in other parts of the World Ocean, *e.g.*, in the Arctic Ocean (Ji *et al*., 2013). A previous study in the CS also demonstrates similar spatial patterns in the sea ice timing in the region and stated a correspondence between the observed timing of sea ice formation in different regions of the NCS with historical observations of sea ice (Kouraev *et al.*, 2004). An explanation for the delay in the sea ice break-up in the eastern part of the NCS can be the weak circulation in the north-eastern part of the CS after melting the sea ice that causes the last

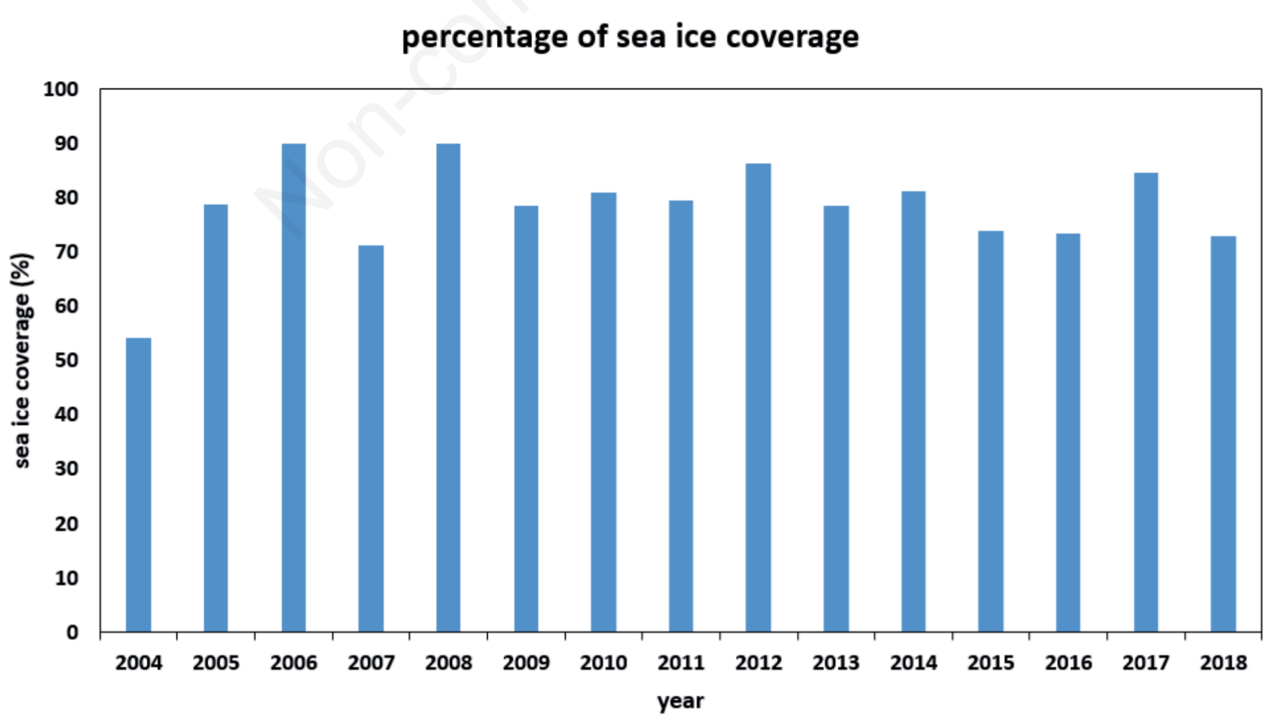

Fig. 1. Percentage of sea ice coverage in the north Caspian Sea from 2004 to 2018.

cold-water patch in that region to stay undistributed (Fendereski *et al*., 2014). Spatial differences in the sea ice timing can partly explain spatial changes in the phytoplankton bloom features in the region. The later increase in water temperature in the eastern NCS compared to that in the western parts of this basin can be one reason for the delay in the occurrence of the phytoplankton bloom in the eastern parts of the NCS (Fendereski *et al*., 2014).

The formation, break-up, and duration of sea ice in the CS changed from year to year during the study period. Most parts of the NCS did not show significant trends in the timing and duration of their sea ice (P>0.05; Fig. 3). Only 12.5% of the NCS showed a significant trend in the timing of the ice freeze-up from 2004 to 2018 towards earlier ice formation dates (P<0.05; Fig. 3a). 10.9% of the NCS shows significant trend in the length of sea ice period and towards longer ice cover periods (P<0.05; Fig. 3b). No significant trend was observed in the time of ice decay in the NCS (P>0.05). For the interannual changes in the sea ice phenology in the NCS, generally, timing of the ice formation and the duration of ice coverage showed a higher degree of interannual variability from 2004 to 2018 than the timing of ice disappearance (Fig. 4). More than 90% of the NCS showed more than half a week of interannual variability in the timing of the beginning/end and duration of their ice season (Fig. 4). Similar to the sea ice phenology metrics, no pronounced spatial gradient in the interannual changes of ice phenology characteristics were observed during the study period (2004 to 2018; Fig. 4).

