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**Social-ecological systems on walleye pollock under changing environment: Inter-disciplinary approach**

# Walleye pollock: global overview

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**Abstract** Walleye pollock is the second most extensively fished species in the world. The major fishing grounds include the Bering and Okhotsk Seas. Large-scale fishing started in the 1960s and continues to date with average annual landings over this 50-year period of 1.5 million tons. Yet over this period catches were characterized by considerable volatility. This volatility makes rational management of stock and planning of annual fishing activities difficult. The changes in annual catches correlate with the changes in the biomass of walleye pollock. Existing data suggest a close link between climate change in the northern Pacific and biomass, which allows quantitative estimates of future trends in the biomass, and consequently annual catch, of walleye pollock. Cooling of the northern Pacific is expected to increase the biomass in the Sea of Japan and decrease it in the Bering Sea and Sea of Okhotsk. The opposite is predicted to occur if the northern Pacific experiences warming.

**Keywords** Walleye pollock · Biomass · Fishery · Temperature · Climate

## Introduction

For 40 years walleye pollock *Theragra chalcogramma* has been one of the leading fishery targets in the world. The history of large-scale fishing dates back to the early 1960s, with the first large-scale fishery being located in the eastern Bering Sea. The historical maximum catch of walleye pollock was observed in the late 1980s, when it reached about 7.0 million tons, which made walleye pollock the most intensively fished species in the world. From 2000 to 2009 according to the FAO [1] the global catches have decreased substantially relative to the 1980s, amounting to an average of about 2.8 million tons. Despite this fact, over the last 10 years walleye pollock has consistently ranked as the second most fished species worldwide. Currently, fishing, processing and marketing of walleye pollock is a major contributor to the economic activity in numerous countries (mainly Russia, USA, Japan, Korea, China, the European Union), making the ability to forecast catches exceedingly important. Such predictions require fundamental understanding of the reasons for the volatility of walleye pollock stocks.

In the early 1970s Japanese fishermen were the undisputed leaders in catches of walleye pollock, landing over 3.0 million tons annually. Between 1990 and 2011 the Japanese catch declined further from 900,000 to 200,000 tons (Fig. 1). In the 1980s and 1990s the leader in catches of walleye pollock was the Soviet Union, and then Russia, with the historic maximum of 3.6 million tons reached in 1986. Subsequently, the annual catch steady declined to a minimum of 820,000 tons in 2002 before recovering to 1.6 million tons between 2010 and 2012.

### The Bering Sea

Immediately after World War II the Japanese fished for walleye pollock in the Bering Sea, but the catches were

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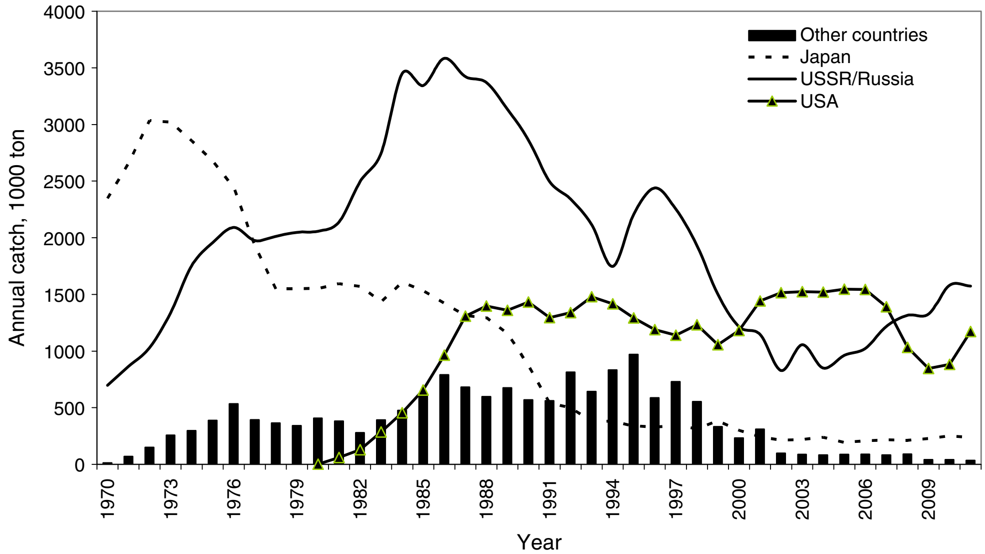


