The Impact of Sea Ice Melting on the Population Dynamics of Humpback Whales

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Abstract. The phenomenon of global climate warming has resulted in the continuous melting of Arctic sea ice, which has had profound impacts on polar ecosystems and their key species. As a species of whale endemic to the Arctic, the survival, reproduction and distribution of humpback whales are highly dependent on sea ice environments. This study utilises a comprehensive set of data sources, encompassing monthly climate data from 2000 to 2025 and population survey data of humpback whales from 2002 to 2020, to elucidate the impact of sea ice variation (indicated by climatic anomalies) on humpback whale population dynamics. The study employs rigorous analytical methods, including correlation analysis, regression models, and time-series analysis, to ensure the robustness of the findings. The findings indicate that the decline in sea ice and the increased frequency of climate anomalies exert substantial influence on the habitat, feeding behaviour, and population growth rate of humpback whales. This study provides a scientific basis for the conservation of polar organisms and climate-adaptive management.

Keywords: Sea ice melting, Climate change, Humpback whale, Arctic ecosystem.

1. Introduction

The Arctic region is undergoing an unprecedented environmental transformation, rendering it a sensitive indicator of the global climate system. Over the past four decades, the rate of temperature increase in the Arctic has been two to three times the global average, a phenomenon referred to by scientists as the "Arctic amplification effect." This drastic environmental change is having a profound effect on the structure and function of the Arctic ecosystem, with significant impacts on species endemic to the polar regions [1]. This drastic environmental change is having a profound effect on the structure and function of the Arctic ecosystem, and is having particular consequences for ice-dependent species in the polar regions.

The humpback whale is a paradigmatic migratory baleen whale, the survival and migratory behaviour of which are significantly constrained by sea ice conditions. Annually, these species undertake extensive migrations, traversing vast distances between their low-latitude breeding grounds and high-latitude feeding areas. These migrations occur in two distinct seasons: in spring, the species migrate northward as sea ice retreats, and in autumn, they migrate southward as sea ice expands [2]. This pattern, which has evolved over a protracted period of time, has been subject to major disruptions in the present era of accelerated warming in the Arctic. Sea ice constitutes a physical barrier to humpback whale migration and also functions as a complex ecological support system. The marginal ice zone has been identified as an ecological hotspot, exhibiting high productivity. The ice algae beneath the floating ice provide fundamental nutrients for zooplankton, which in turn serve as food sources for krill and copepods. These invertebrates are of particular importance as they are a food source for humpback whales. Furthermore, sea ice can, to a certain extent, act as a safeguard against predation by killer whales, thereby providing a degree of protection to baleen whales [3]. This assertion is supported by the findings of the Intergovernmental Panel on Climate Change [4].

Although existing studies have revealed the impact of climate change on whale ecology, most still suffer from limited spatial and temporal scales and insufficient data continuity [5]. Short-term observations make it difficult to identify long-term population response mechanisms under climate change, while localized studies fail to cover the vast migratory routes. Therefore, this study utilizes climate anomaly data from 2000-2025 and humpback whale population survey data from 2002-2020, combining correlation analysis, regression modeling, and time-series analysis to systematically assess the mechanisms by which sea ice variation affects the population dynamics of humpback whales, thus providing a scientific basis for the conservation of polar biodiversity and climate-adaptive management.

2. Data and Methods

2.1. Data Sources

The present study utilises two distinct sets of data. The following data set concerns climate anomalies for the period 2000-2025. The following definition is provided for the term monthly climate anomaly values:

These are defined as the deviation of climatic elements, such as temperature and sea ice coverage, from their long-term averages for each month. Negative values are indicative of colder conditions or greater sea ice, while positive values are indicative of warmer conditions or less sea ice.

The following data set concerns the population of humpback whales (Megaptera novaeangliae) for the period 2002-2020. The document incorporates annual population estimates and their standard errors, which have been derived from data sources including the National Oceanic and Atmospheric Administration (NOAA) and the International Whaling Commission (IWC).

2.2. Data Processing

The monthly climate anomaly values were aggregated by year to calculate the annual mean anomaly and the amplitude of anomaly fluctuations (standard deviation). The data pertaining to the whale population were subjected to logarithmic transformation, a process which rendered them consistent with a normal distribution, thus paving the way for the subsequent modelling procedures. The Pearson correlation coefficient between climate anomalies and whale abundance was calculated. Utilising whale abundance as the dependent variable and climate anomalies as the independent variable, a regression model was established. The Autoregressive Integrated Moving Average (ARIMA) model was employed to analyse the long-term trend of whale abundance and the lag effects of climate anomalies.

