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Caspian Seasonal Ice Volume Trends in the Recent History

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ABSTRACT

The persistent reduction trend of ice volume and coverage over the whole Northern Caspian Sea through the record of the latest seasons in history illustrates the effect of climate change on the ice regime. Ice volume and coverage indexes are derived from consistent daily observations of ice cover. Direct hierarchy of relationship between these aggregated indexes and detailed records of ice conditions enables quantitative climate change impact assessment on operations occurring in the region. This paper is intended to demonstrate the trend and some of the expected consequences to operations under continued projected warming of the region.

KEY WORDS Caspian Sea; FDD (Freezing Degree Days); Ice volume variations; Regional ice monitoring; Climate change.

NOMENCLATURE

CMIP (Coupled Model Intercomparison Project), FDD (Freezing Degree Days), IPCC (Intergovernmental Panel on Climate Change), RCPs (Representative Concentration Pathways portrayed possible future greenhouse gas and aerosol emissions scenarios)

INTRODUCTION

A lot of studies exist on polar sea ice extent and thickness changes, and their associated consequences and impact on biodiversity, economic activities and communities. These studies are well reviewed and summarized with periodic reports issued by the Intergovernmental Panel on Climate Change (https://www.ipcc.ch/). The effects of climate change on the Caspian Sea have been focused around continuously falling sea level and the assessment of water balance, e.g., Koriche et al. (2021). A lot of research performed by state owned and corporate organizations has already led to implementation of mitigation measures. These can be observed with changing infrastructure and operational schemes of major offshore projects like dredged navigation channels in the Northeastern part of the sea.

Impact assessments and other effects of changing environmental conditions on local scale are scarce. The focus of this article is on the changing ice environment of the Northern Caspian Sea. Fragile ecosystem, unique species (including nearly extinct Caspian seals) and dependency of many communities along the coastlines on offshore economic activities are to a certain degree affected by the presence of seasonally forming ice cover. These factors necessitate more detailed and complex studies to increase the level of preparedness for the anticipated changing ice environment.

Declining trends of seasonal ice coverage and thicknesses became obvious to the authors of this article through extensive ice cover classification hindcast performed during recent years as described in Vernyayev et al. (2023) along with increasing number of queries on climate change impact on operations in ice covered waters. The focus of this article is to demonstrate the seasonal ice volume and coverage trends at the Caspian based on historical records. Connection these high-level regional scale climate indexes to local scale impact analysis is illustrated with a couple of showcases.

AIR TEMPERATURE RECORD AND SEASONAL FREEZING DEGREE DAYS

Intergovernmental Panel on Climate Change's (IPCC) sixth assessment report (AR6) was not fully published when drafting this article; hence, the findings from its fifth assessment report (AR5;IPCC, 2014) were used to illustrate the annual average air temperature increase in the Caspian region. This trend is shown with the left panel in Figure 1. The right panel indicates projections into the future indicating further rise in air temperature will persist both with optimistic RCP2.6 scenario and pessimistic RCP8.5 (IPCC, 2014).

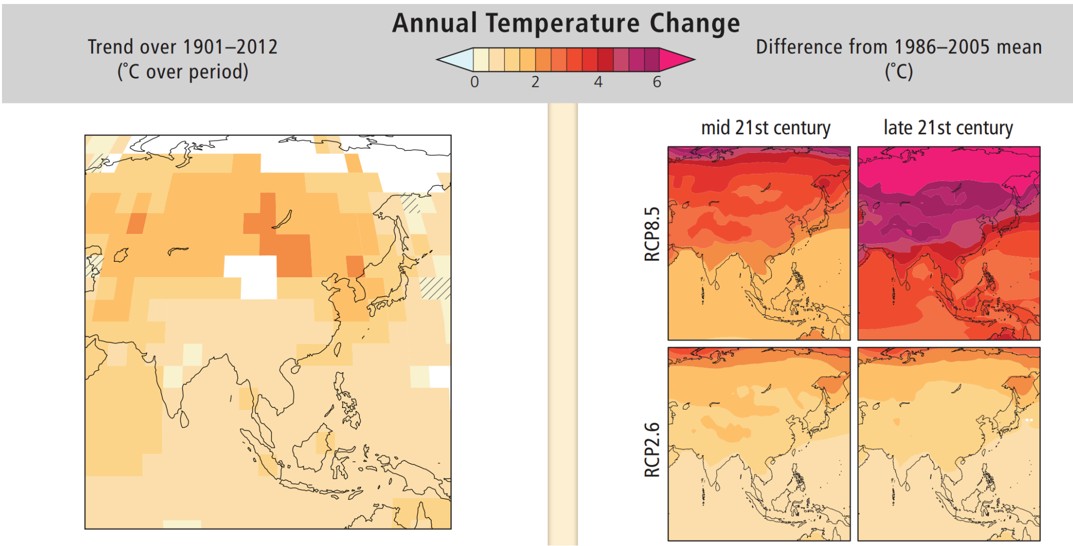

Figure 1 Observed and projected changes in annual average temperature in Asia. Left: Map of observed annual average temperature change from 1901–2012, derived from a linear trend \. Right: Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model mean projections of annual average temperature changes and average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and RCP 8.5, relative to 1986–2005. (IPCC, 2014)