**Fig. 1** The annual catch of walleye pollock by country for 1970–2011, in metric tons. Landings varied considerably in all commercial fishing grounds

small. Soviet fishermen, while developing commercial fishing in the eastern Bering Sea in the late 1950s to early 1960s did not observe any significant concentrations of walleye pollock: their catches were dominated by flounders, herring, cod, pacific halibut and rockfishes. Soviet research based on field data showed [2] that the early 1960s saw a sharp (10-fold or more) increase in walleye pollock by catch, which indirectly indicated a sharp increase in the biomass. Data are scarce but appear to suggest that this increase did not extend to the 1970s.

Yet reliable data indicate a sharp growth in the biomass of walleye pollock near Bogosloff Island in the 1980s, when the biomass grew to 12,800,000 tons [3], and subsequently drastically decreased 42-fold to 300,000 tons. These large fluctuations are unlikely to be related to fishing, since a moratorium on fishing for walleye pollock over the past 20 years has not increased the size of its biomass. During 1965–2012 the average annual catches of walleye pollock in the eastern Bering Sea was about 1,151,000 tons. Over the same period the average annual catches in the secondary (Navarin area) and tertiary (Donut hole, international waters in the middle of the Bering Sea) fishing grounds were 391,000 and 222,000 tons, respectively. However, large-scale fishing in the international waters in the middle of the Bering Sea was only practiced between 1984 and 1991. The western part of the Bering Sea has historically played a small role, with the maximum annual catches never exceeding 400,000 tons (Fig. 2).

The total annual catch of Bering Sea walleye pollock reached a maximum of 4 million tons in 1988, and it came a few years after the biomass of walleye pollock peaked at 30 million tons (Fig. 3). The decline of the stocks and the catches between 1988 and 1991 was synchronous and probably associated with large-scale unregulated fishing for walleye pollock in the international waters in the middle of the Bering Sea. However, over the whole period of 1979–1992, the correlation between the annual catch and biomass was weak ($r = 0.23$). The strong correlation thereafter (0.89) attests to the success of stock management resulting from ratification, in 1993, of the "Convention on the conservation and management of pollock resources in the central Bering Sea", which stopped unregulated fishing in the international waters in the middle of the Bering Sea.

## Sea of Okhotsk

Walleye pollock is the most valuable fish species in the Sea of Okhotsk. The Russian pollock fishery started in the 1960s and the first considerable landings (35,000 tons) occurred in 1962 [4]. The large-scale exploitation of walleye pollock resources began in 1965, when the landings totaled 293,000 tons and subsequently increased to an impressive 675,000 tons in 1968. The first historic maximum occurred in 1975 when 1.3 million tons of walleye pollock was landed. In those years the fishery was exclusively concentrated in the eastern part of the Sea of Okhotsk, off the western Kamchatka. Then landings started to decrease, reaching a low of 482,000 tons in 1981. The second period of large catches (>1.5 million tons) occurred between 1988 and 1998 (Fig. 4). The discovery of a new fishing ground in the northern part of the Sea of Okhotsk

