Climate states and variability of Arctic ice and water dynamics during 1946–1997

Andrey Y. Proshutinsky, Igor V. Polyakov &
Mark A. Johnson

Recently observed changes in the Arctic have highlighted the need for a better understanding of Arctic dynamics. This research addresses that need and is also motivated by the recent finding of two regimes of Arctic ice – ocean wind-driven circulation. In this paper, we demonstrate that during 1946–1997 the Arctic environmental parameters have oscillated with a period of 10–15 years. Our results reveal significant differences among atmosphere, ice, and ocean processes during the anticyclonic and cyclonic regimes in the Arctic Ocean and its marginal seas. The oscillating behaviour of the Arctic Ocean we call the Arctic Ocean Oscillation (AOO). Based on existing data and results of numerical experiments, we conclude that during the anticyclonic circulation regime the prevailing processes lead to increases in atmospheric pressure, in ice concentration and ice thickness, river runoff, and surface water salinity – as well as to decreases in air temperature, wind speed, number of storms, precipitation, permafrost temperatures, coastal sea level, and surface water temperature. During the cyclonic circulation regime the prevailing processes lead to increased air and water temperatures, wind speed, number of storms, open water periods, and to decreases in ice thickness and ice concentration, river runoff, atmospheric pressure, and water salinity. The two-climate regime theory may help answer questions related to observed decadal variability of the Arctic Ocean and to reconcile the different conclusions among scientists who have analysed Arctic data obtained during different climate states.

A. Y. Proshutinsky, I. V. Polyakov & M. A. Johnson, Institute of Marine Science, University of Alaska Fairbanks, P.O. Box 757200, Fairbanks, AK 99775-7220, USA.

Introduction

Recently observed changes in the Arctic Ocean's hydrographic characteristics (Quadfasel 1991; Rudels et al. 1994; Carmack et al. 1995; Carmack & Aagaard 1996; Morison 1996) and ice conditions (Maslanik, Serreze et al. 1996; Cavalieri et al. 1997) have highlighted the need for a better understanding of Arctic climate variability. For example, Morison (1996) reports that the new observational data "indicate a fundamental change in the circulation of the Arctic Ocean beginning in the early 1990s." In addition, Carmack & Aagaard (1996) conclude that "remarkable new observations call for a revised conceptual model of the Arctic Ocean, and a rethinking of theory and process parameterization." Our research may help explain these observed changes in the Arctic. It builds upon the recent findings of two regimes of Arctic Ocean ice and water circulation described by Proshutinsky & Johnson (1997).

The two-climate regime theory may help answer questions related to the observed variability of the Arctic Ocean, and to reconcile the different conclusions among scientists who have analysed hydrographic data, water circulation, ice thickness, ice motion, and other parameters obtained during different climate states.

Wind-driven circulation regimes

Proshutinsky & Johnson (1997) simulated wind-driven ice and water motion in the Arctic Ocean from 1946 through 1993 and validated the

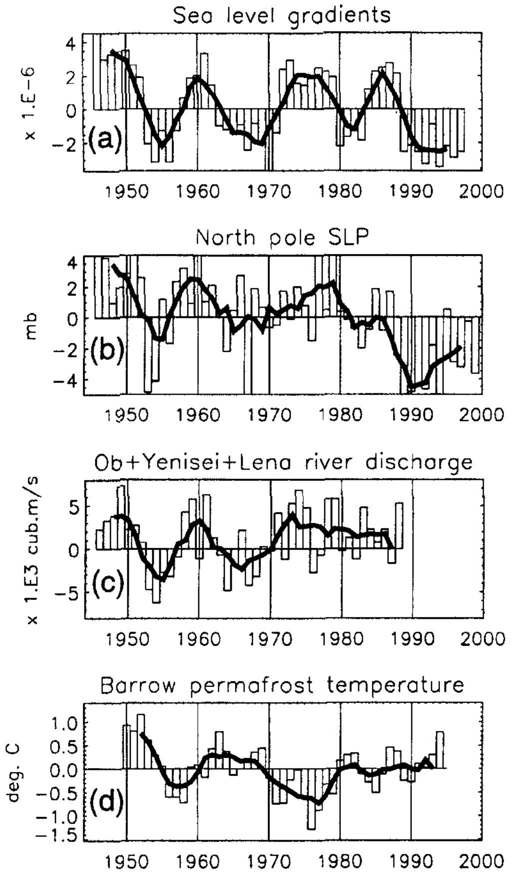

Fig. 1. Decadal variability of (a) sea level gradients in the center of the Arctic Basin (Arctic Ocean Oscillation), (b) north pole SLP anomaly, (c) Siberian rivers discharge anomaly, and (d) Barrow permafrost temperature anomaly. Bars represent annual mean anomaly and solid thick line shows 5 year running mean anomaly.

