The Arctic Sea Ice Ecosystem and Global Warming

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Introduction

The Arctic Ocean is a major component of the world's atmosphere-ocean system and within this ocean, sea ice is the dominant environmental feature. This several-meter-thick sea ice cover affects the magnitude of both heat and matter fluxes from the atmosphere and upper ocean and supports a unique and tightly coupled biological community – the Arctic sea ice ecosystem (Melnikov 1997).

A peculiar feature of the sea ice cover in the Arctic Ocean is the presence of permanent ice remaining after summer ice melting, as well as the seasonal ice that is formed on the surface of the Arctic Seas mainly in winter. The area of the sea ice cover at the time of its maximum development is formed by the areas of the deep Arctic Basin (4.47 million km^2) and areas of the shallow Arctic Seas (3.96 million km^2) for a total of 8.43 million km^2 (Gorshkov 1980). The annual cycle of sea ice formation, consolidation, and ablation is a fundamental process in the Arctic Ocean, significantly enhancing the degree of ecological variability as well as overall productivity (Legendre *et al.* 1992). Because sea ice is a physical layer dividing two environments different in thermal capacity – the atmospheric air and the ocean water – there is a sharp gradient between the environmental factors affecting its top and bottom surfaces. As a consequence of thermodynamic processes of melting and freezing, the ice continually modifies its thickness: growth from below during winter may be considered necessary to restore the ice layers lost as a result of summer melting. The sum of these processes and their seasonality is the homeostasis of the ecosystem supporting the equilibrium ice thickness (Zubov 1945).

Observations carried out in the early 1970s have shown that in spite of interannual variability in environmental factors, the time-scale characteristics, physical structure, chemical compounds, and species composition of the sea ice cover were stable within the vertical thickness of ice and within the geographical scale of the Arctic Ocean. These facts have allowed us to consider the sea ice cover as an integral and stable ecological system (Melnikov 1980, 1997).

Warming of the Arctic Ocean during the last decade is a phenomenon that has been the subject of wide discussion in the literature. Many general models predict a greenhouse-gas-induced warming in polar regions associated with a warming of the upper ocean and a substantial retreat of sea ice cover (*e.g.*, Walsh 1991, McPhee *et al.* 1998, Johannessen *et al.* 1995, 1999, Vinnikov *et al.* 1999). As a physical layer between warm air and warm upper ocean water, sea ice changes its thickness due to melting from both its top and bottom surfaces. Modern observations in the high Arctic have shown dramatic changes both in environmental factors and in the composition, structure, and dynamics of ice-associated biological communities in the Arctic Ocean. What changes do we really observe in the modern Arctic Ocean and how do these variations change the biological and geochemical characteristics of the sea ice cover?

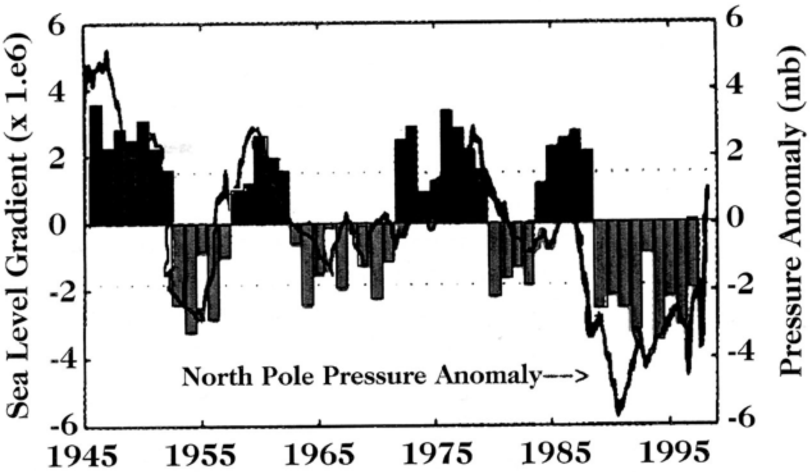


FIGURE 1. FROM 1946 TO 1997, FOUR ANTICYCLONIC AND FOUR CYCLONIC REGIMES TRACK THE ARCTIC OCEAN OSCILLATION. RECENT SLP DATA SUGGEST THAT THE OCEAN-ATMOSPHERE SYSTEM WILL SHIFT TO AN ANTICYCLONIC STATE (JOHNSON *ET AL.* 1999).

From 1975-1981, the Soviet Ice Station "North Pole-22" (NP-22) drifted within the Beaufort Gyre in the Canadian Basin of the Arctic Ocean. From October 1997 to October 1998, the U.S. National Science Foundation conducted the round-year experiment SHEBA (**S**urface **HE**at **B**udget of the **A**rctic Ocean), supported by the Canadian Coast Guard icebreaker *Des Groseilliers* (Perovich *et al.* 1999). The drift of the Ice Station SHEBA was in the same area where the NP-22 had drifted two decades before. During the NP-22 and SHEBA drifts, multi-disciplinary studies of the sea ice/water system were carried out, including micro-scale sea ice observations and observations at the ice/water interface (Melnikov 1997, Sherr *et al.* in press). This workshop presents an opportunity to show preliminary data related to the questions of global change in the Arctic Ocean.

