Available online at www.sciencedirect.com
SCIENCE DIRECT®
Global and Planetary Change 48 (2005) 175–186
GLOBAL AND PLANETARY CHANGE
www.elsevier.com/locate/gloplacha

Linkage of Arctic atmospheric circulation and Siberian shelf hydrography: A proxy validation using $\delta^{18}O$ records of bivalve shells

Thomas Müller-Lupp[a,*], Henning Bauch[b]

[a]IFM-GEOMAR, Leibniz Institute of Marine Sciences, Wischhofstr. 1-3, D-24148 Kiel, Germany
[b]Mainz Academy of Sciences, Humanities and Literature, c/o IFM-GEOMAR, Wischhofstr. 1-3, D-24148 Kiel, Germany

Received 24 November 2003; accepted 9 December 2004

Abstract

High resolution oxygen isotope profiles of aragonitic bivalve shells (*Astarte borealis*) collected alive in different years are used to trace hydrographical changes on the Laptev Sea shelf, which are mainly forced by changes in riverine freshwater discharge and arctic atmospheric circulation patterns. By merging individual isotope profiles, a high resolution time series of relative changes in bivalve $\delta^{18}O$ is obtained for the eastern Laptev Sea for the period 1969 to 1998. The resulting pattern in the $\delta^{18}O$ time series reflects seasonal bottom-water salinity changes in the Laptev Sea, which is dominated by the peak input of freshwater discharged by the Lena River onto the Laptev Sea shelf during summer. The relative changes in summer bottom-water salinity, deduced from the $\delta^{18}O$ values in the bivalves and the discharge anomaly of the Lena River, show a significant negative correlation. It is therefore suggested that the annual and subdecadal variations of the riverine freshwater and its influence on the shelf hydrography are imprinted in the bivalve shells. Moreover, we note that extreme summer precipitation anomalies in the Lena River catchment area affect the river discharge characteristics, events which are detectable in the $\delta^{18}O$ time series. This all implies that $\delta^{18}O$ records of bivalve shells have the potential to build long-term records of atmospheric-forced changes in arctic circulation.

Keywords: atmospheric circulation; river runoff; hydrography; bivalve shells; Arctic shelves

1. Introduction

The arctic region is expected to be disproportionately affected by global warming, and the Arctic in turn may exert a strong feedback on global climate (Kerr, 1999; Overpeck et al., 1997). Many of the linkages between the arctic system and the global

* Corresponding author. Tel.: +49 431 6002857; fax: +49 431 6002941.
E-mail address: tmueller-lupp@ifm-geomar.de (T. Müller-Lupp).

0921-8181/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.gloplacha.2004.12.012

climate involve the hydrological cycle, including atmospheric moisture transport from lower to higher latitudes (Macdonald et al., 2003). This transport of moisture is predicted to increase in proportion to increases in mean hemispheric temperature (Moritz et al., 2002; Peterson et al., 2002). While global surface air temperature has increased by 0.6 °C over the past century (IPCC, 2001), the precipitation in the high latitudes has increased by up to 15% during the last century (Macdonald et al., 2003). A synthesis of river-monitoring data from the six largest Eurasian rivers reveals that the average annual discharge of freshwater into the Arctic Ocean increased by 7% from 1935 to 1999 (Peterson et al., 2002). The freshening of the Arctic Ocean and the export of cold and low-saline surface water from the Arctic Ocean is a climate-sensitive mechanism potentially capable of directly reducing the intensity of thermohaline circulation in the Nordic seas (Rahmstorf, 1995; Bauch et al., 2000). The fraction of riverine freshwater in the surface waters over the Eurasian Basin can exceed 14% (Bauch et al., 1995) and thus arctic river runoff is one of the principal freshwater sources for balancing the budget of the Arctic Ocean. The Laptev Sea, as one of the key regions affecting the arctic freshwater budget, is influenced by large quantities of freshwater supplied during summer by several rivers, especially by the Lena River (Aagaard and Carmack, 1985, 1989; Carmack, 2000). Because 83% of the total Lena river runoff is discharged during the summer (R-ArcticNet, 2004), the hydrography of the shallow Laptev Sea is subject to strong seasonal changes (Dmitrenko et al., 1999). Knowledge of the seasonal and interannual variability of arctic shelf hydrology is therefore essential to better understand both modern and past arctic environments.

Our study seeks to reconstruct hydrographical variations in the river-proximal region of the Laptev Sea, using oxygen isotope compositions in carbonate shells of bivalves as a recorder. The oxygen isotopic composition of marine carbonates is controlled by the isotopic composition of the water from which the carbonates precipitated and the temperature of the ambient water (Epstein et al., 1953; Grossman and Ku, 1986). Because of the accretionary growth of bivalve shells, $\delta^{18}O$ profiles taken from along their axis of maximum growth can provide time series of hydrographical variations of the bivalve habitat during its lifetime. Thus a number of studies have dealt with stable oxygen and carbon isotope profiles from recent and fossil bivalve shells to reconstruct environmental and physiological changes (Erlenkeuser and Wefer, 1981; Arthur et al., 1983; Jones et al., 1986; Krantz et al., 1987, 1988; Weidmann and Jones, 1994; Bemis and Geary, 1996; Hickson et al., 1999; Khim et al., 2000; Schöne et al., 2002). These studies focused on within-shell variation and its relation to seasonal water temperature cycles, water masses, habitat and shell growth characteristics.

The particular applicability of the bivalve species *Astarte borealis* (Schumacher, 1817) as a recorder of hydrographical conditions in high arctic coastal regions was shown for East Greenland (Israelson et al., 1994) and for Bering Strait region and the Chukchi Sea (Khim et al., 2001, 2003), and more recently also for the Laptev Sea (Mueller-Lupp et al., 2003). Using oxygen isotope profiles from modern bivalves collected alive from the eastern part of the Laptev Sea between 1984 and 1998, this study investigates variations in the bottom-water hydrography over the past 30 years and how the temporal changes relate to the overall hydrological and atmospherical regime in the Laptev Sea area.

2. Hydrography

2.1. General settings

The modern hydrographical settings on the eastern Laptev Sea shelf are the result of interaction between an advection of arctic water masses from the north and the riverine freshwater discharge from the south, mainly from the Lena River. In terms of discharge volume, the Lena River is the second largest among all arctic rivers with an annual discharge of 532 km^3 (Global Runoff Data Center, 1998). With a drainage area of 2.46 million km^2 (R-ArcticNet, 2004) the Lena River water reflects the hydrological regime of wide areas of central Siberia.

