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Was the Atlantic water temperature in the West Spitsbergen Current predictable in the 1990s?

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[1] A major source of heat (and salt) for the Arctic Ocean is the Atlantic Water (AW) imported from the Norwegian Sea by the West Spitsbergen Current (WSC). Analysis of temperature records from the WSC has helped to link the warming of the Arctic Ocean to changes in the North Atlantic Oscillation (NAO) index. Here we analyze, using summer hydrographic data from a meridional section at 15°E in the northern Norwegian Sea, the interannual variability in the AW hydrography and its relation to the NAO index in the 1990s. We show that while the AW temperature exhibited a tendency to lag the NAO index, the AW salinity exhibited a tendency to lead the index. A surprising conclusion is that the AW temperature in the WSC was predictable one year in advance from the AW salinity. **Citation:** Schlichtholz, P., and I. Goszczko (2005), Was the Atlantic water temperature in the West Spitsbergen Current predictable in the 1990s?, *Geophys. Res. Lett.*, *32*, L04610, doi:10.1029/2004GL021724.

1. Introduction

[2] The reduction of sea ice thickness and extent in the Arctic was dramatic in the 1990s [*Rothrock et al.*, 2003; *Johannessen et al.*, 1999], and so was the warming of intermediate layers of the Arctic Ocean filled with Atlantic Water (AW) [*Quadfasel et al.*, 1991; *Grotefendt et al.*, 1998]. A major source of heat for the Arctic Ocean is the AW imported from the Norwegian Sea by the West Spitsbergen Current (WSC) [*Aagaard et al.*, 1985]. Analysis of temperature records from the WSC has helped to link the warming of the Arctic Ocean to changes of the wintertime weather pattern over the North Atlantic expressed by the North Atlantic Oscillation (NAO) index [*Dickson et al.*, 2000; *Blindheim et al.*, 2000; *Saloranta and Haugan*, 2001]. Identification of a systematic time-lag between the NAO index and temperature in the WSC would be encouraging for prediction of the Arctic Ocean change, but such a lag has not been evidenced.

[3] Here we show, using hydrographic data from the northern Norwegian Sea in the 1990s, that while the AW temperature exhibited a tendency to lag the NAO index, the AW salinity exhibited a tendency to lead the index. A surprising conclusion is that the AW temperature in the WSC was predictable one year in advance from the AW salinity.

2. Hydrographic Data

[4] For several years the Institute of Oceanology in Sopot has carried out summer hydrographic measurements in the northern Norwegian Sea from R/V *Oceania*, typically in July [*Jankowski and Schlichtholz*, 1993; *Piechura and Walczowski*, 1996; *Piechura et al.*, 2001]. Here we use data acquired along a meridional section at 15°E (Figure 1a) in the period 1991–99. The section starts at 70°N, to the south of the location where the Norwegian Atlantic Current (NwAC) bifurcates into a branch entering the Barents Sea and a branch continuing along the continental slope into Fram Strait as the WSC [*Gascard et al.*, 2004]. The section ends at ~75.5°N, which is ~1° of latitude to the south of the standard Norwegian hydrographic section across the WSC (the Sørkapp section) [*Blindheim et al.*, 2000]. Before 1996 the measurements along the 15°E section were typically made every 0.5° of latitude, and in 1996 the horizontal resolution was doubled (Figure 1b).

[5] AW can be identified along the entire (WHOLE) 15°E section in the upper, warm layer (Figure 2a) as a core of saline water (Figure 2b). We define this water mass in the $T - S$ (temperature-salinity) space as $T > 2°\text{C}$ and $S > 34.9$ [*Aagaard et al.*, 1985; *Schlichtholz and Houssais*, 1999]. The isotherm $T = 2°\text{C}$ runs in the main thermocline at the depth of ~500–600 m and separates the AW layer from the colder water beneath. The salinity limit $S = 34.9$ excludes some fresh surface water. To account for changes in the number and position of hydrographic stations in time, the average properties of the AW layer have been first calculated for each station, and then interpolated year by year on a common grid along the section. For final analysis, these interpolated AW properties have been further averaged over the WHOLE section and its southernmost (NwAC) and northernmost (WSC) parts (Figure 1b).