Annual average air temperature increase captured with the above trends is observed over each forecast zone of the Northern Caspian as delineated during ice cover classification hindcast through accumulated Freezing Degree Days (FDD) index. FDD indicates the severity of winter seasons and can be used to estimate maximum ice thickness that can be expected in an area of interest. Figure 2 illustrates seasonal FDD accumulated over a zone situated in the shallower North-Eastern part of the sea. Severity classification of the mild, moderate and severe seasons was first introduced in 1970s with early studies of sea ice in the region.

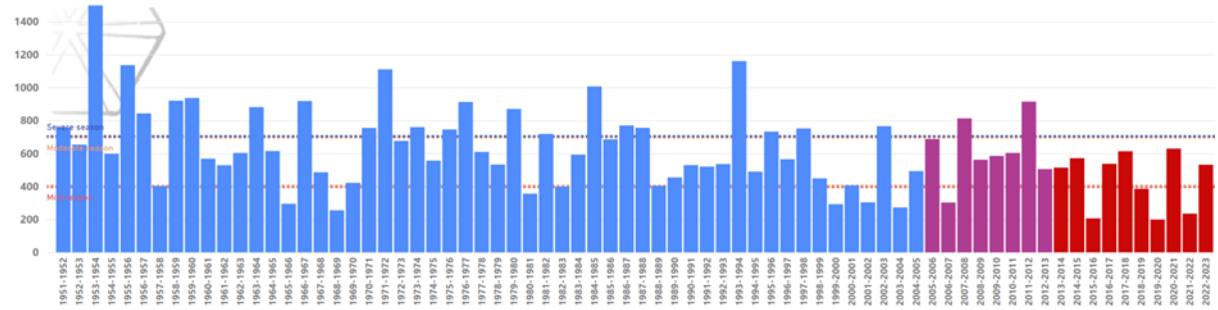

Figure 2 Freezing Degree Days accumulated over a forecast zone in the Northeastern part of the Caspian Sea as observed from 1951 to 2023.

Annual variation of FDD indicates that mild winters occurred in the history of observations over the region every 15-20 years in 1900s. The 2000s started with four mild seasons during the first ten years. Generally speaking, warmer winters experienced during the last ten years include the three warmest winters. In our analysis, we introduce the "extra-mild" category in the severity classification to differentiate the extra-mild from the mild ice seasons. Lower ice coverage, shorter duration of season, shorter persistence of landfast ice cover and lowest ice thickness explain the difference. Thus, the recurrence interval of warmer winters has shortened, and milder winters become warmer than previously in history.

ICE VOLUME AND COVERAGE

FDD index is used best to predict landfast ice thickness. Immobile ice that is not subjected to drift induced deformation, break up into floes and recurring reduction of concentration with freeze-up and growth of different age ice. Recuring break-up and freeze-up, mobile ice cover, ice floes refrozen leads and areas of older thick ice drifting in the basin of the Northern Caspian form concise and descriptive ice cover behavior during mild and most part of moderate seasons in the Northern Caspian. Highly dynamic ice cover behavior, significant variability of ice season duration that varies from 1.5 to 5 months, variable frequency persistence and intensity of consequent cold snaps and thaw periods combined with solar radiation make basic calculations of ice thickness based on FDD an approximation towards conservative estimates.

With differentiated ice thickness calculation on a regional scale that accounts for up to three ice thicknesses varying by age with tracked origin, Sigitov et al. (2023b) introduces greater accuracy in the estimation of ice masses generated in the region. Greater accuracy in ice thickness estimation coupled with their daily partial concentration observation enables high precision in ice volume estimate according to area of sea ice coverage. Geographically and temporally consistent data allows aggregating area specific and aggregated regional statistics. Resulting indexes are more informative in terms of ice cover description as they account both for thermal processes associated with air temperature and for wind related ice masses redistribution over the region and deformation of ice cover. The last one is important during climate change impact analysis, being the indicator of changing weather patterns.