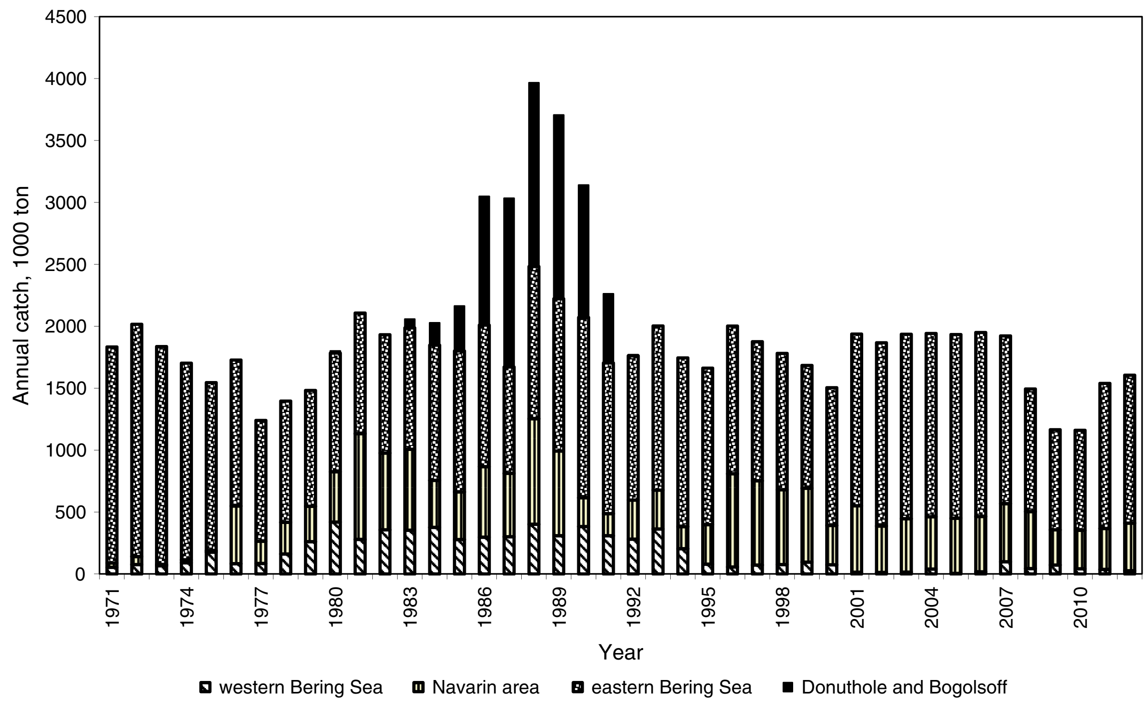


**Fig. 2** The annual catch of walleye pollock by region in the Bering Sea for 1965–2012, in metric tons

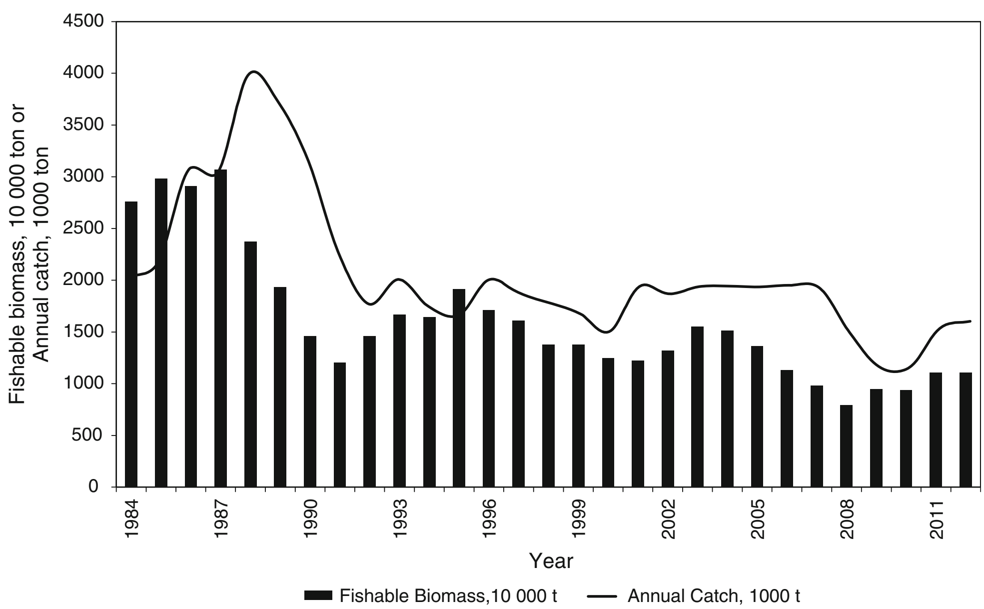


**Fig. 3** Walleye pollock biomass dynamics (*bars*, in ten metric tons) and annual catch in the Bering Sea (*line*, in metric tons) for 1979–2012

contributed to this growth. These successful years were followed by another period of low landings with a minimum of 178,000 tons in 2007. The subsequent years saw a significant increase in landings (up to 381,000 tons).