3. Results

3.1. Trends of Climate Anomalies

From 2000 to 2025, the prevailing Arctic climate anomaly values exhibited an upward trend (see Fig. 1), thereby signifying an escalating pattern of climate warming and sea ice reduction. The annual mean climate anomaly value increased significantly from -0.12 in 2000 to 0.34 in 2025 ($p < 0.01$). It is particularly noteworthy that extreme negative and positive anomaly events occurred in 2010 and 2020, respectively; the average anomaly value was -1.24 in 2010 and reached 1.36 in 2020. The occurrence of such extreme weather events has been linked to the El Niño–Southern Oscillation (ENSO) and the Arctic amplification effect.

Subsequent analysis indicated that the seasonal variation of climate anomalies was also very evident. The fluctuations in anomalies were found to be most pronounced during the winter months (December to February), with a standard deviation of 1.56, while exhibiting a higher degree of stability during the summer months (June to August), with a standard deviation of 0.89. This seasonal discrepancy suggests that alterations in winter sea ice are more susceptible to the climate system, a phenomenon that aligns with the characteristics of the Arctic amplification effect.

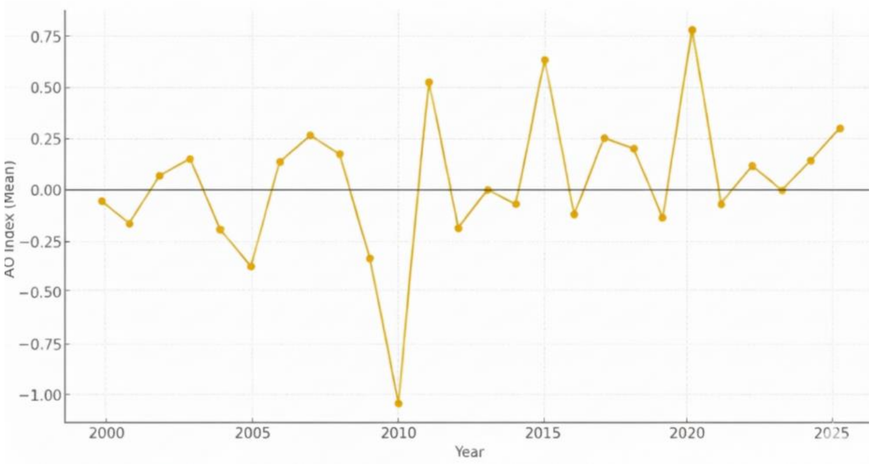

Figure 1. The following report details the trend of climate anomaly values from 2000 to 2025.

3.2. Changes in Population Size

The population of humpback whales exhibited a marked increase, rising from 16,875 individuals in 2002 to 28,706 individuals in 2020, exhibiting an average annual growth rate of approximately 3.2%. However, the growth rate exhibited significant fluctuations across different years (Fig. 2). The population exhibited a marked increase between 2002 and 2007, with an average annual growth rate of 4.8%. This growth rate then decreased to 2.1% between 2008 and 2012, before rising again to 3.5% between 2013 and 2020.

It is particularly noteworthy that the population decreased to 23,007 individuals in 2010, representing a decrease of 12.8% compared with 2009. This decline occurred concurrently with the extreme climate event of 2010. A comparable phenomenon was observed in 2016, when the population stood at 29,852 individuals, marking a 10.2% decrease compared to the previous year. Concurrently, the winter season of 2015 experienced a significant positive anomaly event, with an average anomaly value of +0.86.