3. Interannual Variability

[6] A considerable interannual variability is seen in the development of both properties of the AW layer, its temperature and its salinity (Figures 3a and 3b, respectively). The average AW properties on the WHOLE section attain maximum values of ~5°C and ~35.08 in 1992 and 1999. Minimum values, lower by ~0.9°C and ~0.04 than the respective maximum values, are found in 1997. These interannual contrasts are comparable to the long-term trends between the 1960s and the 1990s on the Sørkapp section [*Dickson et al.*, 2000].

[7] Not all parts of the WHOLE section show exactly the same variability. For instance, a secondary temperature maximum, observed in 1995, is particularly large in the NwAC and the WSC. At both locations, the 1995 maximum attains the same value as the corresponding maximum in 1992 (Figure 3a). On the other hand, a secondary salinity maximum, clearly appearing in the NwAC in 1996, is not well pronounced in the WSC. In this part, the primary salinity

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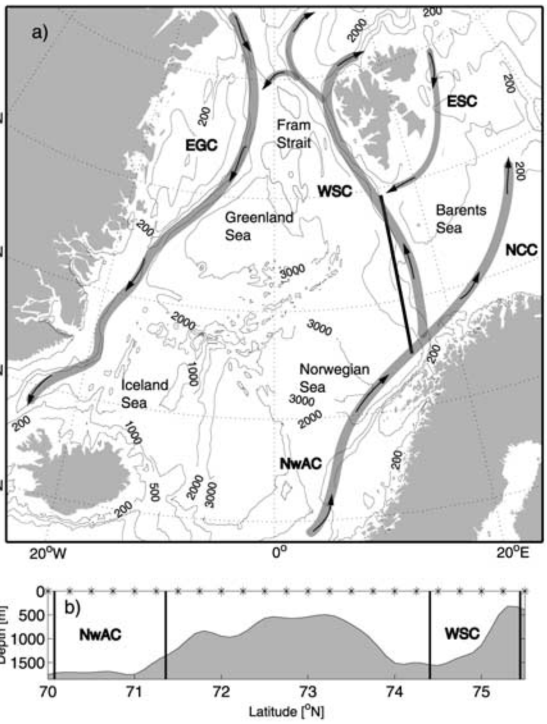


Figure 1. Area of interest. a) Bottom topography (in m) and schematics of main currents: NwAC- Norwegian Atlantic Current, NCC- North Cape Current, WSC- West Spitsbergen Current, ESC- East Spitsbergen Current, and EGC- East Greenland Current. The bold strait line indicates the location of the 15°E hydrographic section made on the cruises of R/V *Oceania* in the 1990s. b) Bottom topography along the 15°E section and the extent of the section parts referred to as the NwAC and the WSC in the text. The stars indicate typical locations of the hydrographic stations in the late 1990s.

maximum appears one year later than the corresponding maximum in the NwAC, i.e., in 1993 (Figure 3b). Some of these features may reflect noise in the data. However, high values of the AW properties in the beginning and the end of the 1990s, with an absolute minimum in 1997, are robust features. They are observed all along the WHOLE section. The absolute minimum appears one year later than a minimum in the average temperature of the 50–500 m layer at a more eastern location on the Sørkapp section [*Dickson et al.*, 2000].

4. Correlations With the North Atlantic Oscillation

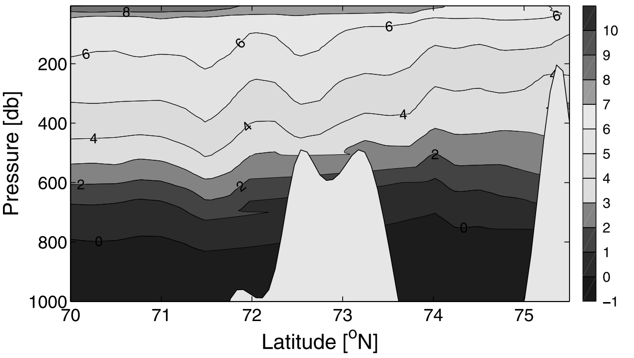
[8] The appearance of atypically cold AW on the Sørkapp section in summer 1996 was associated with a spectacular year-to-year change of the winter NAO index [*Dickson et al.*, 2000]. Table 1 gives values of correlation (r) between the winter NAO index, updated from *Hurrel* [1995], and the average AW properties on the WHOLE section and its parts calculated using the unsmoothed data (7 degrees of freedom) and the 3-yr running means (5 degrees of freedom).