The walleye pollock fishery in the open part of the Sea of Okhotsk known and described as "peanut hole" is much younger than in the other fishing grounds. The first information on the walleye pollock catches taken by foreign fishing vessels in this area appeared in the late 1980s, when large-scale unregulated fishing for walleye pollock was carried out in the open part of the Bering Sea (donut hole). The walleye pollock fishery continued in the peanut hole between 1991 and 1994 and produced a maximum of 698,000 tons annually.

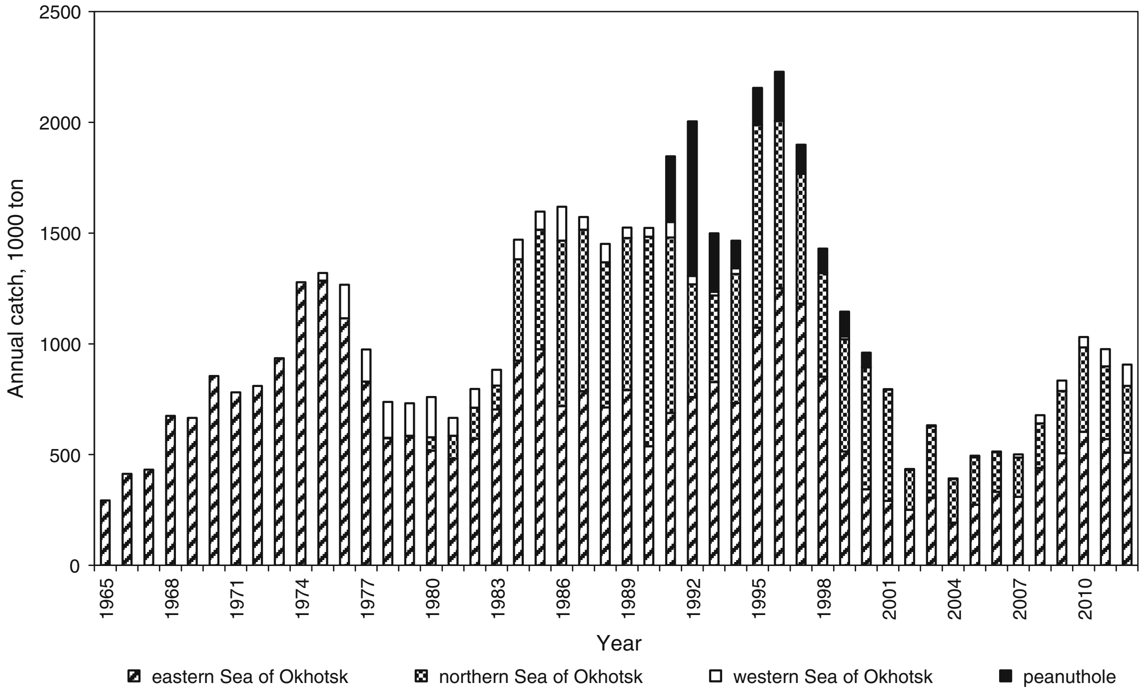


**Fig. 4** The annual catch of walleye pollock by region in the Sea of Okhotsk, 1965–2011, in metric tons

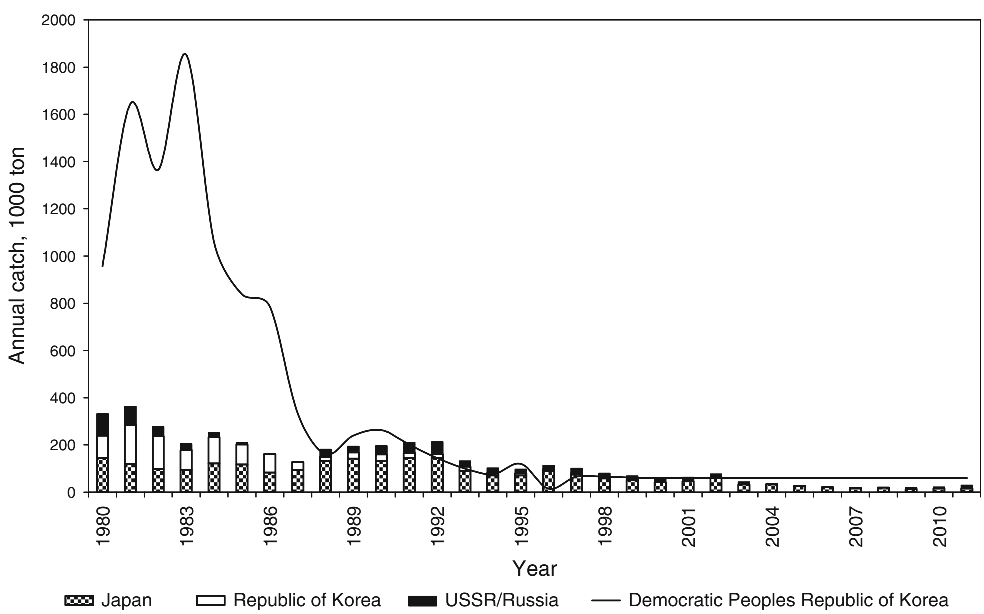


**Fig. 5** The annual catch of walleye pollock in the Sea of Japan by country for 1980–2010, in metric tons

## The Sea of Japan

While the main fishing grounds of the last three decades have been located in the Bering and Okhotsk Seas, the statistics