modelled ice motion with data from 630 drifting surface buoys and 31 "north pole" stations. We have updated our model results through 1997. To determine the variability of the Arctic Ocean's circulation, the sea level slope near the center of the Arctic Basin was examined as a measure of cyclonicity and anticyclonicity (see Protushinsky & Johnson 1997 for details). The time series of the sea level gradients from 1946 through 1997 shows an Arctic Ocean Oscillation (AOO) (Fig. 1a) with two major regimes describing the modelled wind-driven ice and water motion. One regime is characterized by anticyclonic circulation (positive anomaly) and the second regime is characterized by cyclonic ice and water motion (negative anomaly). Regime shifts between cyclonic and anticyclonic flow occur at 5–7 year intervals, resulting in a 10–15 year period. The anticyclonic circulation regime (ACCR) is observed in the model results for 1946–1952, 1958–1962, 1972–79, and 1984–88. The cyclonic circulation regime (CCR) prevailed during 1953–57, 1963–1971, 1980–83, and 1989–1997. In this paper, we compare the simulated and observed sea level at stations along the Arctic Ocean coastline (Fig. 2). Coefficients of correlation between observed and simulated sea level are higher than 0.7. The good agreement between modelled and observed parameters confirms a generally accurate reproduction of the ice and water circulation, and further validates the two-regime theory.

Observations

The north pole sea level atmospheric pressure (SLP), Siberian river runoff (Ob, Yeanisei and Lena rivers), Barrow permafrost temperature, index of the North Atlantic Oscillation (NAO), dynamical heights in the Beaufort Gyre, ice extent in the Arctic Ocean, sea ice anomalies in Davis Strait and in the Bering Sea, and some other environmental parameters have similar variability to the AOO (Fig. 1, Table 1). For example, increased Bering Sea ice extent occurs in the periods of anticyclonic circulation. High atmospheric pressure at the north pole drives the anticyclonic wind-driven regime and low SLP at the north pole leads to the cyclonic circulation. Siberian river runoff increases during ACCR and decreases during CCR.

We have examined the recent findings of others on changes observed in the Arctic and have attempted to characterize their results in terms of the two regimes of circulation (Table 1). Some of these relations can be easily explained while others are difficult to understand. A full comparison is in progress. To compensate for the lack of observational data in many of the Arctic Ocean regions, we have analysed results of a set of numerical experiments using a three-dimensional thermodynamic coupled ice–ocean model.