Changes in the Arctic Ocean

Ocean-atmosphere system oscillation

There is evidence that atmospheric circulation is changing, including a reduction in surface level pressure (SLP) over the Central Arctic Ocean. From 1946 to 1997, four anticyclonic and four cyclonic regimes track the SLP oscillation (Figure 1). Proshutinsky and Johnson (1997) identified anticyclonic wind-driven ice and surface water motion in the central Arctic for the periods 1946-1952, 1958-1962, 1972-1979, 1984-1988, and cyclonic motion for the periods 1953-1957, 1963-1971, 1980-1983, and 1989-1997. Recent SLP data suggest that the ocean-atmosphere system will again shift, or has already shifted, to an anticyclonic state (Johnson *et al.* 1999). The results of recent research on arctic climate oscillatory behavior show a standing SLP oscillation over much of the northern hemisphere associated with a sea ice anomaly propagating anticyclonic (clockwise) circulation around the Arctic Ocean (Mysak and Venegas 1998) and forcing upper ocean and ice circulation (Carmack *et al.* 1995, Morison *et al.* 1998) and river discharge (Johnson *et al.* 1999).

Water masses

Hydrographic data gathered during the last decade (icebreaker transects in 1990-1994, SCICEX cruises in 1993-1997) have supplied intriguing evidence that Atlantic Water flowing into the Arctic Ocean has warmed relative to previous years and has increased in volume by about 20% (Carmack *et al.* 1995, Morison *et al.* 1998). Warming relative to historical data was observed, as well as freshening of the upper ocean. A warm core of Atlantic Water with temperatures of 0.5^{o} to 1.7^{o}C was observed above the Lomonosov Ridge, and another less apparent warm core with a temperature of 1^{o}C existed over the Mendeleev Ridge. According to Carmack *et al.* (1995) and Morison *et al.* (1998), these data indicate a fundamental change in the circulation of the Arctic Ocean since the early 1990s. Changes were occurring at different depths and locations for different variables. Pacific Water transport since 1940 to 1998 also showed a remarkable trend in decreasing inflow through the Bering Strait (Coachman and Aagaard 1988).

Ice extent

Field and satellite-based observations show a rapid decrease in Arctic Ocean sea ice extent over the past 46 years (Cavalieri *et al.* 1999, Johannessen *et al.* 1999, Vinnikov *et al.* 1999). Satellite observations indicate a decrease in the area of ice extent of nearly 3% per decade since the late 1970s, accelerating in this decade (Cavalieri *et al.* 1999). Johannessen *et al.* (1995) reported a reduction of the annual mean ice cover of the Arctic Ocean between 1978 and 1994. Using satellite-derived ice maps, they estimated a decrease of the total sea ice extent of 0.05 x 10^6 km^2/yr, of which 14% is due to a reduction of the area of multiyear ice. Reduction of sea ice cover is very noticeable in the Amerasian basin of the Arctic Ocean. Ten-year mean concentrations of the permanent sea ice cover following summer minimum ice area were remarkably lower and, conversely, the area of ice-free ocean (mainly in Chukchi and Beaufort Seas) was two to three times greater (Figure 2). As a reflection of the decrease in the surface area of permanent sea ice, the ice edge has migrated northward; e.g., the position of the ice edge in the Beaufort Sea in autumn 1998 was farther north than its historical mean autumn position (Figure 2).

Ice thickness

Rothrock *et al.* (1999) compared sea ice thickness data acquired by the Scientific Ice Expedition (SCICEX) in the mid-1990s with data from 1958 and 1976, finding a mean decrease of 1.3 m (around 40%) in ice thickness over the deep Arctic Ocean with greater decreases in the eastern and central Arctic than in the western Arctic. Data on reduced concentrations and thickness of perennial ice in different parts of the Arctic Ocean since 1970s were based on indications from subma-