Laptev Sea waters are formed under conditions of extreme seasonal contrasts. The surface water generally starts freezing in October (Eicken et al., 1997). After river ice-breakup in early summer, a large brackish surface plume is formed that extends northward onto the shelf (Dmitrenko et al., 1999; Piv-

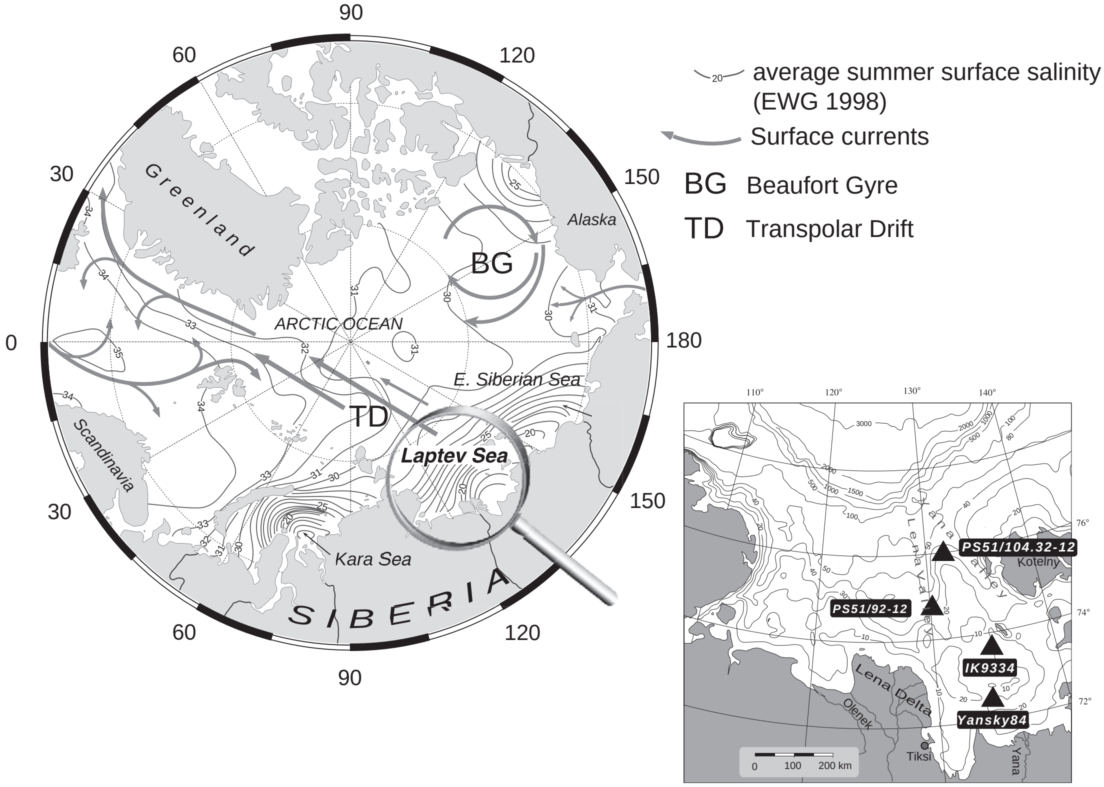

Fig. 1. Main surface currents and average surface water salinity in the Arctic Ocean (1950 through 1990) emphasizing the importance of freshwater discharge from the Siberian rivers (EWG, 1998). Bathymetric map of the Laptev Sea (depth contours in meters) showing the collection sites of the investigated bivalves.

ovarov et al., 1999). This offshore spreading of riverine waters typically results in a steady increase of salinity which decelerates with increasing distance from the Lena River mouths. The temperature distribution pattern has weaker gradients and is less regular than that of salinities, but warmest water temperatures are consistent with low salinities, occurring in the very shallow, river-proximal areas just east of the Lena Delta.

The hydrography of the bivalve collection sites (Fig. 1) is affected by strong seasonal variations due to a direct influence of the freshwater discharge. Long-term hydrographical data of all investigated sites (1950–1990; EWG, 1998) show on average a higher bottom-water salinity in winter than in summer (Table 1). Average bottom-water temperatures remain relatively constant, ranging between −1.1 and −1.6 °C. Only at the near-coastal sites is a more variable temperature range observed throughout the year (0.5 to −1.7 °C).

2.2. Oxygen isotopes in Laptev Sea waters

The $\delta^{18}O$ signatures of the Laptev Sea surface and bottom waters vary between −1‰ and −15‰ with a salinity range from 4.7 near the Lena River mouth to 33.7 in the northern Laptev Sea (Mueller-Lupp et al., 2003). The significant, linear correlation between salinity and the $\delta^{18}O$ values documents the linear mixing between freshwater discharged by the rivers and sea water with a $\delta^{18}O_{water}$ to salinity ratio of 0.50‰/salinity.[1] Hence a $\delta^{18}O$ composition of the Lena runoff (Salinity = 0) can be estimated at −18.86‰, which is very close to actually measured values of −18.9‰ (Létolle et al., 1993). These end-

[1] In the Practical Salinity Scale salinity is defined as a pure ratio, and has no dimensions or units (UNESCO 1985; The International system of units (SI) in oceanography, UNESCO Technical Papers No. 45).

Table 1
Description of bivalve specimens and sites

Specimen	Sample ID/station	Collection date	Water depth [m]	Salinity[a]		Temperature [°C][a]	
				Winter	Summer	Winter	Summer
Bivalve 1	PS51/104.32	05.08.1998	32	32.5	31.2	−1.6	−1.1
Bivalve 2	PS51/92.137[1]	03.08.1998	32	32.5	31.6	−1.6	−1.3
Bivalve 3	IK9334[2]	19.08.1993	22	28.4	26.5	−1.4	−0.9
Bivalve 4	Yansky84[3]	summer 1984	11	22.0[b]	17.4[b]	−1.4[b]	0.3[b]

We acknowledge [1] M. Schmidt (Institute for Polar Ecology, Kiel University), [2] I. Richling and V. Wiese (Malacological Museum "Haus der Natur-Cismar"), and [3] A. Gukov (Hydrometeorological Department Tiksi/Yakutia) for providing the bivalves.
[a] Temperature and salinity data of bottom water obtained from the "Russian Arctic Ocean Atlas for Winter and Summer Period" (1950–1990) of the Joint U.S.–Russian Environmental Working Group (EWG, 1998).
[b] Salinity and water temperature data were kindly provided by I. Dmitrenko and S. Kirillov (AARI, St. Petersburg, Russia).

member values fit into the longitudinal trend of riverine $\delta^{18}O$ decrease across northern Eurasia from −13‰ in Scandinavia to −23.8‰ in the far east Indigirka River (Létolle et al., 1993); it is also persistent with the prevailing west to east direction of atmospheric vapor transport across northern Eurasia. The mixing of runoff and marine water derived from the Atlantic ($\delta^{18}O$ composition of ~0‰) primarily controls the $\delta^{18}O_{water}$ distribution in the Laptev Sea (Mueller-Lupp et al., 2003) in the surrounding arctic shelves (Bauch et al., 2003; Macdonald et al., 2002) and in the Arctic Ocean (Bauch et al., 1995). In arctic estuarine systems like the Laptev Sea the linear mixing of riverine freshwater and sea water can be influenced by sea ice as a third end member. The influence of ice is inserted as deviations either to the right (sea ice formation) or to the left (sea ice melt) of the linear mixing line (Macdonald, 2000). However surface and bottom water data from the Laptev Sea (Mueller-Lupp et al., 2003) reveal a highly significant linear relationship (p-value 0.01, n=64, r=0.992) of salinity and $\delta^{18}O_{water}$ and show no relevant dilution with freshwater from ice melt or isotopic enrichment related so sea ice formation.