Thermodynamic aspects of two circulation regimes

The experiments with the 3-D thermodynamic

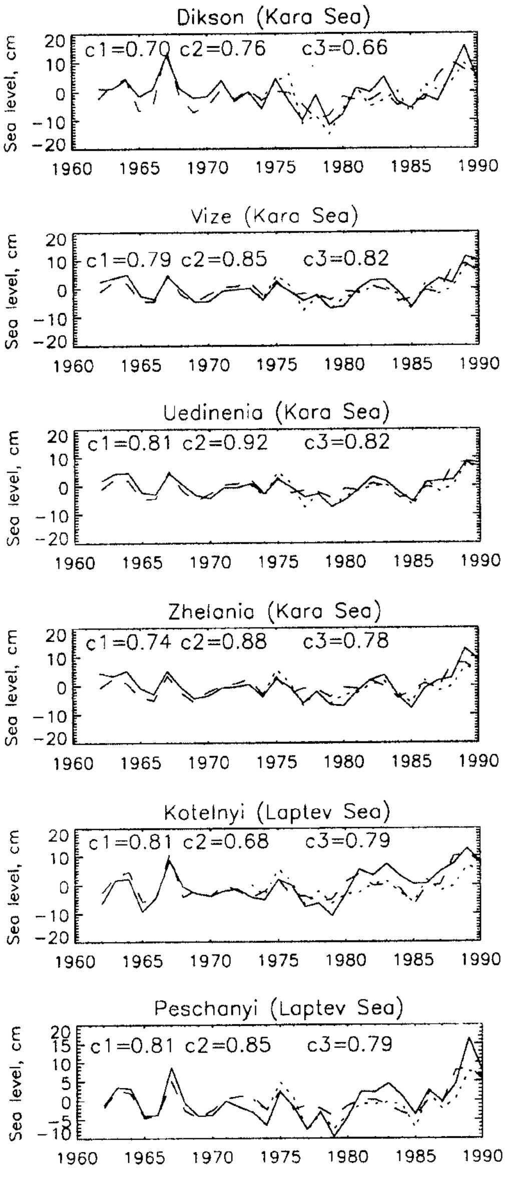

Fig. 2. Annual mean sea level (cm) at the coastal stations and islands of the Kara and Laptev seas. Solid line depicts observations. Dashed line shows simulation result using 1946–1997 SLP derived from observations (Experiment 1). Dotted lines show simulation result based on 1973–1997 NCAR/NCEP reanalysis data set (Experiment 2). C1, C2, and C3 are correlation coefficients between observed and simulated sea level in Experiment 1, Experiment 2, and between simulated sea levels in Experiment 1 and 2, respectively. Location of stations is shown in Fig. 6.

coupled ice-ocean model were specially designed to further test our hypothesis of two circulation regimes. The model description, experiment design, and some preliminary results are presented in Proshutinsky et al. (1997a, b) and Polyakov et al. (1998). Here we discuss results of a simulation of ice and water dynamics for 1987 and 1992, which are typical years of ACCR and CCR, respectively. Analyses of the results of numerical experiments reveal significant differences between environmental parameters during the two different regimes of Arctic system variability. These regimes are not only characterized by differences in the ice drift (Fig. 3, Table 1) and ocean surface currents (not shown), they are also associated with major changes in ice thickness and concentration, water temperature and water salinity of the upper 50 m ocean layer (Fig. 4).

In general, our 3-D model simulations and observational data show that during ACCR, the "winter" conditions with cold (see Fig. 5) and dry atmosphere, increased ice thickness and concentration, increased water salinity, and decreased water temperature (Fig. 4) prevail over the seasonal cycle. During CCR, the "summer" Arctic conditions dominate with a relatively warm and wet atmosphere (Fig. 5), decreased ice thickness and concentration, decreased water salinity, and increased water temperature (Fig. 4).

Variability of ice thickness has been discussed by Wadhams (1994), McLaren et al. (1994), and Vinje et al. (1998). From our theory, this variability is closely related to the two climate regimes (Proshutinsky & Johnson). For example, during the CCR, the ice in Fram Strait is thicker than during the ACCR because thicker ice is transported from the Canadian Basin. At the same time, ice becomes thinner near the north pole because the Transpolar Drift is shifted toward Greenland and carries relatively thin ice from the Siberian seas to the north pole region. An approximately 20% decrease in ice volume occurs in the CCR years. This decrease is defined mainly by changes in the ice thickness. The corresponding decrease of the ice area across the entire Arctic Ocean is less than 5%. The simulated decrease of ice area during CCR (not shown) is in good agreement with observations (Maslanik, Serreze et al. 1996; Cavalieri et al. 1997).

Several processes lead to the ice deficit during CCR. Counter-clockwise summer ice drift causes a flushing of ice from the Siberian sector of the Arctic and decreases ice concentration in the central Arctic while there is an accumulation and ridging of ice along the coast of the Canadian

Table 1. Interpretation of observed and simulated anomalies of environmental parameters in terms of the two regimes theory. N = negative anomaly, P = positive anomaly, A = anticyclonic circulation, C = cyclonic circulation.