Data Aggregation Mechanism

Seasonal statistics on regional area coverage and volume of sea ice cover in the North Caspian Sea during ice seasons in the period from 2005 to 2022 is presented with Figure 3. Both values are based on daily ice cover classification hindcast observations as described by Vernyayev et al. (2023). Ice coverage is derived from concentrations aggregated separately for each forecast zone and the whole region. Thus, quartiles (Turney, 2023) indicate the number of coverage occurrences per day of averaging period in selected focus area. Averaging hierarchy comprising daily, weekly, monthly and seasonal periods enable analysis with detail corresponding to application and required precision. Ice volume is derived based on thickness component being average ice thickness weighted by partial concentration of up to three thicknesses as recorded in the dataset and following the same hierarchy by periods.

Averaging, filtration and visualization of observations are performed using Microsoft Power BI connected to the virtual PostgreSQL object-relational database management system scripted to extract geographical information from the hindcast database. Real time connection ensures all latest entries are considered when compiling statistical aggregates.

Regional Perspective

Seasonal distributions presented in this article are most suitable for discussion on interannual variation that illustrates long-term changes in the regional climate. Variation of ice volume and coverage over the whole Northern Caspian Sea illustrates persisting reduction of ice volume and coverage throughout the last 15 seasons confirming the impact of warmer seasons described above with FDD on key regional ice cover characteristics. Median value is indicative of significant ice volume generated over the region per season. Thus, the coldest 2020-2021 season of the last ten years is comparable to the previous severe season in 2011-2012 by areal coverage, but quartiles of ice volume indicate significantly larger number of lower values observed.

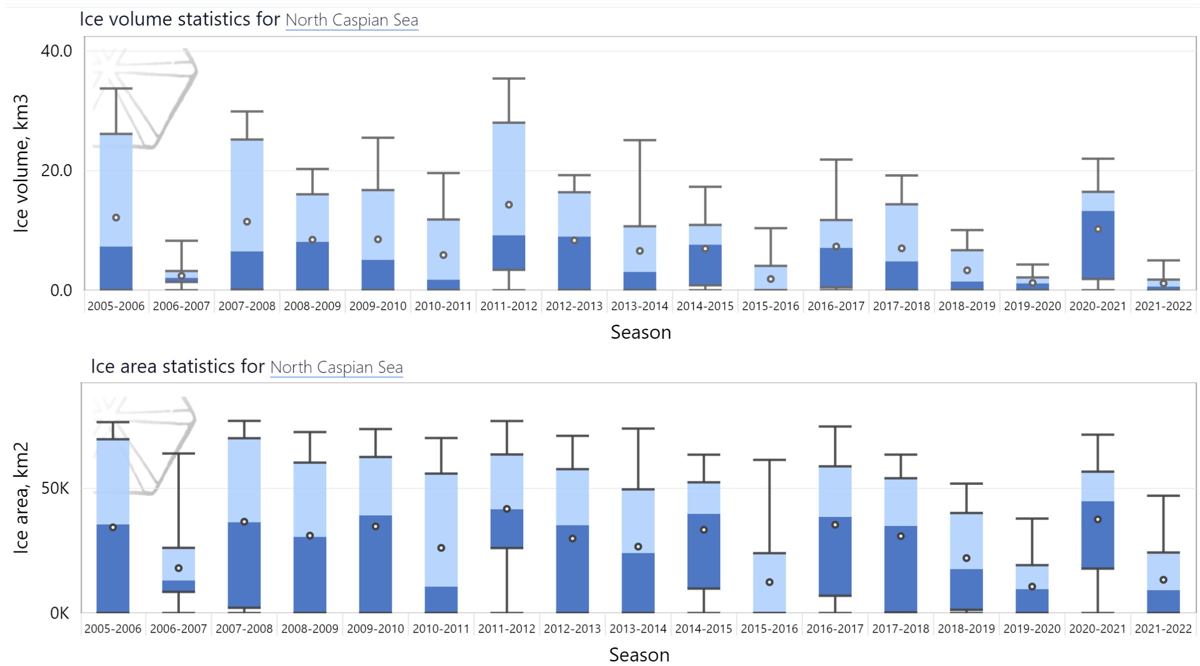

Figure 3 Seasonal ice volume (top) and area coverage (bottom) statistics for North Caspian Sea during the period from 2005 to 2022. See Dutoit (2012) for box plot visualization of quartiles. Point indicates average for observations in box plot.

Interannual variation of ice volume and coverage as described above creates a clear picture on general ice conditions development in a region. These indexes are closely correlated to regional air temperature indexes and observed anomaly values used for climate projections and long-term forecasts.

Seasonal Variation

Development of ice volume through a season aggregated per month for three discrete periods from 2005 to 2022 shows consistently continuous reduction of larger volume quartiles. This reduction has been more intense during the last five years. It should be noted that even though typically FDD continues to increase into March, different thermodynamic processes affect ice thickness development towards the end of a season. Solar radiation in March, for example, becomes more significant contribution to melting than sea-air temperature gradient that is near negligible this time of the season. Normally, no further ice growth is observed in the areas of the older thick ice. New ice that might form during colder nights over open water leads would normally melt away by the end of the next day. Significant reduction of ice volume quartiles in March during the latest period points out that lower volumes of ice are generated through the colder part of season and more efficient thermal erosion process in the end of a season.