[9] The only significant correlation between the unsmoothed series (at 95% level) is for the AW temperature in the NwAC ($r = 0.69$). The main discrepancy between that series and the NAO index is in the timing of the extreme negative anomaly, which in the AW temperature appears one year later, i.e., in 1997 (Figure 4a). The development of both variables in the beginning of the 1990s is similar, with maxima in 1992 and 1995 and a minimum in 1993. Moreover, the discrepancy in the timing of the negative extreme disappears in the smoothed series, in which both variables show a minimum in 1997 (Figure 4b). The smoothed AW temperature is well correlated with the smoothed NAO index not only in the NwAC ($r = 0.94$) but also in the WSC ($r = 0.88$). In the latter, also the correlation with the 1-yr advanced NAO index is high ($r = 0.88$).

[10] Contrary to the AW temperature, the AW salinity is better correlated with the NAO index in the WSC ($r = 0.91$). There the positive salinity anomaly in the beginning of the 1990s and the negative anomaly in the second half of the period lead (in the smoothed series) the corresponding extremes in the NAO index (Figure 4c). This results in a (moderately) high correlation also for the 1-yr delayed NAO index ($r = 0.83$). In the NwAC, the correlation for the 1-yr delayed NAO index ($r = 0.78$) is even higher than in the no-lag case.

[11] The maximum correlation values obtained here are relatively high compared to those from other studies on links between the NAO and the hydrography in the WSC area. The highest values for both, temperature ($r < 0.85$) and

a) Mean potential temperature [°C]



b) Mean salinity [psu]

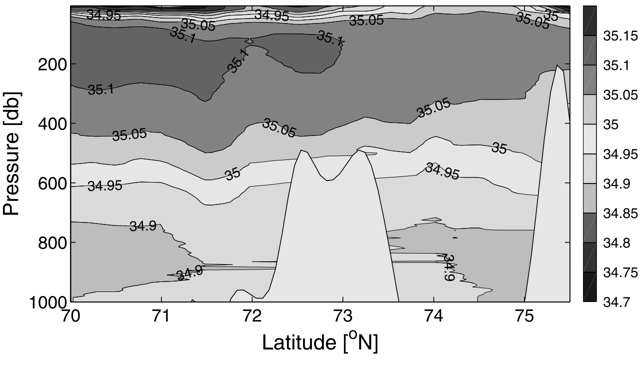


Figure 2. Vertical section of mean properties across the upper 1000-m layer on the 15°E section in the 1990s. a) Potential temperature. b) Salinity. See color version of this figure in the HTML.

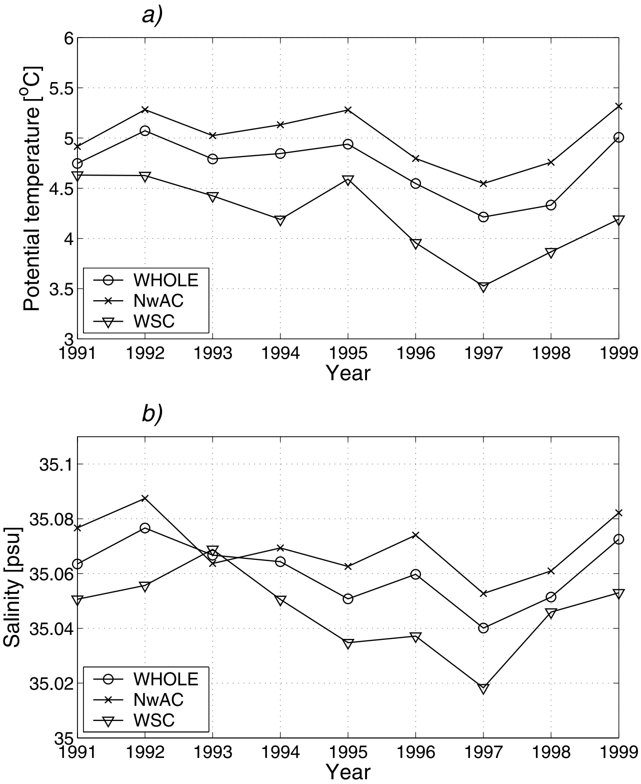


Figure 3. Temporal development of the AW properties averaged over the entire 15°E section (WHOLE) and its parts denoted as NwAC and WSC in Figure 1b. a) Potential temperature. b) Salinity.