Parameter	Anomaly ACCR	Anomaly CCR	Data source
Atmospheric vorticity over the polar cap	N	P	Tanaka et al. 1995
Sea level atmospheric pressure	P	N	Proshutinsky & Johnson 1996, 1997; Walsh et al. 1996
NAO index before 1968	P	N	Hurrell 1995
NAO index after 1968	N	P	Hurrell 1995
Surface air temperature	N	P	Martin & Muñoz 1997
Duration of ice melt season	N	P	Smith 1998
Sea ice extent	P	N	Maslanik, Serreze et al. 1996, Cavalieri et al. 1997
Summer ice concentration	P	N	Maslanik, Serreze et al. 1996
Sea ice thickness	P	N	Proshutinsky et al. 1997a, b, this study
Ice drift	A	C	Proshutinsky & Johnson 1997; Int. Arctic Buoy Program
Ice extent in the Bering Sea	P	N	Niebauer 1988
Ice extent in Davis Strait	P	N	Agnew 1991
Upper 30 m layer circulation	A	C	Proshutinsky et al. 1997a, b; Jones et al. 1998
Upper 50 m layer water temperature in the Arctic Basin	N	P	EWG 1997
Upper 50 m water salinity in the Arctic Basin	P	N	EWG 1997, see references in Introduction
Sea level along coast line	N	P	EWG 1997, Introduction
Depth of upper boundary of Atlantic water along continental slope	P	N	EWG 1997, Introduction
Dynamical heights in the Beaufort Gyre	N	P	EWG 1997, Introduction
Atlantic water temperature	N	P	EWG 1997, Introduction
Atlantic water salinity	N	P	EWG 1997, Introduction
Atlantic water transport through Fram Strait	N	P	EWG 1997, Introduction
Atlantic water transport through the Barents Sea	N	P	Rudels et al. 1994; this study
Deep water formation in the Greenland Sea	P	N	Speculation
Deep water formation in the Labrador Sea	N	P	Speculation
Siberian rivers runoff	P	N	EWG 1997, Introduction
Permafrost temperature	N	P	Osterkamp et al. 1994

Archipelago and northern Greenland. The ice transport through Fram Strait is increased because the ice penetrates to Fram Strait from the Canadian sector of the Arctic, and according to observations and our model results, moves faster during CCR. During the following winter, normally ice-free areas of the Arctic Ocean are covered by first year ice. Repetition of this process during several years of CCR leads to a thinning of ice in the central Arctic where numerous summer openings result in warming and accumulation of heat in the upper ocean layer which in turn increases the length of the ice melt season. This result agrees with observations (Smith 1998). Higher water temperature of the upper ocean layer during CCR is the second factor reducing the ice volume in the Arctic Ocean during CCR. Atmospheric winds redistribute ice mechanically and thermodynamic factors lead to changes of ice thickness. According to our model results, 80% of the ice thickness variability between ACCR and CCR is due to winds and only 20% is due to air surface temperature variability. This conclusion coincides with the results of Harder et al. (1997) and Maslanik, Fowler et al. (1997). Additional ice melt freshens the upper ocean layer and increases the outflow of fresh water from the central Arctic into the Greenland Sea through Fram Strait (not shown).

Discussion

Recent observations show that after 1989 many ocean characteristics changed from the 1951–1980 Russian climate study (Gorshkov 1983). Many researchers have compared atmosphere, ice and ocean parameters before and after 1989 (Walsh et al. 1996; McPhee et al. 1998; Morison 1996; Jones et al. 1998; Steele & Boyd 1998; Zhang et al.