3. Materials and methods

All oxygen isotope records used in this study were carried out on shells from the bivalve species of *A. borealis*, a species generally growing slowly with an adult size in the Laptev Sea of only 3–4 cm. It is the largest of the more abundant bivalves in the Laptev Sea and its habitat is characterized by a wide salinity range (between 10 and 34), and water depth range between 15 and 50 m (Gukov, 1999; Petryashov et al., 1999).

The four investigated specimens (bivalves #1–4) were all collected alive from water depths between 32 and 11 m during several expeditions to the Laptev Sea (Table 1; Fig. 1). While two of the specimens (bivalve 1 and bivalve 2) were gathered in summer 1998, bivalves 3 and 4 were collected in summer 1984 and 1993, respectively.

Because during growth bivalves continuously add new material at the ventral margin of the shell, a serial sampling technique along their growth axis similar to that used in other studies was applied to derive high-resolution isotope records from the shells (Erlenkeuser and Wefer, 1981; Krantz et al., 1987, 1988; Bemis and Geary, 1996). Individual carbonate powder samples (> 15 μg) were sequentially millcut under a microscope from the outer shell layer along the axis of maximum growth with a spatial resolution of approximately 0.15 to 0.3 mm; for detailed sampling technique and isotopic analyses see Mueller-Lupp et al. (2003). Isotope ratios are reported as parts per mill (‰) in the usual δ-notation relative to the PDB standard (defined via NBS20). The methodical error, carried out on sample replicates, amounts to 0.25‰ (S.D.: ± 0.2; n=55) on the $\delta^{18}O$-scale. Sample positions along the profile are reported as distance from the umbo (0 mm) toward the ventral margin (Fig. 2).

The chronology of the four bivalves is constructed by setting minimum $\delta^{18}O$ values in each isotope cycle as the point in time when the riverine freshwater peak reaches the Laptev Sea in early June, and maximum

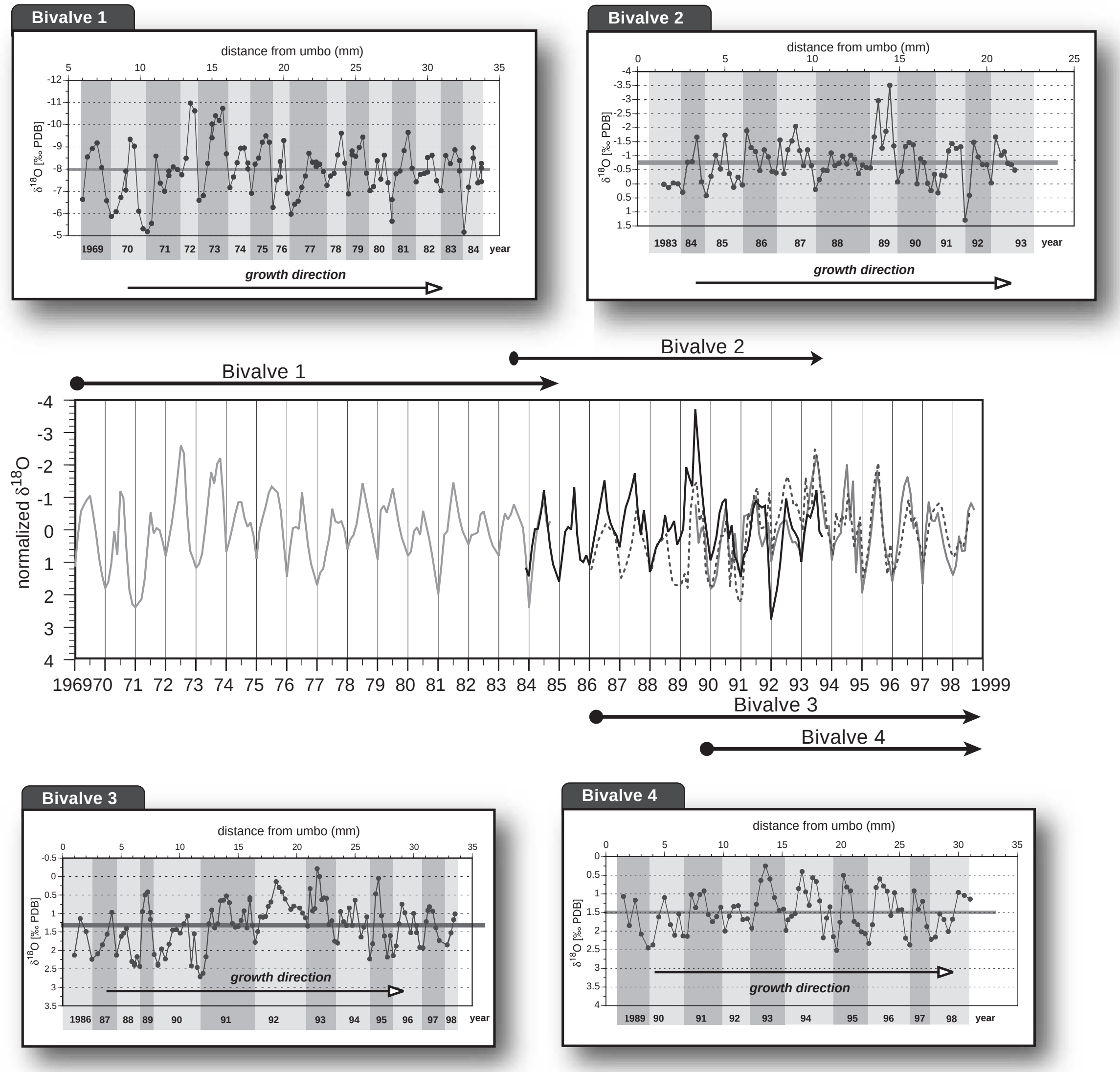

Fig. 2. Oxygen isotope profiles from 4 shells of *Astarte borealis* (bivalve #1, 2, 3, and 4) collected alive in water depth between 11 and 32 m in the eastern Laptev Sea during different summers (Table 1, data from Mueller-Lupp et al., 2003). The sample position is given in mm as distance from the umbo to the ventral margin. The shaded subdivisions represent calendar years, which were calculated by counting back the annual isotope cycles from the ventral margin. The central record shows all individual bivalve records after normalizing them by their mean and standard deviation.

values as winter. In between the maxima and minima a linear growth rate of the bivalve shells is assumed. Because all investigated specimens were collected alive during August–September, the light δ^{18}O-values from the ventral margin are assumed to represent the conditions of the final summer. Therefore, calendar years can be assigned directly by counting back the annual isotope cycles from the margin. For instance, in the δ^{18}O profile of bivalve 4 there are 9 isotopic cycles recognized prior to the year of collection in 1998 (Fig. 2) and represent a record going back to 1989.