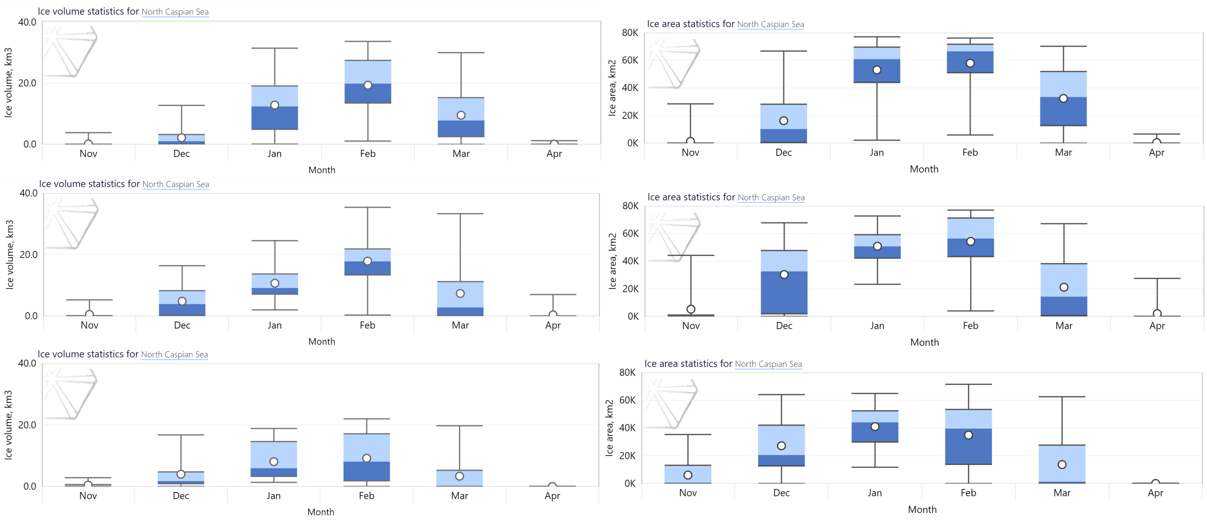

Figure 4 Monthly summary of ice volume (left) and areal coverage (right) development statistics for North Caspian Sea for discrete periods 2005-2011 (top), 2011-2017 (middle) and 2017-2022 (bottom). See Dutoit (2012) for box plot visualization of quartiles. Point indicates average for observations in box plot.

Ice area coverage reduction trends are observed with quartiles shifting towards lower coverage values within comparably consistent maximums. It means that even though the maximum ice extent per month of a season has not significantly changed the number of occurrences has been consistently decreasing through the period of observations.

Spatial distribution

Direct comparison of ice phenomena occurrence between two different zones forming area of interest in terms of volume generated has little sense due to difference in area. Figure 5 presents the average ice thickness index (ITi) defined as maximum seasonal ice volume in a zone divided by zone area. This index enables comparison of ice volume generated in zones disregarding of their area.

The spatial distribution of average ice thickness index plotted for all forecast zones of the region shows significant irregularity with maximum observed values from 2005 to 2022. This is associated with the effect of predominant easterly winds transporting thicker and older ice from the generally cold Northeastern part of the sea to the West into areas with lower accumulated FDD. This effect is less pronounced during the period from 2013 to 2022.

Spatial distribution of average ice thickness index is comparable with pattern of FDD distribution. FDD decreasing from Northeast to Southwest illustrates cumulative effect of atmospheric events associated with arctic cold air intrusion into the region. Comparison between the two periods indicates reduction of frequency and intensity over the whole region. The difference is clearer in the Southwestern forecast zones where key changes with ice cover occur.