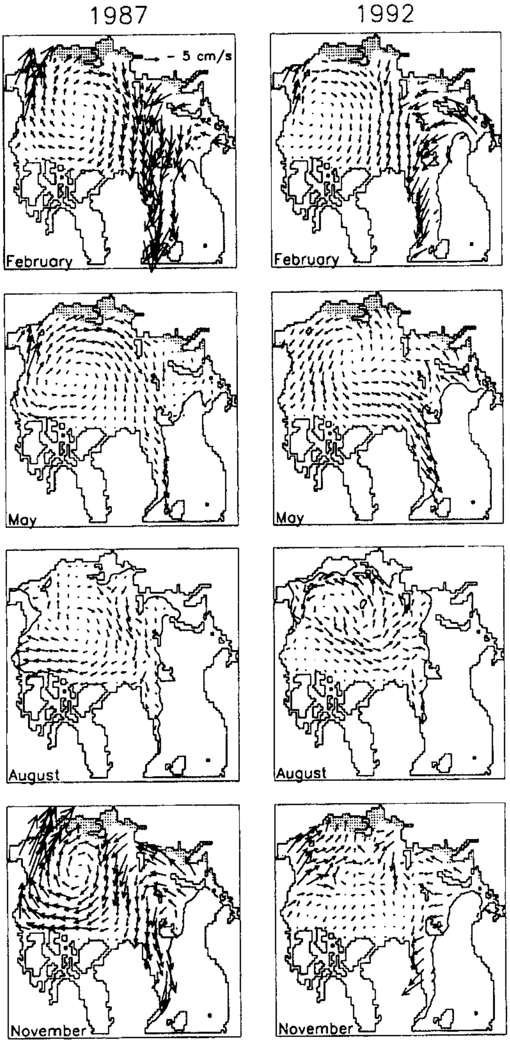

Fig. 3. Seasonal variability of the ice drift and ice edge location (solid line) in 1987 (ACCR) and 1992 (CCR). Vectors are shown at every fourth grid point. Dotted areas depict location of fast ice.

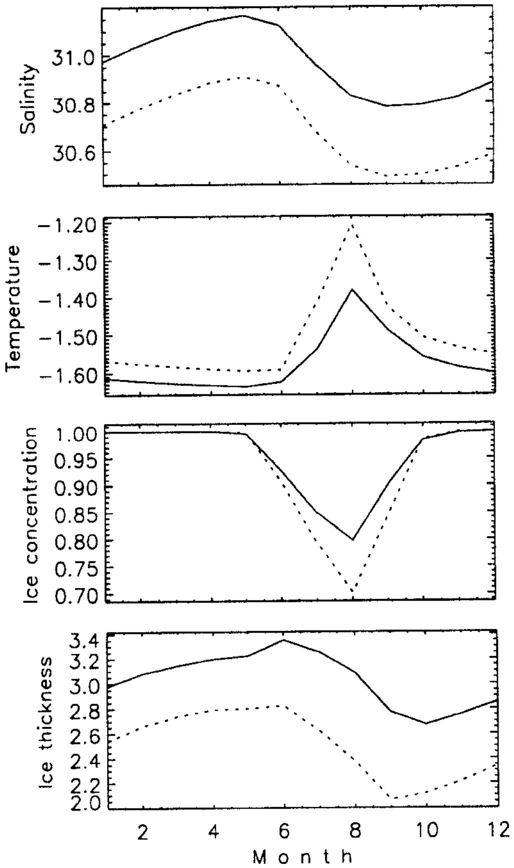

Fig. 4. Seasonal variability of ice and water parameters in 1987 (ACCR, solid line) and in 1992 (CCR, dotted line). Water temperature and salinity are averaged for the upper 50 m ocean layer of the Arctic Basin.

1998), and describe this change as a climate shift. We believe that similar changes in the Arctic have occurred in the past. Satellite and buoy drift observations of Arctic ice demonstrate two modes (defined by Gloerson et al. [1992] as Siberian and Alaskan) in the summer pack ice behavior, which are evenly distributed over the period between 1979 and 1987 (before the climate shift in 1989). The Siberian mode occurs when the Beaufort Gyre and the Transpolar Drift are well-developed (corresponds to ACCR). The Alaskan mode occurs when the Beaufort Gyre weakens and Transpolar Drift shifts toward Greenland (corresponds to CCR). Recent results by Jones et al. (1998) are in agreement with this conclusion about cyclonic ice and water motion in the Arctic after 1989. They deduce circulation patterns from the distribution of Atlantic and Pacific waters in the upper 30 m layer of the Arctic Ocean based on nitrate and phosphate analyses, and conclude that the surface layer moves cyclonically (as in CCR).

The *Joint U.S.-Russian atlas of the Arctic Ocean* (EWG 1997) presents temperature and salinity averaged decadally from the 1950s through the 1980s; unfortunately, this decadal averaging does not coincide with the periods of natural variability based on the AOO. Because the decadal averaging aliases much of the existing natural variability, it would be better to average the