By merging the individual bivalve records, spanning different periods of time, a time series of relative δ^{18}O changes from 1998 back to 1969 is established.

Table 2
Mean $\delta^{18}O$, standard deviation, and mean seasonal amplitudes of the investigated bivalves

Specimen	Mean $\delta^{18}O$ [‰]	S.D.	Mean winter to summer amplitude [‰]
Bivalve 1	1.47	0.54	1.17
Bivalve 2	1.32	0.62	1.23
Bivalve 3	−0.76	0.74	1.59
Bivalve 4	−7.98	1.17	2.73

Because the bivalves were collected from different water depths, which yields different $\delta^{18}O$-means and amplitudes (Table 2) the individual time series were normalized by its mean and standard deviation before merging. The resulting normalized $\delta^{18}O$ records show a good conformity and were therefore averaged in the overlapping sections. For further analysis the merged records were smoothed by a 7-point least square smoothing.

4. Results

The $\delta^{18}O$ profiles of all investigated bivalves exhibit amplitude cycles (Fig. 2) that are interpreted as annual cycles with more negative $\delta^{18}O$ values indicating summer and more positive $\delta^{18}O$ values indicating winter season. In general the oxygen isotope composition of biogenic carbonates is controlled by temperature and isotopic composition of the ambient water (Epstein et al., 1953; Grossman and Ku, 1986), which, in the Laptev Sea, is strongly correlated with salinity. But it is interesting to note that the potential effect of seasonal bottom-water temperature variations in the Laptev Sea for within-shell isotope variations is lower by an order of magnitude compared to the influence of salinity (Mueller-Lupp et al., 2003). Therefore the observed isotope cycles are interpreted by us as reflecting annual salinity changes as a result of the strong seasonal riverine freshwater input.

The merging of the overlapping individual bivalve records results in a composite $\delta^{18}O$ record showing a saw-toothed pattern of relative variations in bottom-water salinity in the eastern Laptev Sea from 1998 back to 1969 (Fig. 3). Besides the recognized seasonal cycles, the summer amplitudes of the relative $\delta^{18}O$ record vary on annual and subdecadal bases. Particularly prominent amplitudes are obvious in the years 1972, 1973, and 1989.

To further manifest the relation between seasonal salinity changes as a result of freshwater discharge and $\delta^{18}O$ values, the annual Lena River discharge anomaly is shown for the period 1935–1998 (Fig. 3).

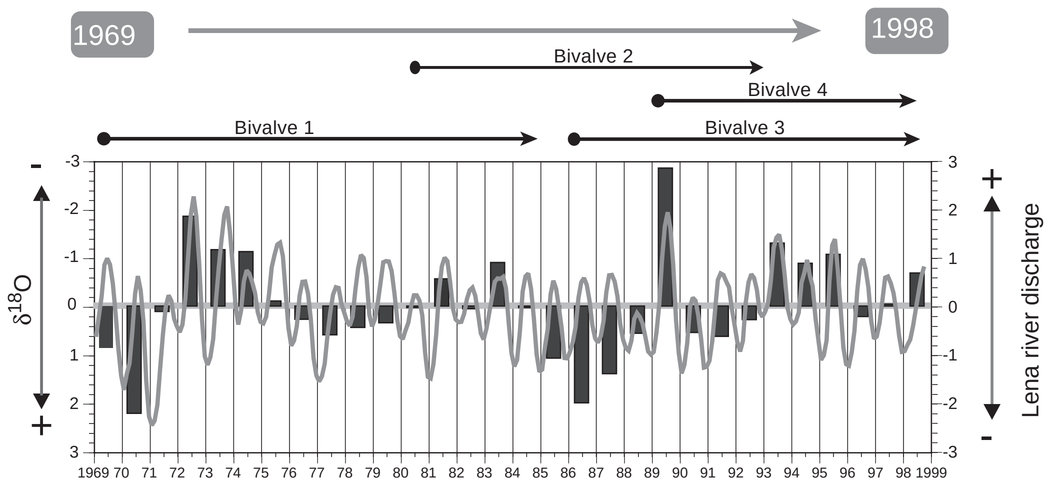

Fig. 3. Smoothed and normalized oxygen isotope time series of the individual oxygen isotope profiles. Before merging each of the individual time series was normalized by their standard deviation and mean. Because the record is plotted with ordinate values in reverse, negative values represent events of light oxygen isotope values in the bivalve shells, i.e. events of low salinity (i.e. hydrographical conditions during summer) and vice versa. The columns represent the relative annual Lena River discharge (1935 through 1998; R-ArcticNet, 2004; Global Runoff Data Center, 1998), normalized with its standard deviation and mean.

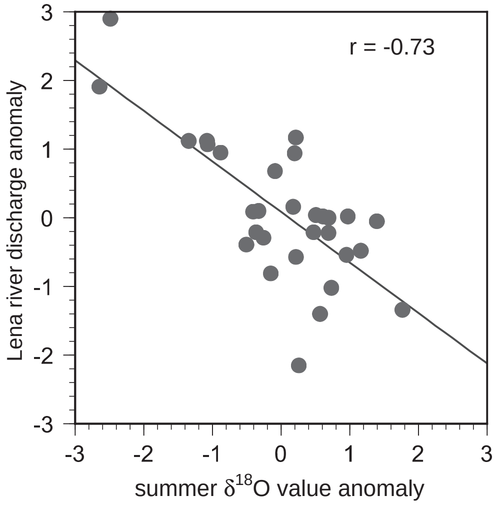

Fig. 4. Summer anomaly values of bivalve δ^{18}O versus Lena River discharge anomaly. The river runoff anomaly refers to variations of the long-term mean (1935–1998). The relation is significantly correlated (p-value 0.01) with $r = -0.73$.

It is noticeable that the extreme negative salinity events in the summers of 1972, 1973, and 1989 coincided with strong anomalies in the Lena River discharge. We observe a good ($r = -0.73$) and highly significant correlation ($p = 0.01$) between summer anomaly values of our δ^{18}O records and the Lena River discharge anomaly (Fig. 4). About 53% of the variance in the relative summer δ^{18}O values of the bivalve time series is explained by the Lena River discharge anomaly. Besides extreme peaks in individual years the time series reveals periods with moderate summer δ^{18}O values and average river discharge like in the early 1980s. At the same time as the Lena River discharge increased during the 1990s, the δ^{18}O became more negative (Fig. 3).