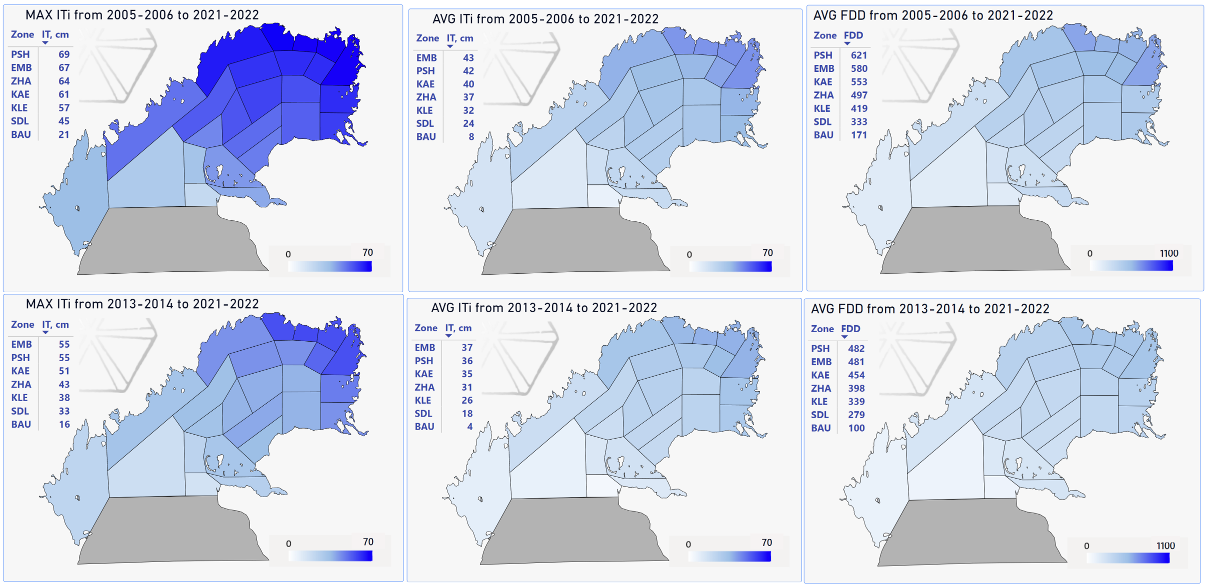

Figure 5 Spatial distribution of maximum (left) and average (middle) of seasonal maximum ice thickness index and average FDD (right) in forecast zones (Vernyayev et al., 2023 for zoning) of the Northern Caspian over periods from 2005 to 2022 (top) and from 2013 to 2022 (bottom).

The stabilizing effect of Kashagan structures deployed in the Northeastern part of the region on ice cover can be observed with significant incremental increase in ice thickness. Westerly zones being downwind with predominant direction are areas with recurring opening leads and thinner ice forming over opening waters. More detailed analysis of ice thickness conditions separately for mild, average and severe seasons indicates higher variability during warmer winters as discussed by Sigitov et al. (2023b). Further analysis of wind induced ice cover mobility state is presented in Sigitov et al. (2023a).

Figure 6 illustrates the inter-seasonal variation of the maximum ice coverage area observed over the whole Northern Caspian Sea during the period of available data. This variation once again clearly demonstrates the reduction of ice cover per season throughout recent history. Similar results were demonstrated by Lavrova et al. (2022). The natural limit for ice extent is bathymetry. The Mid Caspian, being significantly deeper than the shallow northern part, never freezes except for shallower bays and pre-coastal zones with negligible amounts. Ice coverage just below 80000 km^2 corresponds to the boundary conditions for Northern part of the sea as defined with zoning. Therefore, rare occasions of temporary events when ice cover extends into middle part of the sea are not reflected in ice volume and coverage statistics. Colder winters before 2013 regardless of severity have always varied between 60 and just below 80 thousand km^2. Recent observations demonstrate increasingly smaller coverage.

The plot on the right side illustrates the trend for two geographically extended forecast zones.

Peshnoi zone (PSH) is situated near Ural River mouth at the Northern coast in typically immobile pre-coastal ice zone. Saddle (SDL) is a transitional zone between the less mobile eastern part and mostly mobile area in front of Volga Delta and North of banana shaped Kulaly Island. The difference in the patterns shows the response to the atmospheric events is less pronounced in the Peshnoi area. Whereas 2019-20 season shows the ice edge has never been south and west of the zone during that season and the first such observation during the years of observations.