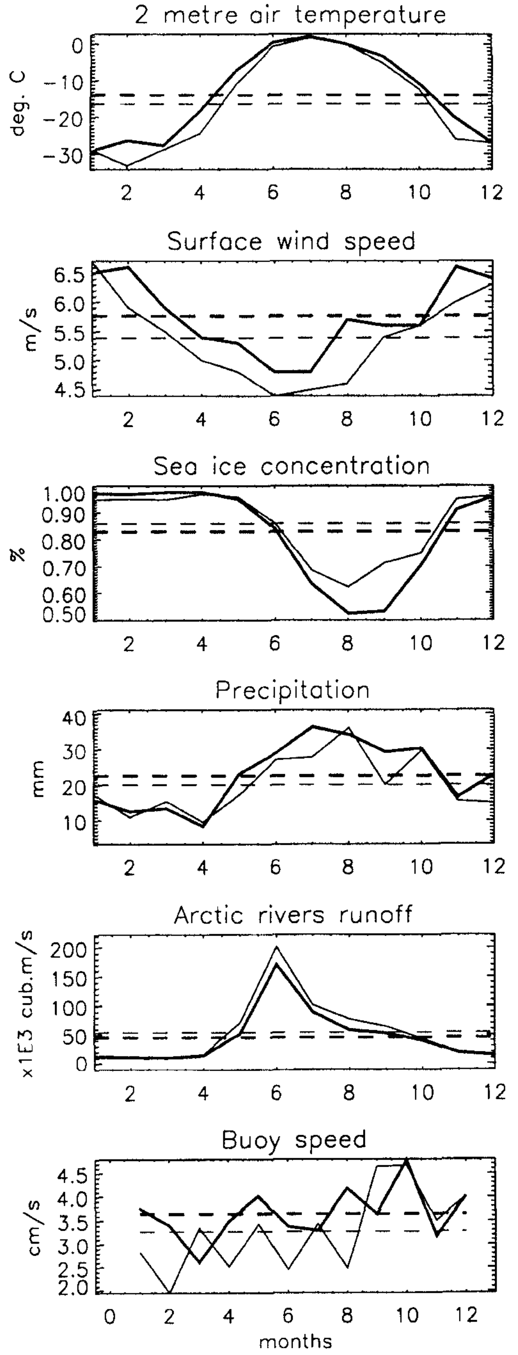

Fig. 5. Seasonal variability of environmental parameters for multi-year mean ACCR (thin lines) and CCR (thick lines) conditions.

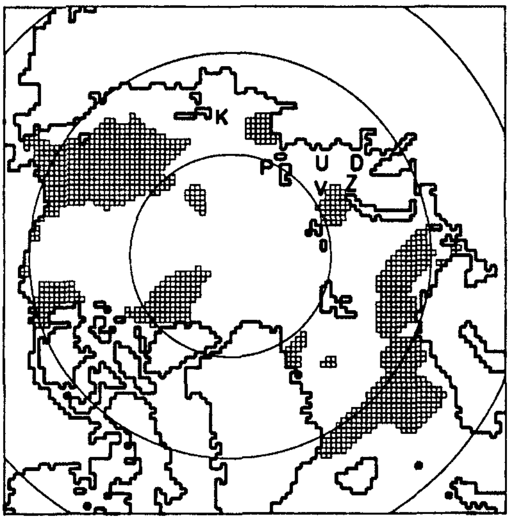

Fig. 6. Salinity difference of the upper 50 m layer between the 1980s and 1970s (data from EWG, 1997). Hatched area depicts regions with salinization of the upper 50 m layer in the 1980s. D, V, U, Z, K, and P show location of stations Dikson, Vize, Uedinenia, Zhelania, Kotelnyi and Peschanyi (see Fig. 2).

information for the periods of ACCR and CCR. Fortunately, some differences between CCR and ACCR have survived even in the decadally averaged atlas data. If we decadally average sea level gradients (not shown) we can conclude that the 1950s experienced climate conditions close to the mean; that the '60s and '80s were decades dominated by the CCR; and that during the 1970s, the ACCR prevailed in the Arctic. The salinity (Fig. 6) and temperature (not shown) anomalies obtained from the atlas show that, indeed, in the 1980s the upper ocean layer was fresher and warmer, and that in the 1970s it was colder and saltier than Russian climatological data presented in Gorshkov (1983). Note that the 1970s and 1980s were not purely anticyclonic and cyclonic; therefore anomalies are not so pronounced as in the 1990s (McPhee et al. 1998; Steele & Boyd 1998).