5. Discussion

An accurate hydrographical reconstruction from the δ^{18}O records of bivalve shells requires information about the species-dependent fractionation offset for *A. borealis*. Previous studies from the Laptev Sea have indicated that *A. borealis* is precipitating its aragonitic shell with an average fractionation offset of −0.37‰ (Mueller-Lupp et al., 2003) from the expected δ^{18}O values of aragonitic mollusks (Grossman and Ku, 1986). As the hydrographic conditions in the Laptev Sea vary considerably during the year, it is important to gain insights into the seasonal growth behavior of the bivalve species (Schöne et al., 2003). The occurrence of a nepheloid layer existing around the year and the current-induced resuspension of sediment and organic particles in the Laptev Sea (Wegner et al., 2003) reveals that the food supply for the bivalves is by no means seasonally limited in this part of the Laptev Sea shelf. In addition, no growth band periodicity as in other bivalves, such as *Arctica islandica* (Weidmann and Jones, 1994), were microscopically discernible so that we can conclude that the annual growth in *A. borealis* is not significantly restricted.

Previous studies in the Kara Sea (Simstich et al., 2003) as well as in the Laptev Sea (Mueller-Lupp et al., 2003) have demonstrated the applicability of oxygen isotope profiles in bivalves shells of *A. borealis* as a recorder for long- and short-term hydrographical changes in arctic river–shelf systems. Although the oxygen isotope composition in bivalve shells is controlled by both temperature and δ^{18}O of the ambient seawater (Grossman and Ku, 1986), which in the Laptev Sea is strongly correlated with salinity (i.e. riverine freshwater), the influence of salinity on the within-shell isotope variations is considerably higher than that of the water temperature (Mueller-Lupp et al., 2003). Thus, the oxygen isotope records of the individual bivalves can be regarded as relative salinity records.

Variations of the shell δ^{18}O values studied here clearly reveal the seasonal fluctuations of salinity and, in particular, the distinct seasonality of riverine freshwater input. Although the investigated bivalves were collected from different locations on the Laptev Sea shelf, hydrographical data for all these sites show a distinct influence of the seasonal freshwater input on the bottom water due to their relatively shallow water depth (EWG, 1998; Dmitrenko et al., 1999). Besides the good correspondence of salinity records reconstructed from δ^{18}O profiles with synoptical hydrographical data (Mueller-Lupp et al., 2003), the oxygen isotope records reflect the influence of Lena river discharge on seasonal as well as on annual and subdecadal timescales.

A negative relationship between the relative δ^{18}O time series and the Lena River discharge anomaly is obvious (Fig. 4) and demonstrates that the summer $\delta^{18}O$ peak can be used as an indicator for Lena River discharge. General variations in annual Lena River discharge and their imprint in the isotopic composition of the bivalve shells should also be affected by the precipitation variability in the Lena River drainage area. Because two thirds of the annual precipitation in eastern Siberia occurs during summer (Semiletov et al., 2000), it is interesting to also compare our record with the surface precipitation rate anomaly from June to August in the drainage area of the Lena River (Fig. 5). For example in 1989 absolute maxima in the annual Lena River discharge (1935–1998) and in the relative $\delta^{18}O$ time series are observed. In connection with these maxima the surface precipitation rate in the drainage area shows strong positive anomalies (Fig. 5), while in a year with minor river discharge and minor $\delta^{18}O$ summer peak, like in 1990, the surface precipitation rate in the watershed was negative. By comparing the macrosynoptical situation over Siberia in years of maximal (1989) and minor (1986) annual discharge it is apparent that during July 1989 fourteen cyclones entered East Siberia, while in July 1986 the cyclone trajectory showed that no cyclones were detected in Yakutia (Semiletov et al., 2000). However, in some years (e.g. in 1986) a prominent negative Lena River discharge anomaly is not recorded in the bivalve record at all (Fig. 3). A reason for this could be that the summer $\delta^{18}O$ peak in the bivalve shell profile is not only a signal for the amount of discharged freshwater rather a signal for the intensity of the peak discharge as well as of the mixing of freshwater to the bottom water. A more detailed correlation of bivalve shell $\delta^{18}O$ and river runoff characteristics on a monthly resolution would be very helpful for answering the question about the response of shell $\delta^{18}O$ in bivalves to riverine freshwater inflow. But this is not possible at present, because the resolution of our reconstruction is so far on a seasonal timescale.

Our interpretation centers around what bivalves record in the $\delta^{18}O$ signal of their shell and what processes are responsible for $\delta^{18}O$ variations. The correlation between the summer $\delta^{18}O$ values and anomalies in the annual Lena River discharge (Fig. 4) show that 53% of the $\delta^{18}O$ peaks can be explained by Lena River discharge anomaly but also suggests that other processes may alter the influence of freshwater on the bottom water.

The advection of more saline and thus isotopically heavier water from the Arctic Ocean as a result of upwelling currents from the north in the near-bottom layer can weaken the freshwater signal of the river plume on the bottom water. During the ice-free season strong southerly winds can cause a deformation of the sea level and can result in reversal, southerly currents in the near-bottom water layer (Dmitrenko et al., 2001). These events are only episodic with a duration of 2 to 7 days and their effect on the $\delta^{18}O$ signal in the bivalve shells is limited. If we consider the mixing process of riverine inflow down to shelf bottom water, variations in bivalve $\delta^{18}O$ can also be affected by

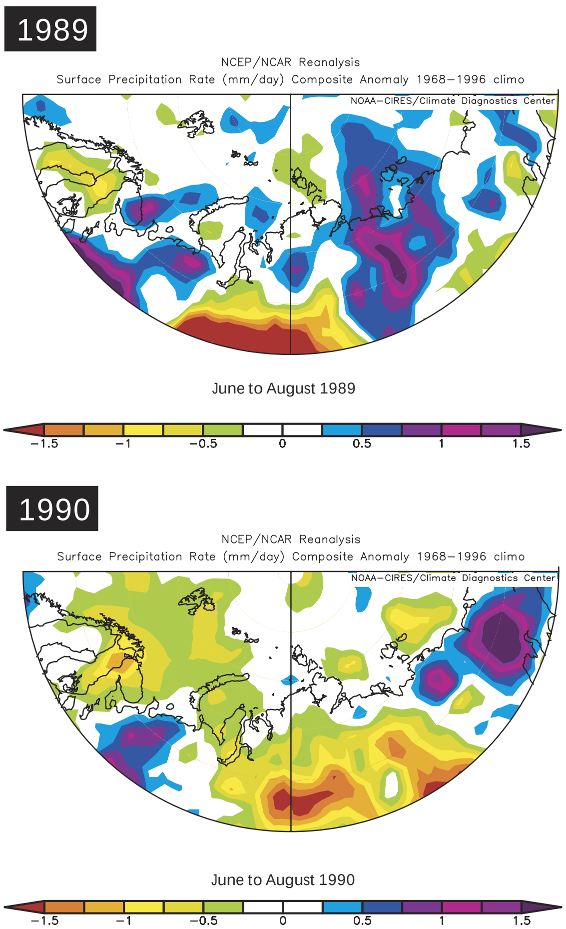

Fig. 5. Composite anomalies of surface precipitation rate (mm/day) over Eurasia from June to September in 1989 and 1990. Data source: NOAA-CIRES, Climate Diagnostic Center (http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl).

wind-induced diversions and increased mixing of the Lena River freshwater plume.