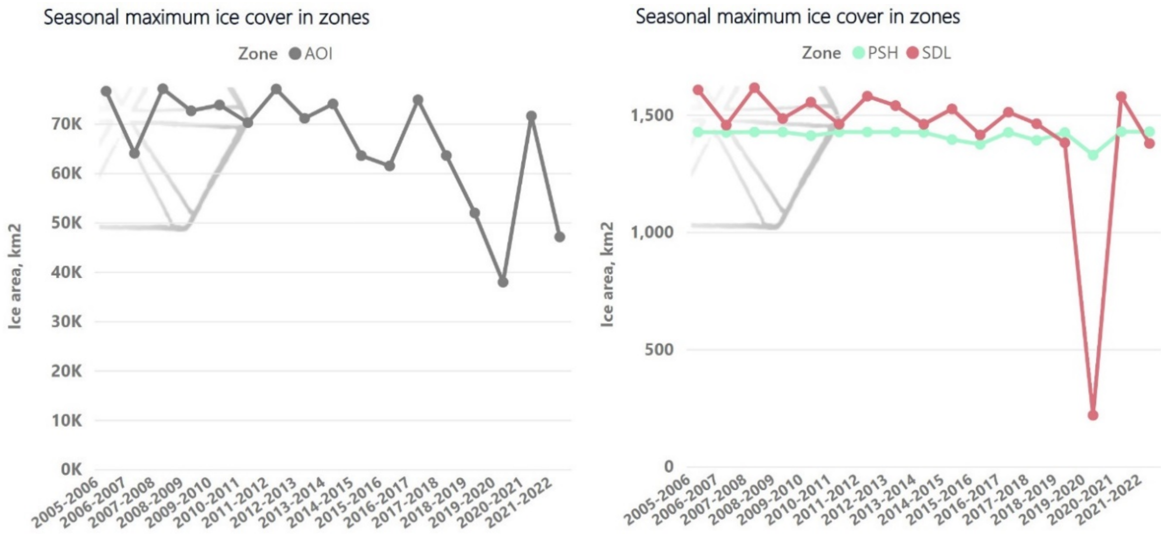

Figure 6 Inter-seasonal variability of maximum ice area observed over the whole Northern Caspian (left), Peshnoi (PSH) and Saddle (SDL) forecast zones (right).

IMPACT ASSESSMENT SHOWCASES

Reduction of ice volume and coverage demonstrated above has diverse impact on various components forming understanding of region's resilience to changing environment. The following subsections present the most obvious showcases of climate change impact assessments for variety of scenarios and applications.

Caspian Seal Pupping Sites

The Caspian seal is a nearly extinct species that resides only in the Caspian as reported by Wilson et al. (2017a). The persistence of their population growth depends on availability of ice cover suitable for their pupping sites from beginning of February to mid-March among other factors limiting their breeding that was described by Wilson et al. (2017b). These ice conditions can be described with range of ice thickness from 15 cm and more at concentrations higher than 8/10 but never exceeding 30 cm when concentrations are above 9+/10 persisting for up to three weeks. These conditions ensure access to water for moms hunting herring and sufficient duration for pups to gain blubber needed as insulation for entry into ice cold water for the first time. The above scenario conditions can be used for exploratory purposes. More specific detailed conditions accounting for seal's attraction to broken ice of navigation channels, possibility for presence of small size cracks that are not visible with remote sensing data, inclusion of more details on partial concentrations of second and third ice thicknesses and knowledge of ability of seals to maintain holes in thick and growing ice.

Figure 7 illustrates annual probability of occurrence for ice conditions that were observed within the limits described above in each 1×1 km grid cell of the region. The top row is based on three consequent discrete periods from 2005 to 2022 that show how probability has evolved under changing environment. 2005-2011 illustrates favorable ice conditions with higher probability situated at an ideal distance from shores and natural predators (eagles and wolves). This is also the area that is imprinted in the seals' instincts as a birth site. The area of probability for favorable ice conditions during the next period from 2011 to 2017 has significantly expanded with higher values appearing near the southern shore and closer to predators. Probability based on observations of the last and the warmest seasons has changed dramatically compared to the earlier two periods. First, the area shifted to the Northeast closer to the Northern coastline, away from the typical birth site and closer to new hazards of persisting pre-coastal immobile ice zone suggesting easier reach by predators and intensive human activities. Note the alternative area with high probability of favorable ice conditions for pupping is in front of Volga delta which is more populous with predators compared to arid areas of the Pre-Caspian Dawn in the Northeast and Mangyshlak Peninsula in the South.