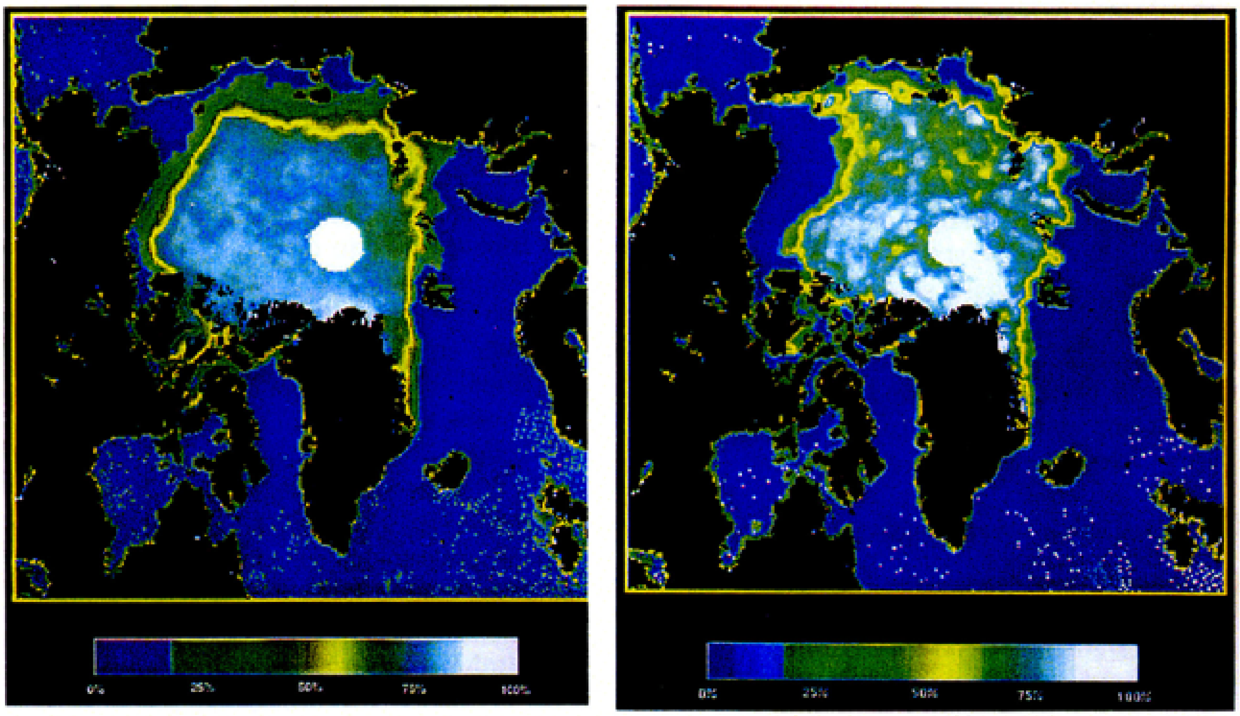


FIGURE 2. TEN-YEAR MEAN CONCENTRATIONS OF SEA ICE ON SEPTEMBER 30 AS OBTAINED FROM SATELLITE PASSIVE MICROWAVE MEASUREMENTS (LEFT) AND SEA ICE CONCENTRATIONS ON SEPTEMBER 30, 1998 (RIGHT). ICE CONCENTRATION RANGES FROM 0% (BLUE) TO 100% (WHITE). SSMI DIGITAL IMAGES COURTESY OF W. CHAPMAN, NASA NATIONAL SNOW AND ICE DATA CENTER.

rine sonar. However, it remains unknown whether the nature of the perennial ice pack as a whole has changed. Perennial multiyear (MY) ice is approximately three times thicker than seasonal or first year (FY) ice, so that changes in ice type and distribution could both reflect and effect climate change in the Arctic Ocean. So, these data need to be supported by field studies to make time-series measurements of the thickness of all types of ice.

TABLE 1. Mean sea ice thickness in the Arctic Ocean for the period 1970-1998

Ice thickness (cm)	Type of Ice	Region	Year	Author
334 593	*MY, non-deformed* *MY, deformed Deformed*	East-Siberian Sea	1967	Busuev (1968)
370 430	*MY, non-deformed* *MY, non-deformed*	Eurasian sub-basin Amerasian sub-basin	1969	Koerner (1973)
390-510	*MY*	Mean for the Arctic Ocean	1981	Wadhams (1981)
140-210	*MY, non-deformed*	Amerasian sub-basin	1997-1998	SHEBA, 1997-1998 personal data

Mean sea ice thickness values of non-deformed and deformed MY ice from different geographical regions in the Arctic Ocean are shown in Table 1. Measurements were carried out directly during field observations at the "North Pole" ice drifting stations of the Soviet Union (Buzuev 1968) and during the transarctic crossing from Alaska to Fram Strait via the North Pole (Koerner 1973). Ice thickness ranged from 3 to 6 meters for the period 1967-1981. By 1997-98, ice thickness had dramatically decreased by 1.4-2.1 m in a region of the SHEBA drift in the Canadian Basin. This remarkable change can be explained by a decrease of cold-day temperature per year (i.e., the sum of daily average sub-zero temperatures at a given location) below the number needed to maintain the equilibrium thickness of ice at 3-6 meters. Since early 1970s, the sum of cold-day temperature decreased from 7000 (NP-22, 1974-1975) to 6200 (SHEBA, 1997-1998) for the same geographical region (Figure 3). Field observations during the SHEBA cruise (Cold Regions Research and Engineering Laboratory [CRREL] data) showed that undeformed MY ice grew 75 cm during the winter, but lost 70 cm through surface ablation plus 40 cm through bottom ablation during the summer. Combining the growth and ablation gives a net thinning of 35 cm during the SHEBA year (Perovich *et al.* 1999).

Changes in the Sea Ice/Water Interface

Salinity/Temperature

Rapid melting of the sea ice cover during the last decade resulted in the freshening and warming of the upper ocean in the Arctic. McPhee *et al.* (1998) give CTD (conductivity-temperature-density) profiles for the upper 0-100 m obtained by the Arctic Ice Dynamics Joint Experiment (AIDJEX) (Oct 1975) and SHEBA (Oct 1997) expeditions in the same area (Figure 4). During this period of time, salinity values declined 3-4 parts per thousand in the 0-30 m layer and the temperature increased up to 0.4°C. A distinct seasonal halocline was formed between 30 and 35 m, which was stable through the SHEBA winter up to April and formed a significant barrier to turbulent mixing, capping the remnant mixed layer. Between October 1997 and April 1998, the SHEBA station had traversed enough of the region to make it clear that the freshening was widespread.

Nutrients

The SHEBA mean annual values of Si concentrations (μg-at/l) per m^2 of the 0-30 m water column were about 60% lower during winter and about 40% lower in summer compared with the NP-22 data (Figure 5a).