A previous study on the CS ice for a period from 1998 to 2002 showed changes in the dates of ice start and break-up and gradual reduction in the ice cover (Kouraev *et al*., 2004), attributed to changes in the thermal regime towards mild winters in this region; however, this study (Kouraev *et al*., 2004) left the open question whether the observed changes are indicative of

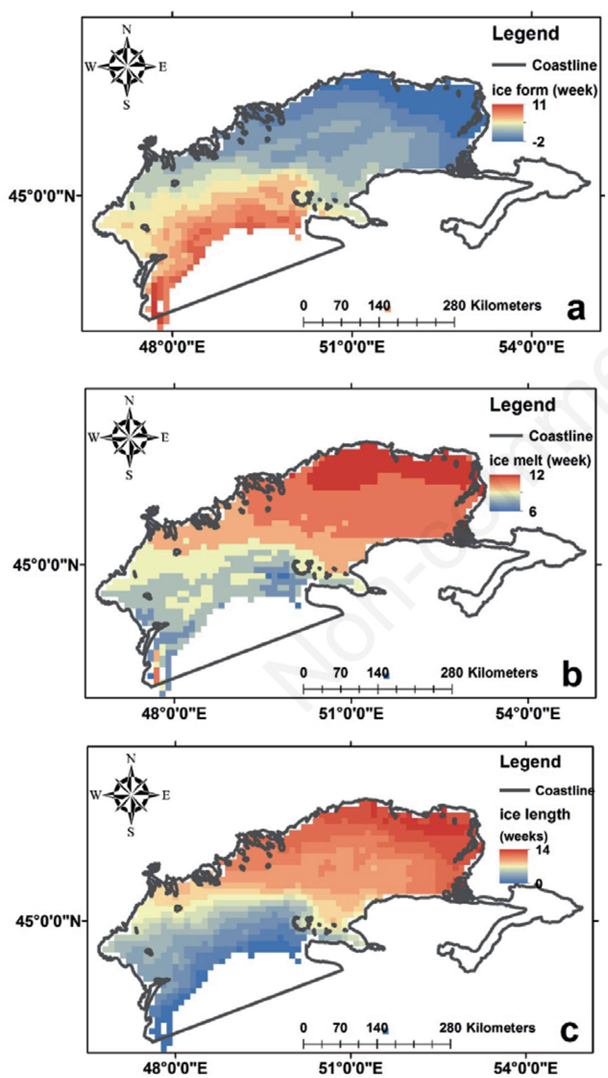

Fig. 2. Climatological mean of the timing of the (a) sea ice formation (week; negative values indicate weeks falling into the previous year of a given year), (b) sea ice melt (week), and (c) duration of the sea ice coverage (weeks) in the Caspian Sea from 2004 to 2018.

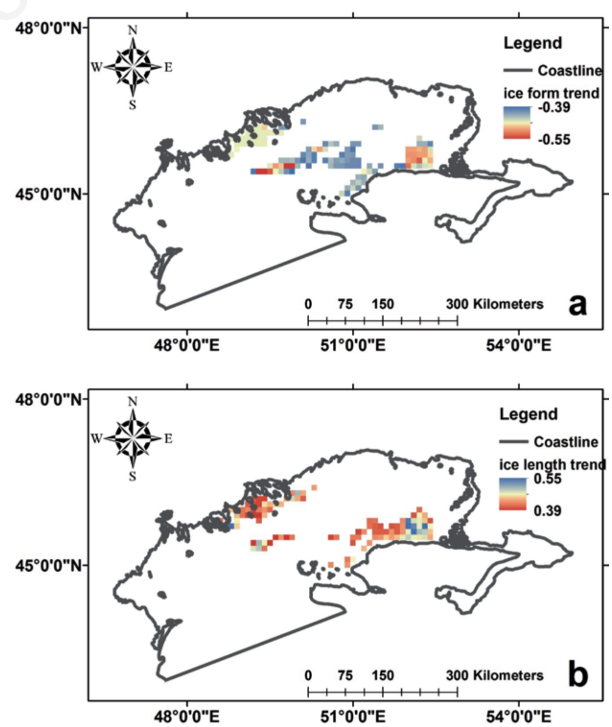

Fig. 3. Trend in the (a) sea ice formation, and (b) duration of the sea ice coverage in the Caspian Sea during 2004 to 2018 (MannKendall test; P<0.05). White pixels indicate no significant trend in the sea ice phenology in the Caspian Sea during the period of study (2004 to 2018; P>0.05). No significant trend was observed in the timing of the sea ice break-up in the CS (P>0.05).

a long-term warming trend or just a series of warm winters and suggested that to answer this question a longer time series is needed. Covering the period from 2004 to 2018, the current study did not show similar patterns as observed between 1998 and 2002. In contrast, rather than a decreasing trend, an interannual fluctuations were observed in the sea ice extent with no significant trends in the sea ice formation, break-up, and duration in most parts of the NCS (P>0.05).