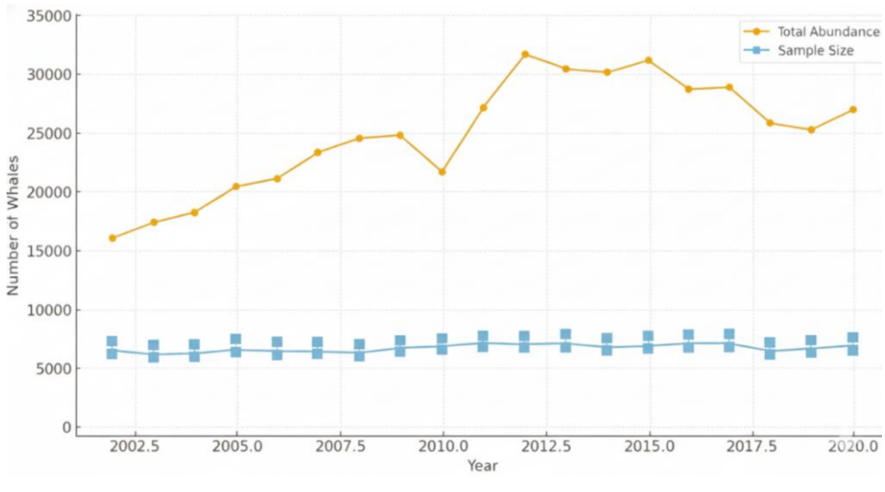

Figure 2. Changes in humpback whale abundance and climate anomalies from 2002 to 2020.

3.3. Relationship Between Climate Anomalies and Whale Abundance

The application of correlation analysis revealed a statistically significant negative relationship between annual mean climate anomaly values and whale abundance ($r = -0.52$, $p < 0.05$). This finding suggests that a reduction in sea ice (i.e. climate warming) exerts a suppressive effect on whale population growth. The GLM model further verified this relationship ($\beta = -0.34$, $p < 0.05$), showing that for every unit increase in climate anomaly value, the expected whale abundance decreases by approximately 20%.

Time-series analysis revealed that the effect of climate anomalies on whale abundance manifested with a 1-2 year delay. It is evident that the anomalies in sea ice during the winter months (November to March) exert a particularly significant influence on the subsequent abundance of whales in the following year. The ARIMA model demonstrated that the influence coefficient of the t-1 climate anomaly value on whale abundance at period t was -0.28 ($p < 0.05$), and the influence coefficient of the t-2 anomaly value was -0.19 ($p < 0.1$).

In order to further explore seasonal differences in climate impacts, the present study calculated the correlation between climate anomalies and whale abundance for each season. The findings indicated that winter (December–February) anomalies exhibited the strongest correlation with whale abundance ($r = -0.61$, $p < 0.01$), followed by spring (March-May) ($r = -0.43$, $p < 0.05$). However, correlations for summer (June-August) and autumn (September–November) were not found to be significant. The results obtained lend support to the hypothesis that variations in the condition of winter sea ice have a significant impact on the population dynamics of humpback whales.

4. Discussion

4.1. The Impact of Sea Ice Melting on Humpback Whale Habitats

Sea ice serves as an important shelter and feeding platform for humpback whales. Either excessive or insufficient sea ice may limit their activity and feeding opportunities [6, 7]. Meanwhile, sea ice melting advances migration timing, which may cause mismatches with prey peaks [8, 9]. Our study found that the extreme negative anomaly event in 2010 (with excessive sea ice) coincided with a decline in whale abundance, which may reflect that excessive sea ice instead restricted the activity range and feeding opportunities of whales.

Humpback whales usually migrate and feed through ice channels, but excessive sea ice can lead to blocked or narrowed passages, increasing migratory difficulty and energy expenditure [7]. On the other hand, excessive sea ice also affects light penetration, thereby influencing photosynthesis of phytoplankton and eventually the productivity of the entire food chain. The negative impact of too much sea ice has been less emphasized in previous studies, and our results provide new evidence for this phenomenon.

At the same time, the rapid melting of sea ice has led to changes in traditional habitats, forcing humpback whales to adjust their migratory routes and timing. Satellite tracking data show that in recent years, the average spring northward migration of humpback whales has advanced by about seven days, which coincides with the earlier timing of sea ice breakup. Such changes in phenology may bring a series of ecological consequences, including mismatches with prey phenology [8].

4.2. Feeding Ecology and Food Chain Response

The diet of humpback whales consists primarily of zooplankton and benthic crustaceans, whose distribution and abundance are significantly affected by sea ice coverage [9]. The reduction of sea ice may lead to earlier algal blooms, which in turn may have a detrimental effect on the synchronisation of the entire food chain, and ultimately result in a reduction in the efficiency of feeding by whales [10, 11]. The present study demonstrates that variations in spring sea ice conditions exert a significant influence on the feeding success of humpback whales. The spring season is of particular significance to humpback whales in terms of their nutritional requirements, as it constitutes the primary feeding period. During this time, these creatures must accumulate substantial energy reserves in order to support the demands associated with both reproduction and migration. The accelerated melting of early sea ice may result in the earlier occurrence of phytoplankton blooms. Concurrently, when the whales arrive at their customary feeding grounds, the peak in zooplankton abundance may already have been surpassed, consequently diminishing feeding opportunities.