The nature of these processes is still uncertain. There is a good correlation between river runoff and AOO before 1966, but the later correlation is weaker. There is also good correlation between the NAO and ice concentration in summer in the Laptev Sea (not shown), between NAO and AOO, and between NAO and air temperatures in the Norwegian Sea after 1966 (not shown), between NAO and North Pole SLP after 1978 (not shown); but before 1966, these correlations had different signs or the processes were not correlated at all. A temporal boundary between correlated and uncorrelated processes in the North Atlantic coincides with the beginning of the Great Salinity Anomaly (1964–68). In the North Pacific the temporal boundary coincides with the climate shift that occurred in 1976 (Niebauer 1988). Both climate shifts have changed the interdependence of natural processes in the Arctic–North Atlantic and Arctic–North Pacific systems. The reasons for these shifts should be the subject of future research.

Acknowledgements. – This research has been supported by the Wadati fund of the Geophysical Institute, UAF, and by a grant from the National Science Foundation (OPP 9806926). We would like to express our gratitude to our reviewers. Their suggestions greatly improved this paper.

References

Agnew, T. 1991: Simultaneous winter sea ice and atmospheric circulation anomaly patterns. *Fifth AMS Conference on Climate Variations (preprints).* Pp. 362–365. Denver: American Meteorological Soc.

Carmack, E. C. & Aagaard, K. 1996: The dynamic Arctic Ocean: spatial, temporal, and conceptual heterohenesies. Abstract. *EOS, Trans. Am. Geophys. Union 76(3)*, OS12.

Carmack, E. C., Macdonald, R. W., Perkin, R. G., McLaughlin, F. A. & Pearson, R. J. 1995: Evidence for warming of Atlantic water in the Southern Canadian Basin of the Arctic Ocean: results from the Larsen-93 expedition. *Geophys. Res. Lett. 22(9)*, 1061–1064.

Cavalieri, D. J., Gloersen, P., Parkinson, C. L., Comiso, J. C. & Zwally, H. J. 1997: Observed hemispheric asymmetry in global sea ice changes. *Science 278*, 1104–1106.

EWG (Environmental Working Group) 1997: *Joint U.S.-Russian atlas of the Arctic Ocean.* CD-ROM. Boulder: National Snow and Ice Data Center.

Gloersen, P., Campbell, W. J., Cavalieri, D. J., Comiso, C., Parkinson, C. L. & Zwally, H. J. 1992: *Arctic and Antarctic sea ice, 1978–1987: satellite passive-microwave observations and analysis.* Washington, D.C.: NASA.

Gorshkov, S. G. 1983: *Arctic Ocean.* Vol. 3. in S. G. Gorshkov (ed.): *The world ocean atlas.* Oxford: Pergamon.

Harder, M., Hilmer, M., Lemke, P., Steiner, N. & Windmuller, M. 1997: Modeling the variability of sea ice, 1973–1997. *Proceedings of the Conference on Polar Processes and Global Climate.* Rosario, Orcas Island, Washington, USA, 3–6 November 1997. Pp. 74–75.

Hurrell, J. W. 1995: Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science 269*, 676–679.

Jones, E. P., Anderson, L. G. & Swift, J. H. 1998: Distribution of Atlantic and Pacific waters in the upper Arctic Ocean: implications for circulation. *Geophys. Res. Lett. 25(6)*, 765–768.

Martin, S. & Muñoz, E. A. 1997: Properties of the Arctic 2-meter air temperature field for 1979 to the present derived from a new gridded dataset. *J. Clim. 10*, 1428–1440.

Maslanik, J., Fowler, C., Emery, W. & Weatherly, J. 1997: On the interannual variability of Arctic sea ice transport: relationships to atmospheric circulation modes and significance for GCM assessments. *Proceedings of the Conference on Polar Processes and Global Climate.* Rosario, Orcas Island, Washington, USA, 3–6 November 1997. Pp. 156–158.

Maslanik, J. A., Serreze, M. C. & Barry, R. G. 1996: Recent decreases in summer ice cover, and linkages to anomalies in atmospheric circulation. *Geophys. Res. Lett. 23(13)*, 1677–1680.

McLaren, A. S., Bourke, R. H., Walsh, J. E. & Weaver, R. L. 1994: Variability of sea-ice thickness over the north pole from 1958 to 1992. In O. M. Johannessen et al. (eds.): *The polar oceans and their role in shaping the global environment.* Pp. 363–371. Washington, D.C.: American Geophysical Union.