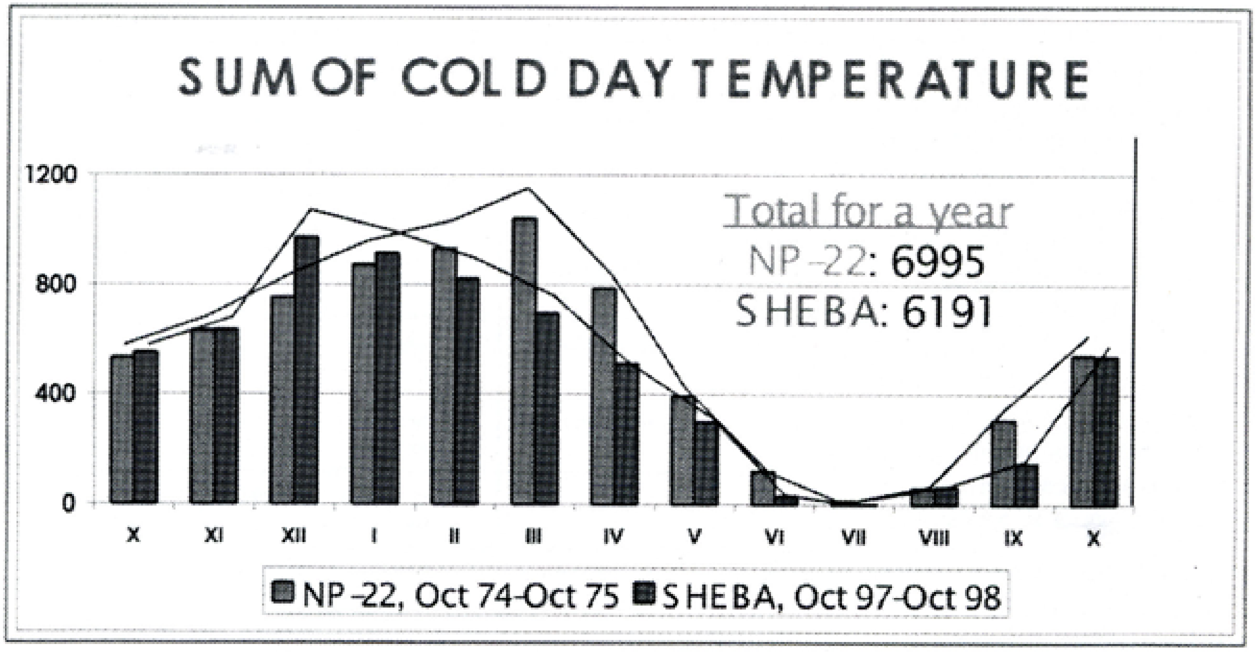
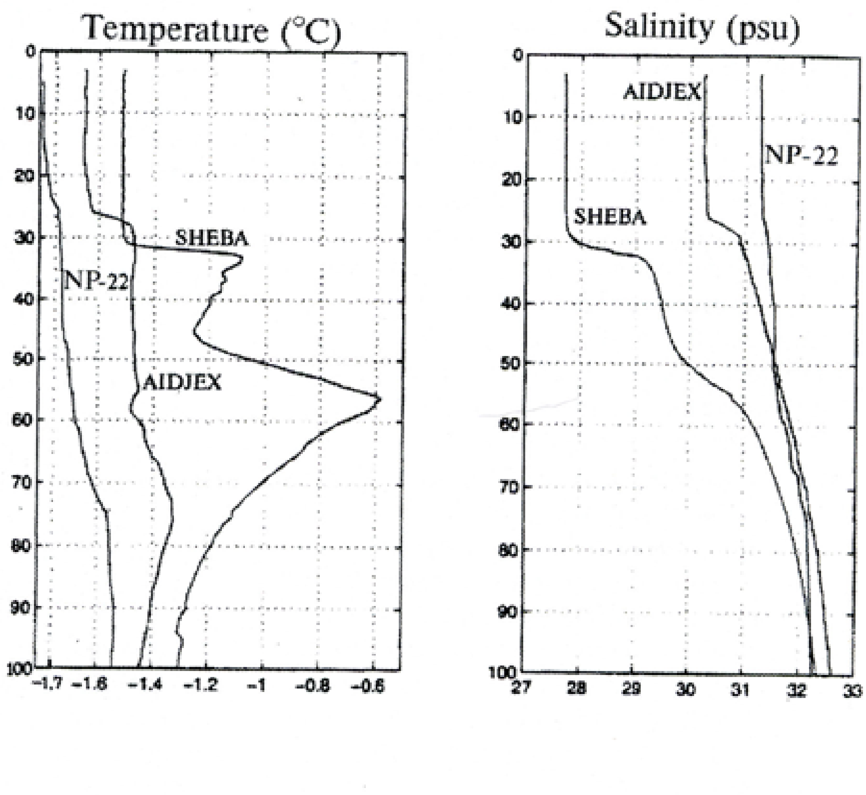


Figure 3. Sum of cold day temperature during the period October 1974-October 1975 (North Pole-22) and October 1997-October 1998 (SHEBA) in the region of the Beaufort Gyre (Canadian Basin of the Arctic Ocean). Within the same region, the cold day temperature period was longer in the early 1970s than in the late 1990s. The coldest month at NP-22 was March, but at the SHEBA Ice Camp it was December; in autumn (September), it was twice as warm during the SHEBA period than that of NP-22.

Figure 4. Temperature and salinity profiles from ice stations in the Beaufort Gyre: NP-22 (21 Oct 1975), AIDJEX (01 Oct 1975), and SHEBA (23 Oct 1997). Adapted from McPhee *et al.* (1998).