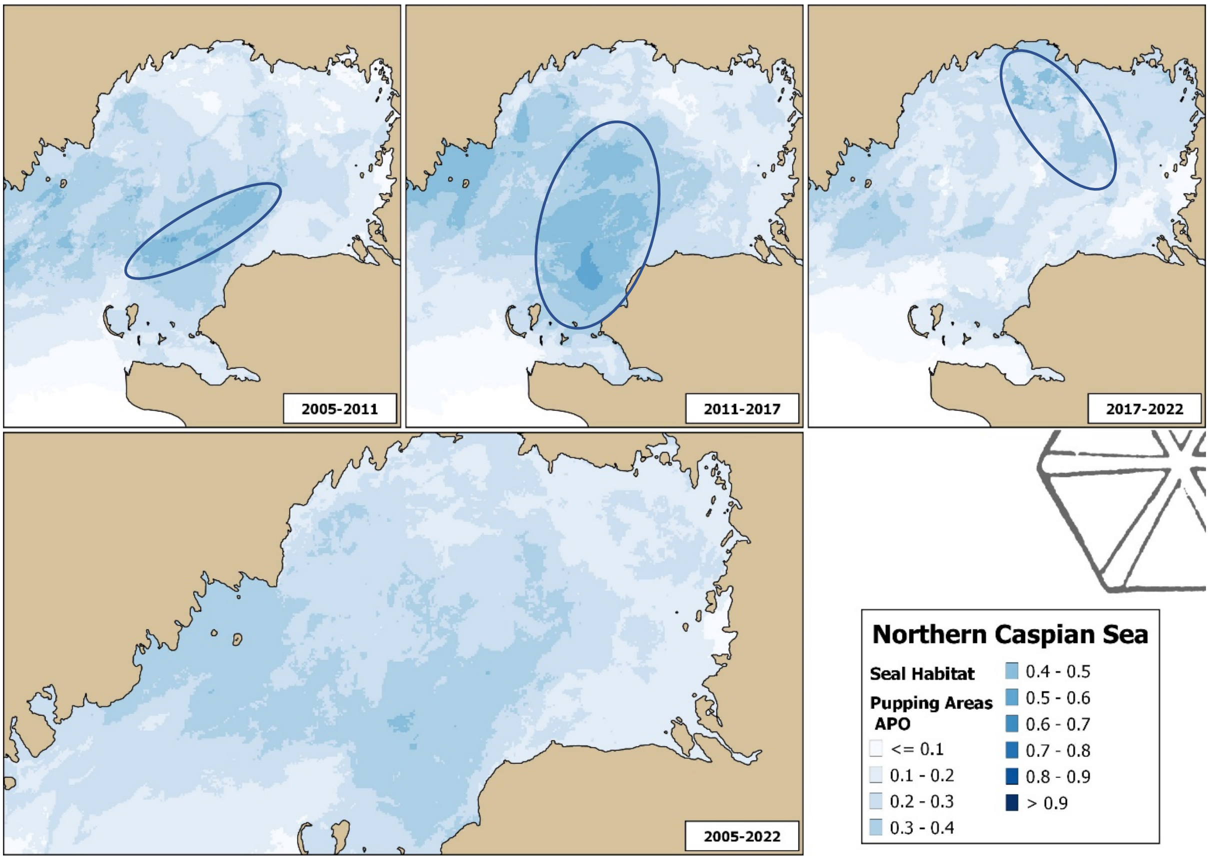

Figure 7 Annual probability of occurrence for favorable ice conditions of pupping sites based on observations for discrete periods (top) and totally (bottom) over the period from 2005 to 2022.

Resulting distributions illustrate reducing annual probability of occurrence for favorable conditions of pupping sites. Considering the thousands of years of instinct that drives these seals to the same location for pupping it will not be easy for them to adapt to new conditions when the pupping sites do not provide the security that they are used to. With the population not gaining, the new generations ending up too early in the water and perishing from pneumonia, the consequences are dire for the species that are already at the level of extinction.

Excess Brash Ice Thickness in Ports

Brash ice is a typical issue in ports with ice covered water. Persisting and intensive navigation over an enclosed area during a cold period of intensive freezing generates fine brush that is unevenly distributed along the vertical profile. Pieces of overcooled ice from the top surface are mixed with warmer ice from the bottom with water at freezing point filling voids in between suggesting perfect conditions for rapid refreezing. With more intensive navigation this process is more effective and ice cover gains significant thickness (sometimes exceeding ambient ice thickness in the surrounding area by the factor of two or more) over a short period. The Sub-Arctic Caspian Sea has seen this type of event during severe and moderate winters. Mitigation measures are discussed in the range of procedural suspension of non-critical marine operations to installation of engineered solutions designed to limit brash ice growth.

A data driven decision on the matter could be based on the impact assessment in context of changing environment. Daily average air temperature below -10°C persisting for more than one week with immobile ice cover conditions could potentially lead to significant brash ice formation alongside a quayside. A hypothetical structure with requirement for frequent reattendance by icebreaking supply vessel and deployed in the Northern Caspian was used to derive annual probability of occurrence for these conditions based on observations from 2005 to 2022. Persistence of daily average air temperature below -15°C for the same scenario can lead to severe brash ice formation events that is considered in this assessment to illustrate sensitivity to 3, 5 and 7 days of continuous coincidence.

Figure 8 illustrates results of persistence analysis in form of maximum and average duration and count for every square kilometer of the Northern Caspian and accounting for the significant and severe scenarios of conditions favorable for brash ice generation for the three considered persistence periods based on observations in separate ranges of 2005-2011, 2011-2017 and 2017-2022. The average values illustrate the general trend with less events propagating through the history from early observations to the latest. Note the effect of the last severe winter in the 2011-2017 range that dominates through the persistence periods that were defined and observations of other seasons in the range.

The showcase above is only one example of impact assessment that could be performed to analyze resilience of operations at any offshore activity given sufficient knowledge or data are available to compile a credible scenario. Considering general availability of data across the whole region of the Caspian, analysis can be performed for a specific location in one or several forecast zones or entirely for the whole region with the same effort.