from the fishery for walleye pollock in the Sea of Japan suggests that this area may have also played a significant role until the early 1980s [4]. Analysis of the fishery data suggests that in 1981 and 1983 the total catch of walleye pollock in the Sea of Japan exceeded 2.0 million tons (Fig. 5). Today these numbers may defy belief, but the maximum catches may have been even greater. The question, therefore, is why has the Sea of Japan lost almost all its commercial importance since the mid 1990s?

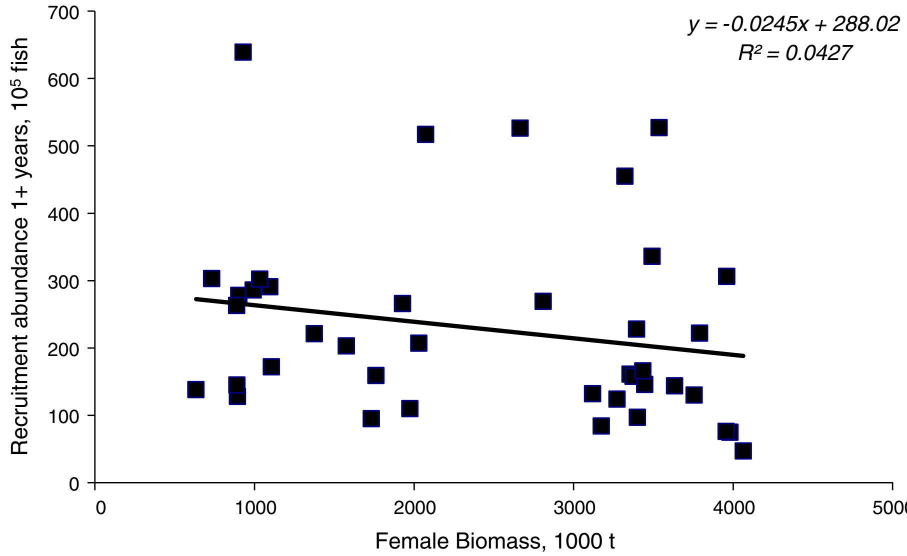


**Fig. 6** Relationship between the female biomass of walleye pollock and recruitment abundance in eastern Bering Sea (data from Ianelli et al. [3])

In summary, despite rational management of the walleye pollock stocks in the northern Pacific, the history of walleye pollock fisheries shows a considerable inter annual variability in the yield, which introduces large uncertainty in planning and managing of these fisheries.