Dissolved oxygen

The SHEBA mean seasonal concentrations of O_2 within 0-30 m were 8% higher in the winter and 13% higher in the summer compared with NP-22 data. The NP-22 O_2 concentrations were seasonally stable, so that the summer-winter differences measured by SHEBA show a remarkable increase in seasonal variability (Figure 5b).

Chlorophyll a

The winter values from both SHEBA and NP-22 are similar but the summer concentrations for SHEBA were 55% higher than those of NP-22. In terms of chlorophyll, the annual standing stock during the SHEBA time was 0.273 µg/l, compared with 0.159 µg/l during NP-22. Increases in chlorophyll production (approximately 30%) may be explained by an activation of the phytoplankton photosynthesis beneath the sea ice that is, probably, connected with increasing of the dissolved oxygen concentrations in 0-30 m layer during the SHEBA time (Figure 5c).

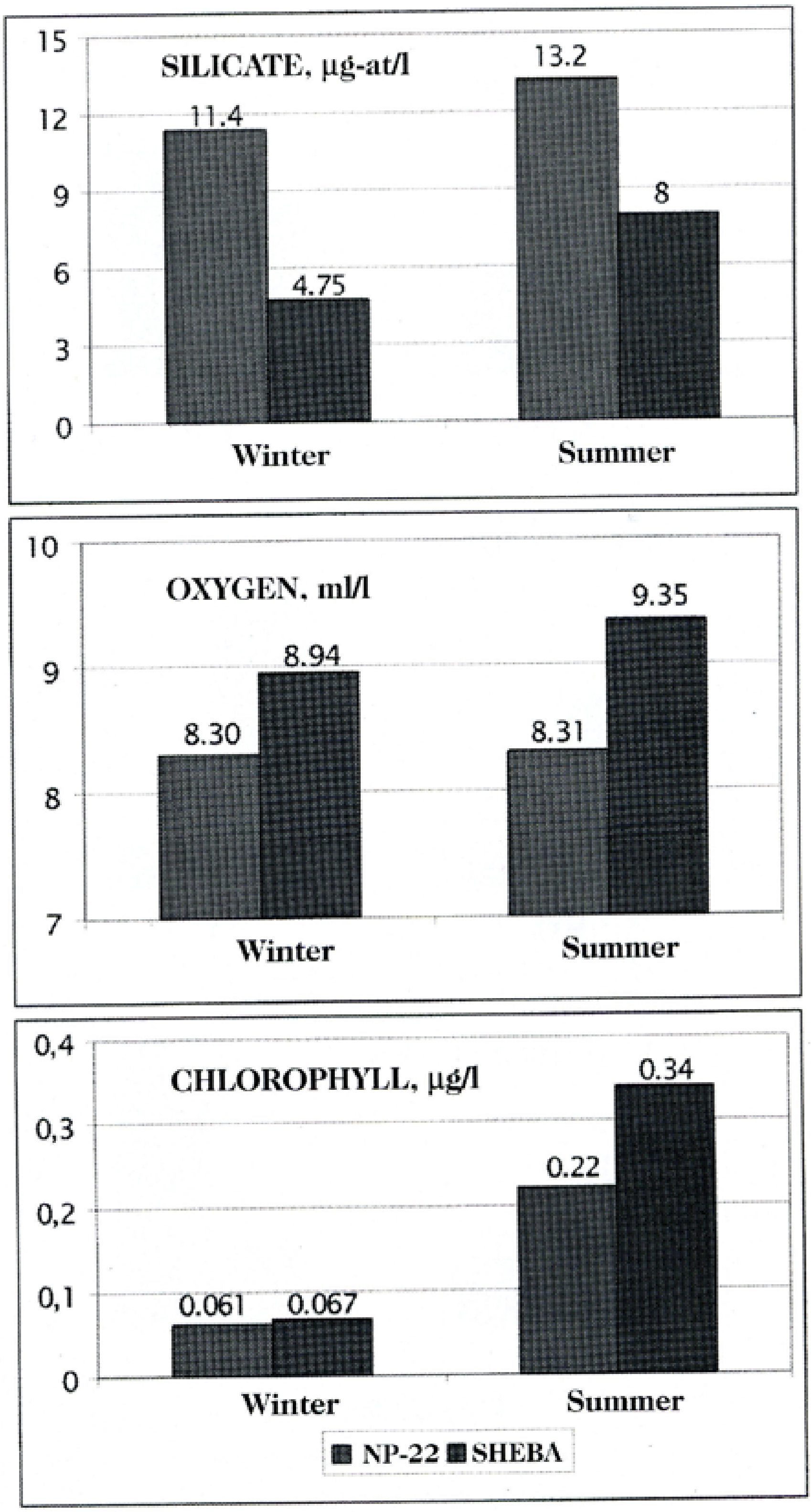


FIG. 5. MEAN CONCENTRATIONS OF SILICATE, OXYGEN AND CHLOROPHYLL A IN THE 0-30M WATER COLUMN AT NP-22 (1975-1976) AND SHEBA (1997-1998).

Changes within the Sea Ice Interior

Salinity

SHEBA and NP-22 mean salinity values of the multi-year (MY) ice are approximately equal (about 1 psu/m^2) (psu = salinity in parts per thousand) but

SHEBA values of the first-year (FY) is higher of NP-22 salinity (2.2 psu/m^2 and 1.6 psu/m^2, respectively) (Figure 6a).