The assumption that the annual and subdecadal variability of river discharge and the mixing process of riverine freshwater to bottom water respond to large-scale hemispheric climate patterns is supported by recent investigations, which suggest a correspondence between Eurasian river discharge and arctic atmospheric circulation like Arctic Oscillation (AO), or the North Atlantic Oscillation (NAO) (Peterson et al., 2002).

The AO, a key component of arctic climate variability, is a seesaw pattern in which atmospheric pressure at polar and middle latitudes fluctuates between positive and negative phases (Thompson and Wallace, 1998). The negative phase brings higher-than-normal pressure over the polar region and lower-than-normal pressure at about 45° North. The positive phase brings the opposite conditions, steering storm tracks and intensity farther north and bringing wetter conditions to Northern Europe and farther eastward into central Siberia. Strongly correlated with the AO is the North Atlantic Oscillation (NAO), which has also been suggested as a regional manifestation of the more general mode of AO (Mysak, 2001; Gimeno et al., 2002; Moritz et al., 2002). With a positive NAO index as in the 1990s, the Iceland Low deepens and extends further into the Arctic, from across the North Atlantic into Eurasia (Serreze et al., 2000). This increases wind and moisture transport eastward across the Barents Sea and into the Kara and Laptev seas (Macdonald et al., 2003) and can be recognized in an enhanced Lena River discharge (Fig. 3) and, consequently, in our bivalve records (Fig. 6).

Although the climate anomalies associated with the NAO are most pronounced during winter when the NAO is strongest, a correspondence between winter NAO and Eurasian river discharge, which typically occurs in Arctic rivers during summer, is obvious (Peterson et al., 2002). A positive NAO phase brings more moisture to Eurasia during winter, which is precipitated as snow during the cold season and discharged as riverine water during summer. Because more than 65% of the annual runoff in the Lena River drainage area is initiated by snowmelt (Koronkevitch, 2002), riverine discharge induced by snowmelt is an important factor for the Lena River discharge characteristic. The assumed relation between the wintertime

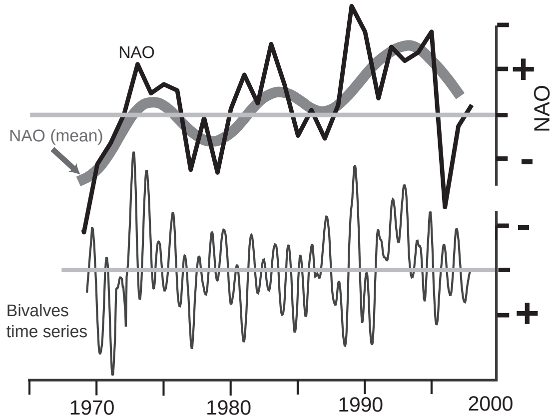

Fig. 6. Winter (December to March) index of the NAO from 1969 to 1998 (Hurrell et al., 1995). The heavy solid line denotes the NAO 4-year running mean. The lower record represents the merged bivalve time series from 1969 to 1998, deduced from the oxygen isotope profiles of the four investigated bivalve shells.

NAO and river discharge is consistent with a spatial analysis of precipitation that indicates that years with a positive winter NAO index are characterized by positive precipitation anomalies in summer, which are highest in Scandinavia but also extend across Siberia to the Lena River watershed (Dickson et al., 2000). Our reconstruction for the last 30 years reveals that there is a negative relation between the relative salinity time series reconstructed from the oxygen isotopes in the bivalve shells and the NAO index. In particular the high positive NAO peaks in 1989 and the positive NAO index in 1972, 1973 and between 1992 and 1995 are consistent with negative peaks in bivalve time series, which represent low-salinity bottom water in the Laptev Sea as a result of increased Lena River discharge. Although there are some similarities of NAO and the bivalve time series, a significant correlation is difficult to ascertain. Certainly, there are clear linkages between atmospheric circulation patterns and the Eurasian river discharge, but only the extreme events seem to be recorded in the oxygen isotope composition of our bivalves shells.

6. Summary and conclusion

The results in this study have shown that oxygen isotope profiles from bivalve shells can be used as a proxy for modern hydrographical changes in the arctic land–shelf system of the Laptev Sea. A composite δ^{18}O time series, merged together using individual records from 4 bivalves collected alive in different years, shows a destinated saw-toothed pattern of δ^{18}O change. These changes reflect the seasonal variations in bottom-water salinity in the eastern Laptev Sea from 1998 back to 1969. More positive δ^{18}O values indicate the hydrographical conditions during winter while more negative values are representative for summer conditions and reflect the strong influence of riverine freshwater discharged by the Lena River on the hydrographical regime in the eastern Laptev Sea. Both seasonal and annual variations can be traced in oxygen isotope time series of the bivalves. While the short amplitude isotope cycles reflect the hydrographical cycle in the eastern Laptev Sea on seasonal timescales, the annual and subdecadal variations of the summer δ^{18}O amplitude appear to be correlated with the amount of freshwater outflow from the Lena River.

In the arctic catchment area of the Lena River the discharge characteristic is primarily controlled by the season-induced discharge peak after river breakup in June, while the precipitation regime in the catchment area dominates the discharge characteristics to a lesser degree. Therefore, only summers with extreme precipitation anomalies in the catchment area are recognized in our oxygen isotope profiles from the eastern Laptev Sea shelf. Because of the assumed correspondence of Eurasian river discharge and arctic atmospheric circulation, we can conclude that the relative salinity changes in Laptev Sea bottom water, reconstructed from oxygen isotope of bivalve shells, are also linked to the variabilities of arctic atmospheric circulation phenomena. Despite some uncertainties, the general trend of arctic atmospheric circulation towards positive NAO or AO indices since the early 1990s is recognized in the shell isotope records from the Laptev Sea shelf.

This study has demonstrated the usefulness of oxygen isotope profiles from bivalve shells as a suitable and reliable recorder for shelf hydrographic processes, in particular with respect to the impact of river runoff and its seasonal, annual and subdecadal variability. Furthermore, it could be shown that the bivalve time series provide a high resolution marine proxy, which gives insight into arctic land–shelf interaction and its causal linkages to arctic atmospheric circulation patterns. Deduced from this applicability using isotope profile, from modern specimens, fossil bivalves can serve as good tool to extent the record of past Siberian river runoff.

Acknowledgment

The authors are grateful to R. W. Macdonald, L. A. Mysak and an anonymous reviewer, whose constructive reviews and comments helped to improve the article. Stable isotope analyses for this study were performed at the Leibniz Laboratory for Radiometric Dating and Stable Isotope Research of Kiel University. Many thanks to H. Erlenkeuser for fruitful discussions about stable isotopes in bivalve shells. This study was financially supported by the German Ministry of Education and Research and is a contribution to the bilateral Russian–German research project "Laptev Sea System".