CONCLUSIONS

This article showed continuous reduction of ice volumes generated in the Northern Caspian Sea based on observations of ice cover from 2005 to 2022 in context of increasing regional air temperature. Aggregation mechanism used to derive regional scale indexes from daily detailed ice cover classification data enables solid and traceable correlation between global warming and consequences on local scale. Sample showcases illustrate impact assessment for biodiversity and operations forming region's resilience to changing environment.

This approach to handle climate change data from regional scale global indexes combined with detailed knowledge of ice cover on local scale is a tool for data driven impact assessment. Most importantly it can be used to simulate mitigation measures performance as illustrated with navigation simulations by Kadranov, Vernyayev and Sigitov (2023).

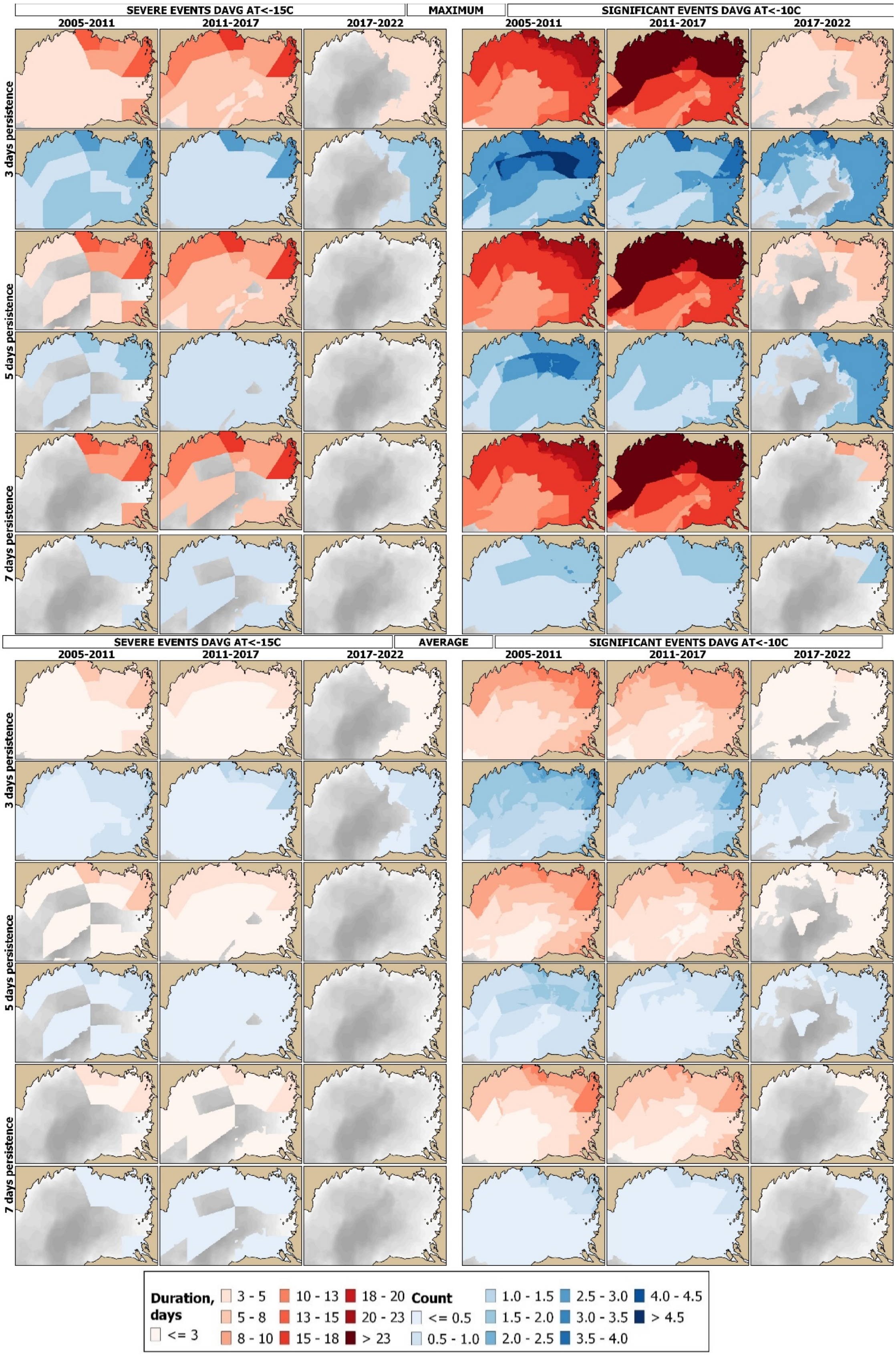

Figure 8 Maximum (top) and average duration in days and count of severe (left) and significant (right) events with favorable conditions for brash ice generation as observed over three discrete periods from 2005 to 2022 persisting for at least 3, 5 and 7 days.

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