salinity ($r < 0.65$) were reported in the core of the WSC farther north in Fram Strait in the period 1975–94 [*Saloranta and Haugan*, 2001]. The differences may partly be attributed to different locations of hydrographic stations, to slightly different layers considered, to noise of any kind, and, first of all, to the period considered since the link between the NAO index and the Arctic Ocean variables depends on the position of the NAO's centers [*Hilmer and Jung*, 2000; *Dickson et al.*, 2000].

Table 1. Correlations of the Winter NAO Index With the AW Properties in the Period 1991–99[a]

Area	−2 Year	−1 Year	No Lag	+1 Year	+2 Year
Correlation for the AW Temperature					
WHOLE ($s = 0$)	−0.29	0.12	0.63	0.53	0.22
WHOLE ($s = 1$)	−0.08	0.49	($\underline{0.93}$)	(0.86)	0.66
NwAC ($s = 0$)	−0.37	0.03	(0.69)	0.44	0.04
NwAC ($s = 1$)	−0.21	0.43	($\underline{0.94}$)	(0.83)	0.58
WSC ($s = 0$)	0.10	0.04	0.62	(0.69)	0.30
WSC ($s = 1$)	0.11	0.50	($\underline{0.88}$)	($\underline{0.88}$)	0.73
Correlation for the AW Salinity					
WHOLE ($s = 0$)	−0.06	0.56	0.31	0.49	0.08
WHOLE ($s = 1$)	0.29	(0.82)	(0.86)	0.64	0.46
NwAC ($s = 0$)	−0.11	0.38	0.09	0.40	0.20
NwAC ($s = 1$)	0.41	(0.78)	0.65	0.55	0.49
WSC ($s = 0$)	0.16	0.58	0.46	0.55	−0.22
WSC ($s = 1$)	0.29	(0.83)	($\underline{0.91}$)	0.63	0.38

[a] The AW properties are averaged over three areas (Figure 1b): the entire 15°E section from ∼70°N to 75.5°N (WHOLE), its southern part from ∼70°N to 71.5°N (NwAC), and its northern part from ∼74.5°N to 75.5°N (WSC). The correlations are calculated using the unsmoothed data ($s = 0$) and the 3-yr running mean values ($s = 1$). The no-lag column refers to the correlation of the summer oceanic variable with the atmospheric variable in winter of the same calendar year, i.e., about half a year earlier. The +1 (−1) year column refers to the correlation for the oceanic variable delayed (advanced) by one year. Values in parentheses (underlined) are significant at 95% (99%) level.

5. Discussion

[12] Even though some correlations obtained for lagged variables are significant, the highest correlations are found in the no-lag case. The conclusion that no obvious time-lag appears between the NAO index and the AW properties at the WHOLE section is in agreement with the investigations in adjacent areas [*Blindheim et al.*, 2000; *Dickson et al.*, 2000; *Saloranta and Haugan*, 2001]. However, the fact that