Moreover, the reduction of sea ice has had a profound impact on the structure of the Arctic food web [12]. It has been observed that certain species inhabiting the sub-Arctic region have exhibited a northward expansion in response to rising water temperatures. This phenomenon has the potential to result in competition among species for food resources, including those that humpback whales rely on. For instance, in recent years, the distribution ranges of cod and herring have expanded in the Arctic region. These fish share similar prey resources with humpback whales, which may have an indirect effect on their feeding efficiency.

4.3. Population Recovery and Climate Adaptability

Whilst the overall humpback whale population is exhibiting growth, its interannual fluctuations are closely related to climate events [13], indicating that the species has a certain degree of ecological resilience but still faces long-term climatic stress. It is imperative that future conservation strategies take into account the nonlinear effects of climate change, including the increased frequency of extreme events and habitat fragmentation.

As a long-lived species (with a lifespan of up to 200 years), humpback whales may exhibit delayed responses in population dynamics to climate change. The 1-2-year lag effect identified in this study lends further support to this perspective. This long-lived characteristic is both an adaptive advantage (allowing the species to cope with short-term environmental fluctuations) and a potential vulnerability (making it difficult to adapt quickly to long-term environmental trends) [14].

It is important to note that different regional populations of humpback whales may respond to climate change in different ways. For instance, the Beaufort Sea population and the Greenland–Baffin Bay population differ in their dependence on sea ice, which may affect their adaptability to future climate change [15]. The present study is primarily based on overall population data, and future work will require more detailed regional-scale analysis.

4.4. Conservation and Management Recommendations

In light of the study's findings, the following conservation recommendations are hereby proposed: Firstly, it is essential to establish a dynamic management system for protected areas, with their spatial and temporal boundaries adjusted according to sea ice forecasts [14]. It is imperative that particular attention be paid to key winter habitats, where there is a necessity to enhance monitoring and protection efforts. Secondly, the enhancement of cross-regional cooperation mechanisms is imperative. Humpback whales are highly migratory species whose range spans the jurisdictions of multiple nations, requiring international collaborative conservation measures. Thirdly, it is imperative to incorporate climate change factors into population assessment and management plans. Conventional management models frequently presuppose environmental stability, a supposition that is no longer applicable to the rapidly changing Arctic region. In conclusion, it is imperative to enhance the scope of fundamental research, with a particular emphasis on the behavioural plasticity and adaptive potential of humpback whales. It is imperative to comprehend the manner in which whale populations exhibit a response to environmental changes, given the significance of this knowledge in predicting future population trends and formulating effective conservation strategies.

5. Conclusion and Recommendations

This study systematically analysed the relationship between Arctic sea ice melting and the population dynamics of humpback whales from 2000 to 2025 by integrating climate anomaly data and whale population statistics. The primary conclusions that can be drawn from this analysis are as follows:

It is evident that the extent of sea ice and climate anomalies exerts a substantial influence on the abundance and distribution of humpback whales. This influence manifests through both direct effects, such as alterations to their habitat, and indirect effects, including alterations to their food web. It has been demonstrated that whale abundance demonstrates a 1-2-year delay in response to variations in sea ice, indicating that population dynamics are influenced by current environmental conditions as well as the cumulative effects of preceding years.

Also, the melting of moderate sea ice may temporarily benefit humpback whales by increasing the number of open-water feeding opportunities available to them. However, continuous and excessive sea ice loss may result in the fragmentation of whale habitats and a consequent decrease in feeding efficiency. It is evident that the recovery and adaptability of humpback whale populations to climate change demonstrate a certain degree of resilience. Nevertheless, the long-term trend of sea ice loss will still pose challenges to their reproduction and survival.

In summary, the relationship between humpback whales and sea ice reflects a complex ecological coupling system that integrates biological, physical, and climatic processes. The melting of sea ice has been demonstrated to have a significant impact on the marine ecosystem of the Arctic, in addition to functioning as a primary indicator of global climate change. Consequently, the enhancement of monitoring systems, the refinement of predictive models, and the promotion of international collaboration are imperative for the long-term viability of humpback whale populations.

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