McPhee, M. G., Stanton, T. P., Morison, J. H. & Martinson, D. G. 1998: Freshening of the upper ocean in the Arctic: is perennial sea ice disappearing? *Geophys. Res. Lett. 25(10)*, 1729–1732.

Morison, J. E. 1996: Changes in upper ocean hydrography measured during the 1993 cruise of the USS Pargo. Abstract. *EOS, Trans. Am. Geophys. Union 76(3)*, OS12.

Niebauer, H. J. 1988: Effects of El Nino-Southern Oscillation and North Pacific weather patterns on interannual variability in the sub-Arctic Bering Sea. *J. Geophys. Res. 93*, 5051–5068.

Osterkamp, T. E., Zhang, T. & Romanovsky, V. E. 1994: Evidence for a cyclic variation of permafrost temperatures in Northern Alaska. *Permafrost Periglacial Process. 5*, 137–144.

Polyakov, I. V., Kulakov, I. Yu., Kolesov, S. A., Dmitriev, N. Eu., Pritchard, R. S., Driver, D. & Naumov, A. K. 1998: Coupled sea ice–ocean model of the Arctic Ocean. *J. Offshore Mech. Arct. Eng. 120*, 77–84.

Proshutinsky, A. & Johnson, M. 1996: Two regimes of Arctic Ocean circulation from ocean models and observations. Abstract. 1996 Ocean Sciences Meeting, San Diego, CA. *EOS, Trans. Am. Geophys. Union 76(3)*, OS29.

Proshutinsky, A. & Johnson, M. 1997: Two circulation regimes of the wind-driven Arctic Ocean. *J. Geophys. Res. 102*, 12493–12514.

Proshutinsky, A., Johnson, M. & Polyakov, I. 1997a: Decadal scale variability of the Arctic system. *Proceedings of Conference on Polar Processes and Global Climate.* Rosario, Orcas Island, Washington, USA, 3–6 November 1997. Pp. 206–208.

Proshutinsky, A., Polyakov, I. & Johnson, M. 1997b: Seasonal variability of the Arctic Ocean processes based on observations and numerical modeling. *Proceedings of Conference on Polar Processes and Global Climate.* Rosario, Orcas Island, Washington, USA, 3–6 November 1997. Pp. 203–205.

Quadfasel, D. 1991: Warming in the Arctic. *Nature 350*, 385.

Rudels, B., Jones, E. P., Anderson, L. G. & Kattner, G. 1994: On the intermediate depth waters of the Arctic Ocean. In O. M. Johannessen et al. (eds.): *The polar oceans and their role in shaping the global environment.* Pp. 33–46. Washington, D.C.: American Geophysical Union.

Steele, M. & Boyd T. 1998: Retreat of the cold halocline layer in the Arctic Ocean. *J. Geophys. Res. 103(C5)*, 10,419–10,436.

Smith, D. M. 1998: Recent increase in the length of the melt season of perennial Arctic sea ice. *Geophys. Res. Lett. 25(5)*, 655–658.

Tanaka, H. L., Kanohgi, R. & Yasunari, T. 1995: Recent abnormal weather in the Arctic. *Proceedings of the Wadati*

Conference on Global Change and the Polar Climate. 7–10 November 1995, Tsukuba Science City, Japan. Geophysical Institute, University of Alaska Fairbanks. Pp. 13–16.

Vinje, T., Nordlund, N. & Kvambekk, A. 1998: Monitoring ice thickness in Fram Strait. *J. Geophys. Res. 103(C5),* 10,437–10,449.

Wadhams, P. 1994: Sea ice thickness changes and their relation to climate. In Johannessen et al. (eds.): *The Polar oceans and their role in shaping the global environment.* Pp. 337–361. Washington, D.C.: American Geophysical Union.

Walsh, J. E., Chapman, W. L. & Shy, T. L. 1996: Recent decrease of sea level pressure in the central Arctic. *J. Clim. 9,* 480–486.

Zhang, J., Rothrock, D. A. & Steele, M. 1998: Warming of the Arctic by a strengthened Atlantic inflow: model results. *Geophys. Res. Lett. 25(10),* 1745–1748.