The dynamics of walleye pollock stocks may depend on recruitment abundance. After spawning, eggs, and then the larvae of walleye pollock, develop in the surface layers of water, therefore the water temperature and food availability are very important factors determining its recruitment abundance. Subsequently, yearlings transition to a bottom-dwelling lifestyle, where they spend a year or more. The rest of their lives are spent primarily in the middle layers.

The initial number of spawning fish, the temperature at which development occurs, and the availability of food all determine the strength of a generation. In the Gulf of Alaska, abundance of walleye pollock depends on rainfall, sea-level pressure and wind [5]. In the Bering Sea, water and air temperature, as well as the ice cover play important roles in determining recruitment [6]. Hunt et al. [7] identified ice cover and temperature at the time of hatching (which determine the early feeding conditions), stratification over the shelf during the first summer, and the abundance and distribution of potential predators as the factors that determine generation strength. In the Sea of Okhotsk, Pacific decadal oscillation (PDO) influences the dynamics of walleye pollock stocks [8]. Along the Japanese coasts, the Oyashio current is thought to be important [9]. In addition, walleye pollock recruitment in the Sea of Japan correlates with temperature [10]. Recent studies have revealed a potential impact of climate on walleye pollock stocks in the Bering Sea [11]. In other words, at present numerous factors have been shown to affect the abundance of walleye pollock recruitment. This review attempts to identify the most important of these factors.

## Temperature and recruitment

There is no consensus as to which factors are the primary determinants of generation strength and alter the biomass size. Some believe that recruitment abundance is formed by the spawning stock [12]. However, accumulated evidence suggests a lack of correlation ($r = 0.05$) between recruitment abundance and female biomass, the so-called Ricker's curve [14], at least for eastern Bering Sea walleye pollock (Fig. 6).

Others are inclined to believe that an essential element in determining the success of a generation is the environment [6–11, 13]. It's commonly found that cold years yield weak generations of walleye pollock and warm years lead to high abundance. Yet others found that especially warm years with early ice retreat appear to favor survival of fish at early life stages [7], but excessively warm temperatures in the autumn result in poor overwinter survival, yielding a dome-shaped relationship between walleye pollock survival and surface temperature. It is clear that water temperature has a significant impact on larval growth rates [15, 16], probably because warm years increase the survival of eggs and larvae, increase food availability, and accelerate metabolism, which ultimately increases the biomass. For example, our data from the south-eastern Bering Sea between 1965 and 1984 show strong correlation ($r = 0.75$) between the abundance of 5-year-old fish and the average water temperature 1 year before spawning (Fig. 7). Although the spawning biomass is important for formation of year class strength at a low stock level, as