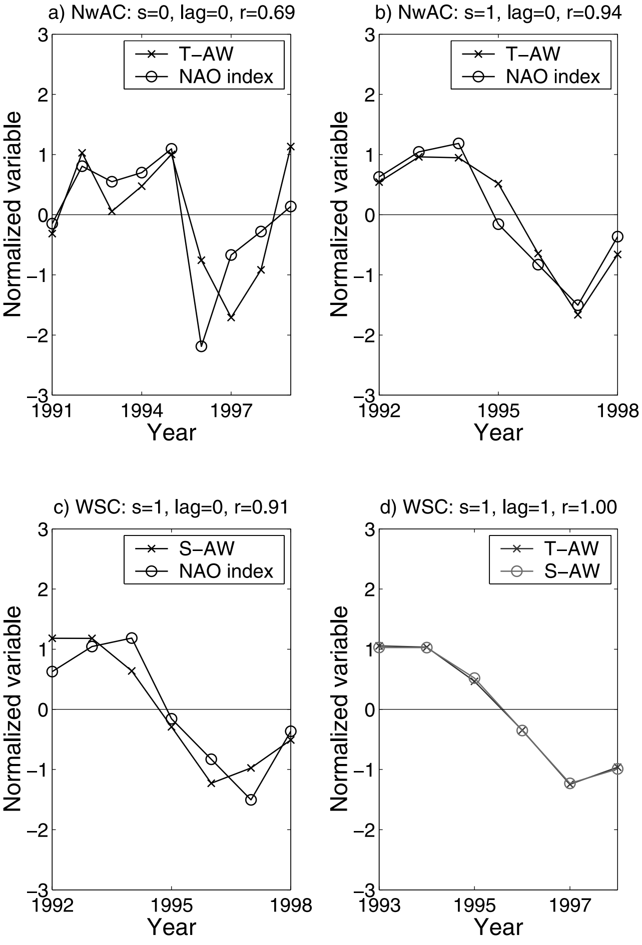


Figure 4. Temporal development of the AW properties on the 15°E section and the winter NAO index in the 1990s. All variables are normalized by subtracting the means and dividing by the standard deviations. Variables in a same subplot are either unsmoothed ($s = 0$) or smoothed using the 3-yr running mean filter ($s = 1$). They are either non-lagged ($lag = 0$) or lagged ($lag = 1$). The correlation value (r) for a pair of variables is given in each subplot. a) Unsmoothed AW temperature in the NwAC and NAO index. b) Same as a) but smoothed. c) Smoothed AW salinity in the WSC and NAO index. d) Smoothed AW temperature and 1-yr advanced salinity in the WSC. See color version of this figure in the HTML.

different AW properties exhibited different tendencies in the 1990s has not yet been noted. Since the AW temperature shows some tendency to lag the NAO index while the AW salinity to lead the NAO index, the AW salinity should lead the AW temperature. Indeed, high values of correlation between the 3-yr running means of the AW temperature and the 1-yr advanced AW salinity are obtained for the WHOLE section (r = 0.94) and in the WSC (Figure 4d), where the correlation is perfect (r = 1.00). The corresponding correlation for the NwAC is not low either (r = 0.77), but is not significant at 95% level. The difference between the correlations for the NwAC and the WSC may reflect not only a different meridional position, but also a different location of the hydrographic stations on the continental slope.

[13] Since the AW salinity in the 1990s led the AW temperature, the latter was predictable one year in advance. The formula for T_i, the unsmoothed AW temperature in year i (i = 1994,. . .,1999), is

$$T_i = a(S_{i-1} + S_{i-2} + S_{i-3}) + 3b - (T_{i-1} + T_{i-2}), \qquad (1)$$

where T_{i-1} (S_{i-1}) is the AW temperature (salinity) in year $i - 1$ etc., while a and b are regression coefficients for the smoothed series. For the WSC, a = 22.650 and b = 789.671. The root-mean-square misfit of the predicted values for the AW temperature in the WSC is only ~0.02°C. Even the maximum misfit of ~0.04°C for 1996 is small (<10%) compared to the change of the AW temperature from 1995 to 1996 (Figure 3a).

[14] The finding of a 1-yr delay between the AW properties in the WSC is encouraging for short-term predictions of the oceanic climate of the Arctic Ocean. Of course, variations in heat flux depend not only on variations in temperature, but also on changes in volume flux, which may not occur in phase with temperature changes. However, the current measurements in Fram Strait between 1997 and 2000 demonstrate that the increase of temperature in the WSC in this period was accompanied by an increase of the flow strength, and both equally contributed to the increase of the northward heat transport [*Schauer et al.*, 2004]. The same measurements show also that the increase of the heat transport in the WSC was not compensated by an equivalent signal in the southward flow in Fram Strait. In addition to the heat transport through Fram Strait, the heat budget of the Arctic Ocean is also influenced by other contributions, e.g., the heat flux from the Barents Sea. Model results show, however, that the major part (three quarters) of the surplus heat input to the Arctic Ocean (associated with the warm event in the beginning of the 1990s) entered through Fram Strait [*Karcher et al.*, 2003]. Work is now required to learn about the extent of the delay between the AW properties in space and time. Hindcasts from regional coupled ice-ocean models will be necessary to elucidate physical mechanisms standing behind the delay.

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