Silicate

The mean Si concentrations of both MY and FY ice from NP-22 are much higher than those from SHEBA. The most curious feature of the SHEBA ice samples is very low concentrations of Si in the MY and FY ice. Decrease of Si values within the sea ice interior may be caused by an active release of these components during the melting of ice, that, in turn, may limit the summer growth of sea ice diatoms (Figure 6b).

Chlorophyll a

The mean NP-22 chlorophyll concentrations in MY ice are twice as high as in samples from SHEBA (0.13 µg/m^2 and 0.06 µg/m^2, respectively) but the SHEBA values of the FY ice are 3 times higher than the FY values from NP-22 (0.24 µg/m^2 and 0.07 µg/m^2, respectively). The main feature of chlorophyll concentrations in the ice is a remarkable decrease of this component in MY ice in contrast to the large increase in the FY ice samples (Figure 6c).

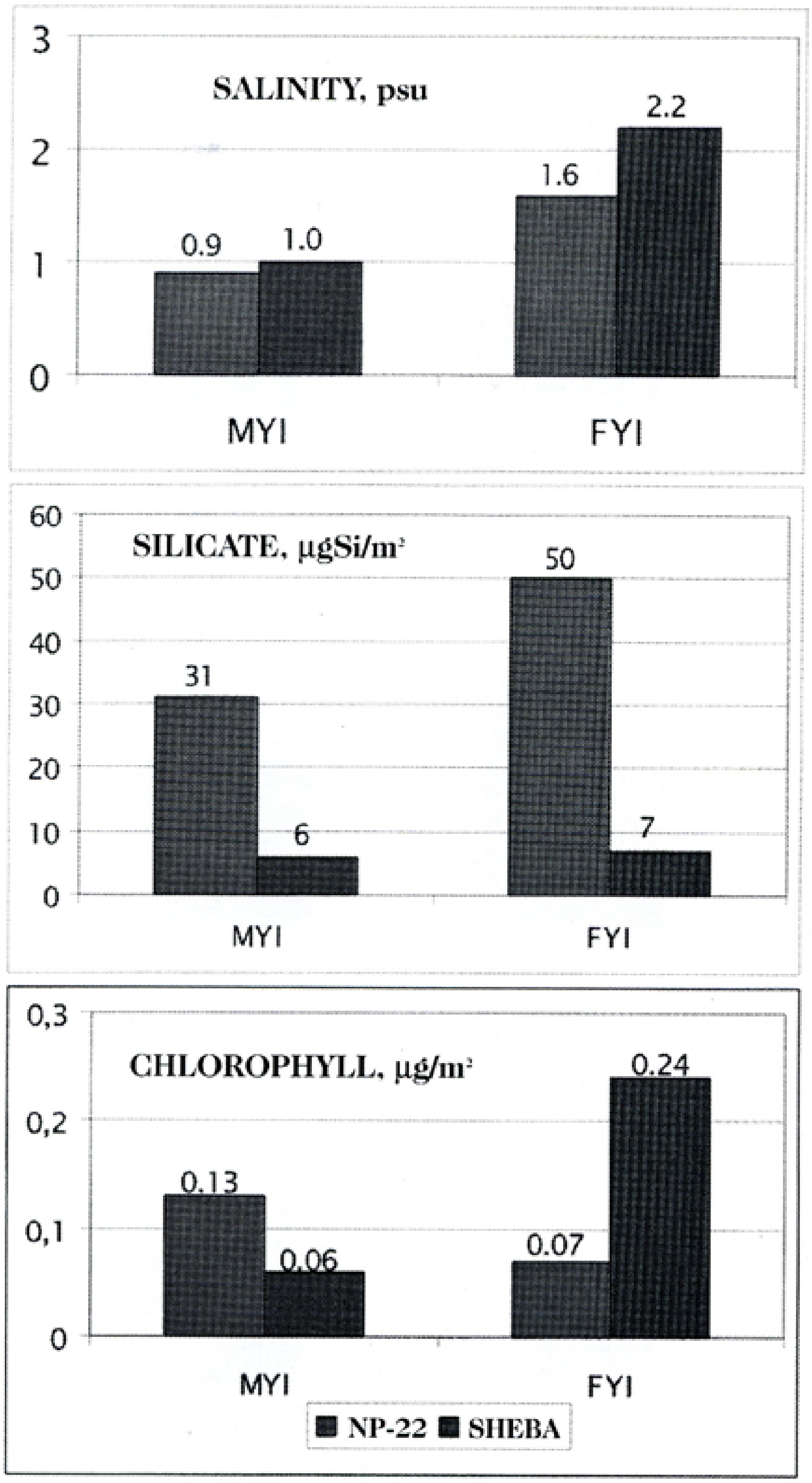


FIGURE 6. MEAN SALINITY AND CONCENTRATIONS OF SILICATE AND CHLOROPHYLL A IN MULTIYEAR (MY) AND FIRST-YEAR (FY) ICE AT NP-22 (1975-1976) AND SHEBA (1997-1998).