References

Aagaard, K., Carmack, E.C., 1985. Thermohaline circulation in the Arctic Mediterranean seas. Journal of Geophysical Research 90 (C3), 4833–4846.

Aagaard, K., Carmack, E.C., 1989. The role of sea ice and other fresh water in the arctic circulation. Journal of Geophysical Research 94 (C10), 14.485–14.498.

Arthur, M.A., Williams, D.F., Jones, D.S., 1983. Seasonal temperature–salinity changes and thermohaline development in the mid-Atlantic bight as recorded by the isotopic composition of bivalves. Geology 11, 655–659.

Bauch, D., Schlosser, P., Fairbanks, R.G., 1995. Freshwater balance and the source of deep and bottom waters in the Arctic Ocean inferred from distribution of $H_2^{18}O$. Progress in Oceanography 35, 53–80.

Bauch, H.A., Cremer, H., Kunz-Pirrung, M., 2000. Siberian Shelf sediments contain clues to paleoclimate forcing. EOS Transactions 81, 233–238.

Bauch, D., Erlenkeuser, H., Stanovoy, V., Simstich, J., Spielhagen, R.F., 2003. Freshwater distribution and brine waters in the southern Kara Sea in summer 1999 as depicted by δ^{18}O results. In: Stein, R., Fahl, K., Fütterer, D.K., Galimov, E.M., Stepanets, O.V. (Eds.), Siberian River run-off in the Kara Sea Characterisation, Quantification, Variability, and Environmental Significance, Proceedings in Marine Science, vol. 6. Elsevier, Amsterdam, pp. 73–90.

Bemis, B.E., Geary, D.H., 1996. The usefulness of bivalve stable isotope profiles as environmental indicators: data from the eastern Pacific Ocean and the Southern Caribbean Sea. Palaios 11, 328–339.

Carmack, E.C., 2000. The Arctic Ocean's freshwater budget: sources, storage and export. In: Lewis, E.L. (Ed.), The Freshwater Budget of the Arctic Ocean. Series 2, Environmental Security, vol. 70. Kluwer Academic Press, Dordrecht/Boston/London, pp. 91–126.

Dickson, R.R., Osborn, T.J., Hurrell, J.W., Meincke, J., Blindheim, J., Adlandsvik, B., Vinje, T., Alekseev, G., Maslowski, W., 2000. The Arctic Ocean response to the North Atlantic Oscillation. Journal of Climate (13), 2671–2696.

Dmitrenko, I.A., Golovin, P., Gribanov, V., Kassens, H., 1999. Oceanographic causes for transarctic ice transport of river discharge. In: Kassens, H., Bauch, H.A., Dmitrenko, I.A., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timokhov, L.A. (Eds.), Land–Ocean Systems in the Siberian Arctic: Dynamics and History. Springer, Berlin, pp. 73–92.

Dmitrenko, I.A., Hoelemann, J., Kirillov, S.A., Berezovskaya, S.L., Eicken, H., Kassens, H., 2001. Wind-forced currents as a linkage between the Laptev Sea (Siberia) and the Arctic ocean. Doklady Earth Science MAIK Nauka 377/1, 1–8 (in Russian).

Eicken, H., Reimnitz, E., Alexandrov, V., Martin, T., Kassens, H., Viehoff, T., 1997. Sea-ice processes in the Laptev Sea and their importance for sediment transport. Continental Shelf Research 17/2, 205–233.

Epstein, S.R., Buchsbaum, R., Lowenstam, H.A., Urey, H.C., 1953. Revised carbonate water isotopic temperature scale. Geological Society of America Bulletin 64, 1315–1326.

Erlenkeuser, H., Wefer, G., 1981. Seasonal growth of bivalves from Bermuda recorded in their O-18 profiles. Proceedings of the 4th International Coral Reef Symposium (Manila) 2, 643–648.

EWG (Environmental Working Group), 1998. Joint U.S.–Russian Arctic Ocean Atlas for Winter and Summer Period (1950–1990). NSIDC, University of Colorado.

Gimeno, L., Ribera, P., Nieto, R., Pérez, J.F., Vidal, O., de la Torre, L., Gallego, D., García, R., Hernández, E., 2002. Imprints of the North Atlantic oscillation on four unusual atmospheric parameters. Earth and Planetary Science Letters 202, 677–692.

Global Runoff Data Center. Bundesanstalt für Gewässerkunde, D-56002 Koblenz, Germany.

Grossman, E.L., Ku, T.-L., 1986. Oxygen and carbon isotope fractionation in biogenic aragonite: temperature effects. Chemical Geology 59, 59–74 (Isotope Geoscience Section).

Gukov, A. Yu., 1999. Ecosystem of the Siberian Polynya. 334 pp. Moscow, Nauchny Mir (in Russian).

Hickson, J.A., Johnson, A.L.A., Heaton, T.H.E., Balson, P.S., 1999. The shell of the queen scallop *Aequipecten opercularis* (L.) as a promising tool for palaeoenvironment reconstruction: evidence and reasons for equilibrium stable-isotope incorporation. Palaeogeography, Palaeoclimatology, Palaeoecology 154, 325–337.

Hurrell, J.W., Kushnir, Y., Visbeck, M., 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. Science 269, 676–679.

IPCC, 2001. Climate change 2001: the scientific basis. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 881 pp.

Israelson, C., Buchardt, B., Funder, S., Hubberten, H.-W., 1994. Oxygen and carbon isotope composition of Quaternary bivalve shells as a water mass indicator: last interglacial and Holocene, East Greenland. Palaeogeography, Palaeoclimatology, Palaeoecology 111, 119–134.

Jones, D.S., Williams, D.F., Romanek, C.S., 1986. Life history of symbiont-bearing giant clams from stable isotope profiles. Science 231, 46–48.

Kerr, R.A., 1999. Climate change: will the Arctic ocean lose all its ice? Science 286, 1828.

Khim, B.-K., Woo, K.S., Je, J.-G., 2000. Stable isotope profiles of bivalve shells: seasonal temperature variations, latitudinal temperature gradients and biological carbon cycling along the east coast of Korea. Continental Shelf Research 20, 843–861.

Khim, B.-K., Krantz, D.E., Brigham-Grette, J., 2001. Stable isotope profiles of Last Interglacial (Pelukian Transgression) molluscs and paleoclimate implications in the Bering Strait region. Quaternary Science Reviews 20, 461–483.

Khim, B.-K., Krantz, D.E., Cooper, L.W., Grebmeier, J.M., 2003. Seasonal discharge of estuarine freshwater to the western Chukchi Sea shelf identified in stable isotope profiles of mollusk shells. Journal of Geophysical Research 108 (C9), 3003.

Koronkevitch, N.I., 2002. Land Resources of Russia. Version 1.1, http://www.iiasa.ac.at/Research/FOR/russia_cd/intro.htm.