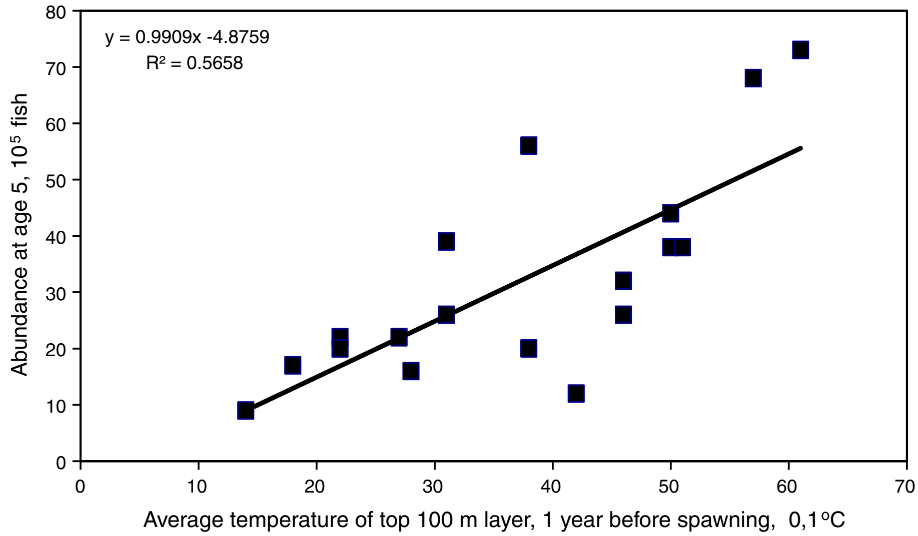


**Fig. 7** The relationship between the abundance of walleye pollock at age 5 and the average temperature of the top 100 m at 1 year before spawning for 1965–1984

shown in the Bering Sea, water temperature is a more important factor. This conclusion is based on the results of correlation analysis, which showed no statistically significant relationship between walleye pollock spawning biomass and recruitment abundance ($r = 0.05$), while the correlation coefficient between recruitment abundance and water temperature was 0.75.

## The effect of the Pacific decadal oscillation on the biomass of walleye pollock

Water temperatures, air temperatures, and currents are local abiotic factors which operate on a scale of tens to hundreds of thousands of square kilometers. Global climate affects enormous areas of the ocean, extending over millions of square kilometers (e.g., northern Pacific). The best known global climate indices are the North Pacific Index (NPI) and PDO. A central question is the relationship between such indices and the biomass of walleye pollock. For example, Kobari et al. [17] found a correlation ($r = 0.636$) between the 10-year running mean of standardized anomalies for phosphate and NPI; the duration of spring bloom is also positively correlated with NPI anomalies ($r = 0.777$). Seasonal weakening of the Aleutian Low Pressure System estimated from NPI correlates positively with the phosphate concentrations at the sea surface, spring-summer abundance of young copepods and their persistence at high abundance. Likewise, biomass of walleye pollock in the Sea of Okhotsk correlates positively ($r = 0.63$) with PDO. Yet it remains unknown whether the same correlation exists for walleye pollock in other fishing grounds. Reliable identification of correlations between PDO and walleye pollock abundance requires uniform application of methodologies for estimating the biomass of the stocks.

Yet, historically, assessment of the biomass of walleye pollock has been derived from different methods, including trawl and acoustic [18], ichthyoplankton and trawl surveys, and an analytical approach [19]. Currently, the analytical approach is favored, based on data from fisheries statistics, including CAGEAN [20], virtual-population analysis (VPA), cohort analysis, etc. US scientists [19, 21] use these approaches for walleye pollock stock assessment in the Gulf of Alaska and eastern Bering Sea. Russian scientists rely on the model SYNTHESIS to get data on commercial stocks of walleye pollock in the Navarin area, western Bering Sea and the Sea of Okhotsk. This uniform approach enabled us to compare these stock assessments with the PDO data from http://jisao.washington.edu. The total biomass of stocks of walleye pollock in the Gulf of Alaska, Bering and Okhotsk Seas correlate strongly with PDO anomalies ($r = 0.73$), corresponding to a decrease of walleye pollock stocks by 25 million tons over the past 25 years, or 1 million tons annually (Fig. 8).

## Summary

In conclusion, I want to note the following trends. Warming of the northern Pacific in the 1980s led to an increase in the concentration of phosphates; phytoplankton blooms; large populations of *Eucalanus,* which is the primary component of the walleye pollock diet at early life stages; and a longer presence of copepods in plankton. These factors create optimal conditions for rapid growth of yearlings and strong generations. What do these data suggest about future trends in walleye pollock biomass? An accurate answer to this question is hardly possible, but a