Changes in the Sea Ice Biota

I. Sea ice/water interface

Flora

Eighty-five species were identified in samples collected at the NP-22 and SHEBA sta-

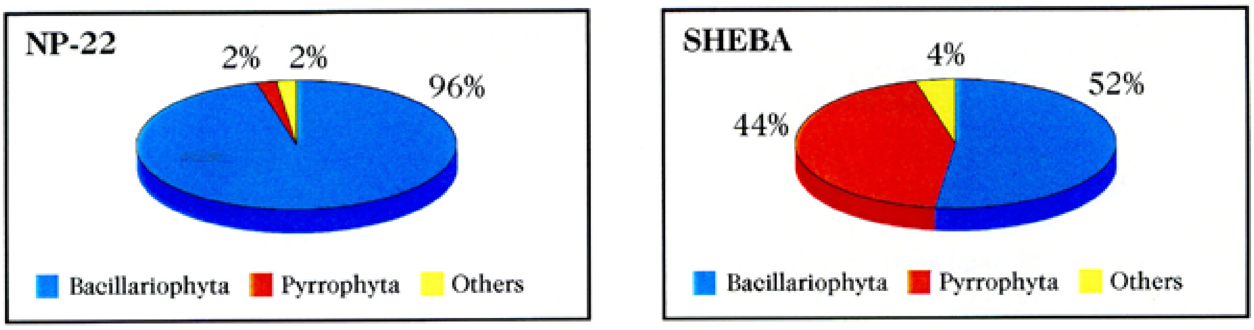


FIGURE 7. SEA ICE FLORA ASSOCIATED WITH THE SEA ICE/WATER INTERFACE AT NP-22 (1975-1976) AND AT SHEBA (1997-1998).

tions from the bottom surface of the ice. These species can be broken down in the following categories for the NP-22 and SHEBA sites respectively: Bacillariophyta – 46 and 22; Pyrrophyta – 1 and 19; Others – 1 and 2 (Melnikov *et al.* 2000). The main features of the SHEBA and NP-22 algal populations associated with the bottom surface of ice are:

1. A remarkable decrease of diatom species from 46 species or 96% of algal populations (NP-22) to 22 species or 52 % (SHEBA) in the under-ice layer (Figure 7);

2. Remarkable differences in species composition between the under-ice phytoplankton of SHEBA and NP-22: only 3 species from diatoms (*Chaetoceros socialis, Cylindrotheca closterium, Thalassionema nitzschioides*), 1 dinoflagelate (*Dinophysis acuta*), and 1 silicoflagelate (*Dictyocha speculum var. octonarius*) were common for both algal communities; the overall similarity between species from the SHEBA and NP-22 algal populations was only 8%;

3. A remarkable increase of Pyrrophyta in the SHEBA samples (19 species) compared with the NP-22 (only 1); and

4. The development within the ice/water interface at the SHEBA station of large aggregations formed by the fresh-water algae *Ulothrix implexa* (Kutz), which is a very common species in brackish waters but which had never been found before in the high marine Arctic.

Fauna

The total list includes 59 species. Of the 43 species in the NP-22 collection and 37 species from SHEBA, only 21 species were in common, or 37% of the total list (Melnikov *et al.* 2000). The main difference is due to amphipods: 14 species or 33% of total populations in NP-22 and 4 species or 11% of total populations in the SHEBA collection (Figure 8). Dominant species of the cryopelagic fauna in the NP-22 collection, such as polychaetes *Antinoella sarsi* and mysids *Mysis polaris*, were not observed by SHEBA. At the same time, in SHEBA water, the role of jelly-like plankton such as appendicularians, medusas, and benthic larvae are remarkably increased compared with NP-22.

II. Sea ice interior

Flora

The total list of sea ice algal populations includes 102 taxa; 84 species or 76% of the total list were indicated in NP-22, whereas in SHEBA they were only 26 species or 23%, respectively (Table 2). Species similarity between the NP-22 and SHEBA was only 8%.

The prevalence of diatoms is most variable in both MY and FY ice at the NP-22 (79 species) compared with SHEBA (18 species). Fresh water algae (mostly *Chlorophyta*) were detected only on the upper surface of ice. The obvious predominance of fresh water algae compared with diatoms is the main peculiarity of the algae populations

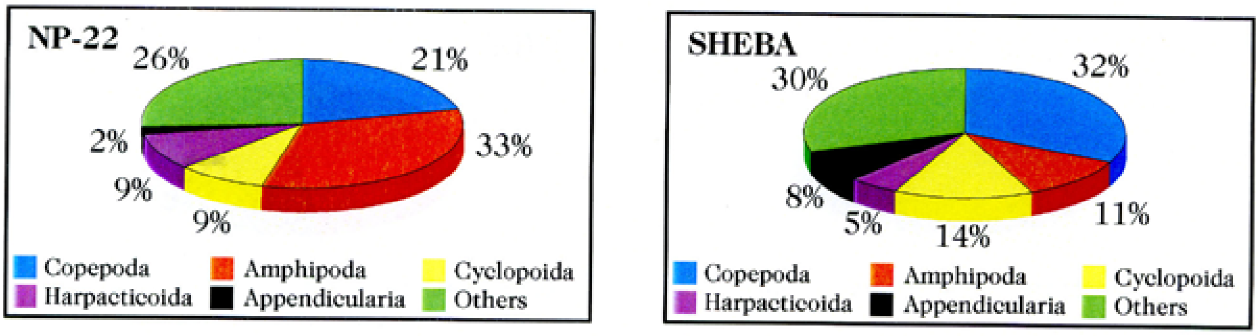


FIGURE 8. SEA ICE FAUNA ASSOCIATED WITH THE SEA ICE/WATER INTERFACE AT NP-22 (1975-1976) AND AT SHEBA (1997-1998).

from SHEBA: fresh water algae (*Pyrrophita*) were dominant by number and were distributed within both the MY and FY ice interior from the snow-ice surface to the sea ice/water interface.