Krantz, D.E., Williams, D.F., Jones, D.S., 1987. Ecological and paleoenvironmental information using stable isotope profiles from living and fossil molluscs. Palaeogeography, Palaeoclimatology, Palaeoecology 58, 249–266.

Krantz, D.E., Kronick, A.T., Williams, D.F., 1988. A model for interpreting continental-shelf hydrographic processes from stable isotope and cadmium:calcium profiles of scallop shells. Palaeogeography, Palaeoclimatology, Palaeoecology 64, 123–140.

Létolle, R., Martin, J.M., Thomas, A.J., Gordeev, V.V., Gusarova, S., Sidorov, I.S., 1993. ^{18}O abundance and dissolved silicate in the Lena delta and Laptev Sea (Russia). Marine Chemistry 43, 47–64.

Macdonald, R.W., 2000. Arctic estuaries and ice: a positive–negative estuarine couple. In: Lewis, E.L., Jones, E.P., Lemke, P., Prowse, T.D., Wadhams, P. (Eds.), The Freshwater Budget of the Arctic Ocean. Kluwer Academic Publishers, Dordrecht, pp. 383–407.

Macdonald, R.W., McLaughlin, F.A., Carmack, E.-C., 2002. Freshwater and its sources during the SHEBA drift in the Canada basin of the Arctic ocean. Deep-Sea Research. Part I 49 (10), 1769–1785.

Macdonald, R.W., Harner, T., Fyfe, J., Loeng, H., Weingartner, T., 2003. AMAP assessment 2002. The Influence of Global Change on Contaminant Pathways to, Within, and From the ArcticArctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xii+ 65 pp.

Moritz, R.E., Bitz, C.M., Steig, E.J., 2002. Dynamics of recent climate change in the Arctic. Science 297, 1497–1502.

Mueller-Lupp, T., Bauch, H.A., Erlenkeuser, H., 2003. Seasonal and interannual variability of Siberian river discharge in the Laptev Sea inferred from stable isotopes in modern bivalves. Boreas 32, 292–303.

Mysak, L.A., 2001. Patterns of arctic circulation. Science 293, 1269–1270.

Overpeck, J., Hughen, K., Hardy, D., Bradley, R., Case, R., Douglas, M., Finney, B., Gajewski, K., Jacoby, G., Jennings, A., Lamoureux, S., Lasca, A., MacDonald, G., Moore, J., Retelle, M., Smith, S., Wolf, A., Zielinski, G., 1997. Arctic environmental changes of the last four centuries. Science 278, 1251–1256.

Peterson, B.J., Holmes, R.M., McCelland, J.W., Vörösmarty, C.J., Lammers, R.B., Shiklomanov, A.I., Shiklomanov, I.A., Rahmstorf, S., 2002. Increasing river discharge to the Arctic ocean. Science 298, 2171–2173.

Petryashov, V.V., Sirenko, B.I., Golikov, A.A., Novozhilov, A.N., Rachor, E., Piepenburg, D., Schmid, M.K., 1999. Macrobenthos distribution in the Laptev Sea in relation to hydrology. In: Kassens, H., Bauch, H.A., Dmitrenko, I.A., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timokhov, L.A. (Eds.), Land–Ocean Systems in the Siberian Arctic: Dynamics and History. Springer, Berlin, pp. 169–180.

Pivovarov, S.V., Hoelemann, J., Kassens, H., Antonov, M., Dmitrenko, I., 1999. Dissolved oxygen, silicon, phosphorous and suspended matter concentrations during the spring breakup of the Lena river. In: Kassens, H., Bauch, H.A., Dmitrenko, I.A., Eicken, H., Hubberten, H.-W., Melles, M., Thiede, J., Timokhov, L.A. (Eds.), Land–Ocean Systems in the Siberian Arctic: Dynamics and History. Sringer, Berlin, pp. 251–264.

Rahmstorf, S., 1995. Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle. Nature 378, 145–149.

R-ArcticNet (Draft v3.0), 2004. A regional hydrographic data network for the pan-arctic region. Water System Analysis Group, University of New Hampshire, http://www.R-arcticnet.sr.unh.edu.

Schöne, B.R., Lega, J., Flessa, K.W., Goodwin, D.H., Dettman, D.L., 2002. Reconstructing daily temperatures from growth rates of the intertidal bivalve mollusk *Chione cortezi* (northern Gulf of California, Mexico). Paleogeography, Paleoclimatology, Paleoecology 184, 131–146.

Schöne, B.R., Flessa, K.W., Dettmann, D.L., Goodwin, D.H., 2003. Upstream dams downstream clams: growth rates of bivalve mollusks unveil impact of river management on estuarine ecosystems (Colorado River Delta, Mexico). Estuarine, Coastal and Shelf Science 57, 1–12.

Schumacher, C.F., 1817.: Essai d'un noveau système des habitations des Vers testacé. pl. I–XXII, Copenhague (L'imprimerie de MR le Directeur Schulz). 287 pp.

Semiletov, I.P., Savelieva, N.I., Weller, G.E., Pipko, I.I., Pugach, S.P., Gukov, A. Yu., Vasilevskaya, C.N., 2000. The dispersion of Siberian river flows into coastal waters: meteorological, hydrological and hydrochemical aspects. In: Lewis, E.L. (Ed.), The Freshwater Budget of the Arctic Ocean. Series 2, Environmental Security vol. 70. Kluwer Academic Press, Dordrecht/Boston/London, pp. 323–366.

Serreze, M.C., Walsh, J.E., Chapin III, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., Barr, R.G., 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change 46 (1–2), 159–207.

Simstich, J., Stanovoy, V., Novikhin, A., Erlenkeuser, H., Spielhagen, R.F., 2003. Stable isotope ratios in bivalve shells: suitable recorders for salinity and nutrient variability in the Kara Sea? In: Stein, R., Fahl, K., Fütterer, D.K., Galimov, E.M., Stepanets, O.V. (Eds.), Siberian River Run-Off in the Kara Sea Characterisation, Quantification, Variability, and Environmental Significance, Proceedings in Marine Science, vol. 6. Elsevier, Amsterdam, pp. 111–124.

Thompson, D.W.J., Wallace, J.M., 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature field. Geophysical Research Letters 25 (9), 1297–1300.

Wegner, C., Hölemann, J.A., Dmitrenko, I., Kirillov, S.A., Tuschling, K., Abramova, E., Kassens, H., 2003. Suspended particulate matter on the Laptev Sea shelf (Siberian Arctic) during ice-free conditions. Estuarine, Coastal and Shelf Science 57, 55–64.

Weidmann, C.R., Jones, G.A., 1994. The long-lived mollusc *Arctica islandica*: a new paleoceanographic tool for the reconstruction of bottom temperatures for the continental shelves of the northern North Atlantic Ocean. Journal of Geophysical Research 99 (C9), 18305–18314.