The highly productive shallow fresh waters of the NCS, in particular the eastern parts of this basin, provide an essential breeding, spawning, nursery, foraging, and transit grounds for commercial fish species such as endemic sturgeons (*Acipenser* sp.; Karpinsky *et al*., 2005; Zonn, 2005) and other unique and vulnerable CS species such as the Caspian seal (*Phoca caspica*; Dmitrieva *et al*., 2015) that is listed on the IUCN Red List of Threatened Species. Given the ecological importance of the NCB and considering the importance of the sea ice timing on phytoplankton bloom phenology (Ji *et al*., 2013) and thereby the whole food web (match-mismatch hypothesis; Cushing, 1990; Platt *et al*., 2003; Hague and Vichi, 2018; Tedesco *et al*., 2019), the observed changes in the NCS ice may have consequences for the CS ecosystem function and ecosystem service provision. Results of the current study suggested the necessity of a comprehensive study on the impact of changes in the CS ice, in particular in the context of global warming, on primary producers' phenology and their implications for higher trophic levels' recruitment success and population dynamics in this area.

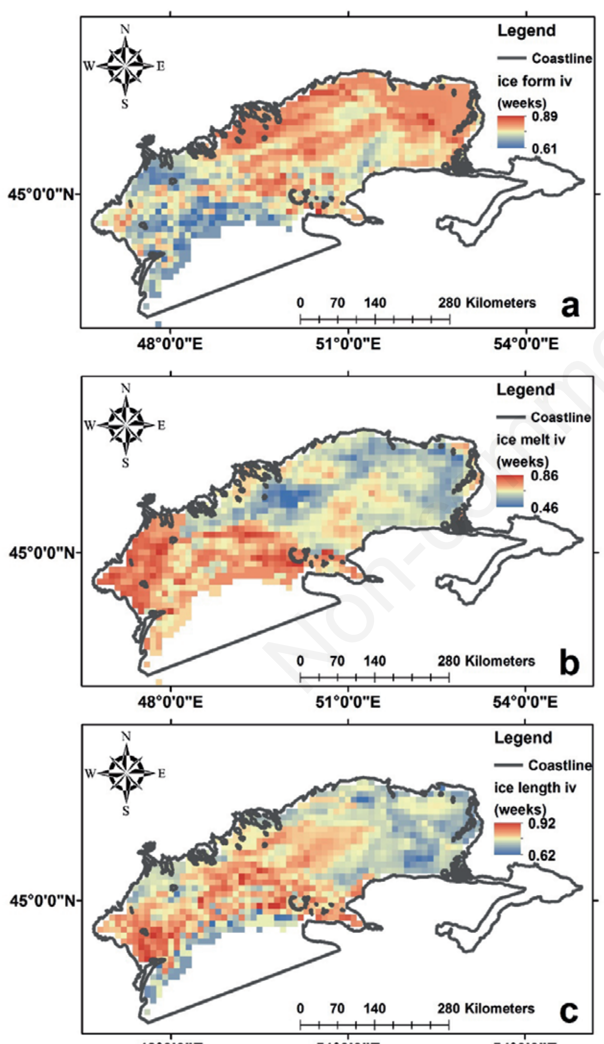

Fig. 4. Climatological mean of the standardized anomaly of the magnitude of interannual variability (iv) in the (a) sea ice formation (ice form; weeks), (b) sea ice melt (weeks), and (c) duration of the sea ice coverage (weeks) in the Caspian Sea during 2004 to 2018.

CONCLUSIONS

In this paper, 15 years (2004 to 2018) of spatial and temporal variability in the sea ice presence and phenology (freeze-up, break-up, and duration) in the North Caspian Sea (NCS) were studied. Results showed year-to-year oscillations in the percentage of sea ice cover and its phenological metrics (timing of start, break-up, and duration of sea ice) in the NCS in the period of study. The study also showed spatial patterns in the sea ice phenology in the NCS, with later formation, earlier break-up, and shorter ice in the western parts of the NCS.

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