Fauna

The main intriguing feature of the MY and FY sea ice faunal populations is an absence of interstitial fauna within the sea ice interior in the SHEBA ice samples; these fauna had previously been detected in high numbers in the NP-22 samples. In contrast to the nine species detected in NP-22 including *Protozoa, Foraminifera, Acarina, Nematoda, Turbellaria, Harpacticoida*, and *Amphipoda*, ice samples from SHEBA held only one specimen of *Foraminifera* (Table 3). The free-living nematode *Theristus melnikovi* associated with the sea ice interior was very common in the ice samples from NP-22, but was never been detected in the sea ice samples from SHEBA.

Implications for Future Climate Change

Thus, observations over the last two decades (SHEBA versus NP-22) confirm dramatic changes due to a warmer climate within the sea ice biological communities in the Central Arctic Ocean:

- SHEBA populations of sea ice diatoms are very scarce by species and number both in the multi-year and in the newly formed ice;
- freshwater green algae previously developed on the upper-ice surface and/or within the upper sea ice layers (NP-22) are now dominant by number and are distributed through the whole thickness of sea ice (SHEBA);
- populations of invertebrate animals like nematodes, copepods, amphipods, and turbellarians that previously lived in the sea ice interior (NP-22) were not found in the multi-year ice and newly formed sea ice (SHEBA); and

NP-22 1979-1980	Interstitial Flora	SHEBA 1997-1998
79	***Bacillariophyta***	18
0	Pyrrophyta	5
0	Chrysophyta	1
0	Silicoflagellatae	1
5	Chlorophyta	1
Total: 84	**Total species number: 102** **Similarities between species: 8%**	Total: 26

TABLE 2. SEA ICE FLORA ASSOCIATED WITH THE SEA ICE INTERIOR AT NP-22 (1979) AND AT SHEBA (1997-1998).

NP-22 1979-1980	Interstitial Fauna	SHEBA 1997-1998
3	Protozoa	0
1	Foraminifera	1
1	Acarina	0
2	Nematoda	0
1	Turbellaria	0
1	Harpacticoida	0
1	Amphipoda	0
Total: 10	**Total species number: 10** **Similarities between species: 10%**	Total: 1

TABLE 3. SEA ICE FAUNA ASSOCIATED WITH THE SEA ICE INTERIOR AT NP-22 (1979) AND AT SHEBA (1997-1998).

- in the SHEBA samples, cryopelagic fauna associated with the bottom sea ice surface as well as the under-ice zooplankton were scarce by species and numbers.

Observed changes in the composition and structure of sea ice biological communities may be explained by the growing melting of the sea ice cover during the last decade. Several factors likely to have been responsible include: (1) drainage of fresh water throughout the sea ice interior, (2) accumulation of fresh water beneath the ice, and (3) formation of the sharp halocline at around 30 m. The recent water/ice system above the halocline may, in fact, be more a freshwater/brackish system than the real marine system. On this basis, it seems that dramatic changes within the sea ice environment can be considered a result of global warming in the Arctic.

Recent scientific meetings and workshops have focused on the impact of future climate change and its potential implications for Arctic indigenous populations (Weller and Lange 1999). Many issues are of the highest concern to both Arctic residents and the Arctic scientific community. What are the potential effects on high Arctic nature due to a drastically shrinking area of polar pack ice, an increase of the seasonal sea ice surface, or a totally ice-free Arctic Ocean, at least in the summer? How will these changes impact the economics, lifestyle, and culture of Arctic residents as well as the political and economic framework of the circumpolar Arctic countries? All these issues are of great concern and urgently need to be discussed and studied.

On the basis of the historical materials and recent observations obtained over the Central Arctic Ocean, it may be concluded and speculated that:

- the modern *permanent sea-ice cover* in the Central Arctic Ocean has rapidly decreased both in surface area and in thickness, and the ice-edge has moved significantly farther north;
- both the *ice-free water surface* and *seasonal sea ice* have increased remarkably, especially in the areas of the Chukchi and Beaufort Seas;
- sea-ice cover of the Arctic Ocean will become more similar in its characteristics to the Southern Ocean, where seasonal rather than permanent sea ice is a dominant component of the marine ecosystem;
- the increase of *seasonal sea ice* versus *pack ice* and the advance of *ice-free areas* will promote photosynthetic activity of phytoplankton within the water column due to strong penetration of light, and ice-associated primary production will be reduced compared with that of the water-column.

From the early 1930s, it has been well known that the ice edge is the area of highest biological production in the ice-covered arctic seas (Usachev 1935, Shirshov 1937, Zubov 1945). The recently observed shrinking of the permanent sea-ice cover in the Arctic may be considered a signal for a strong northward shift of ice-associated animals including birds and marine mammals as the ice-edge retreats. If this scenario is more or less probable, can we speculate that recent observations of beluga whale migration far to north depends on this ice-edge retreat and the degeneration of the quality of pack ice in the Arctic Basin (L. Lowry, Alaska Department of Fish and Game, personal communication, 2000)? If so, the sea-ice-dependent lifestyle of Arctic indigenous people will be sharply changed in the near future. To understand this phenomenon, we urgently need long-term and large-scale observations of sea-ice-associated processes over the whole Arctic.

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