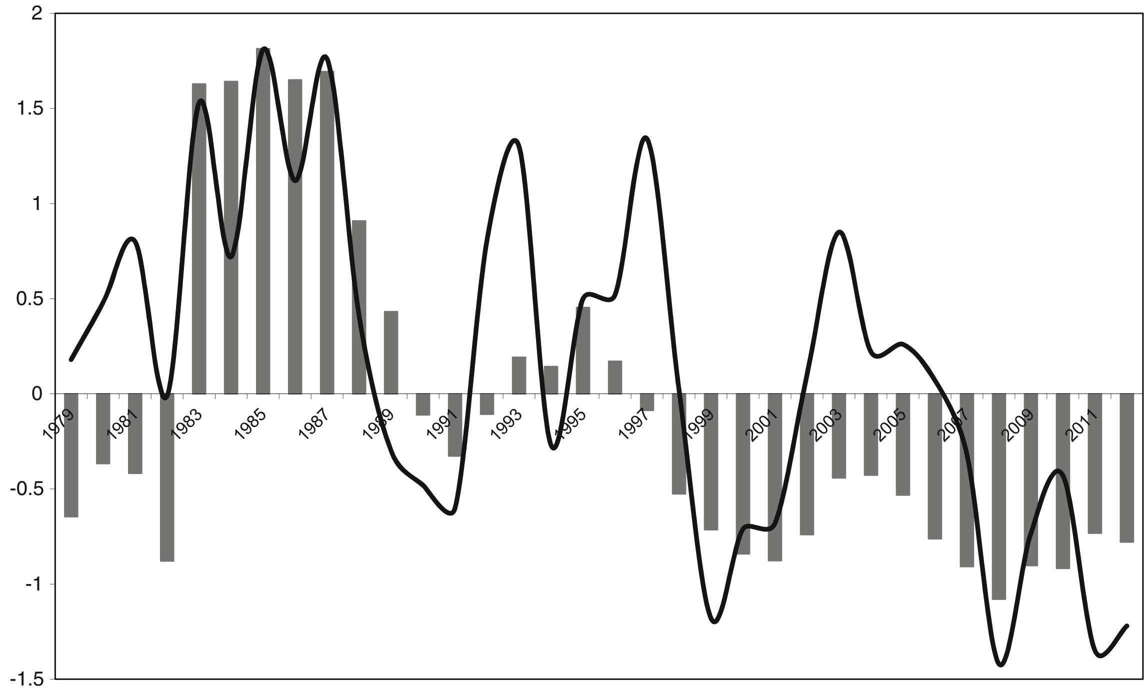


**Fig. 8** Pacific decadal oscillation (*line*) and walleye pollock biomass in the North Pacific (*bars*, 10 million tons) for 1979–2012

working hypothesis could be formulated based on the following relationships. Climatologists consider two future trends: broad global warming (IPCC) or cooling of northern Pacific and Atlantic oceans. In case of global warming an increase in the biomass of walleye pollock in the northern parts of its distribution, i.e., Bering and Okhotsk Seas, is expected, whereas the stocks in the southern parts, i.e., the Sea of Japan and the Pacific coast of Japan, would decrease. This scenario is supported by the historic data observed after the *climate shift,* which occurred from the end of the 1970s to the end of the 20th century.

Russian scientists from the Institute of the Arctic and Antarctic [22] found a 60-year cycle of temperature variation in the Arctic. The so-called Arctic warming was observed in the 1930s and 1940s, followed by another cooling between 1950 and 1960. The maximum of the subsequent warming cycle was observed in 2000 and since then the trend has reversed, leading us to expect that the Arctic will experience long-term average temperatures in 2015, and the years 2020–2035 will be characterized by cooler than normal temperatures.

Consequently, if this Arctic cooling resumes soon, it would lead to a decrease of biomass of the northern stocks of walleye pollock, since abundant generations are associated with a specific optimal temperature. Therefore, the optimal conditions for walleye pollock recruitment will be off the coast of Japan and in the Sea of Japan, leading to abundant generations in these areas. In contrast, the Gulf of Alaska, Bering Sea (with the exception of the south-eastern part) and Sea of Okhotsk (with the exception of the south-eastern part) would experience a significant decrease in walleye pollock stocks after 2020.

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