Causes and development of repeated Arctic Ocean warming events

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[1] A model hindcast for 1948–2002 shows several warming events in the Atlantic layer of the Arctic Ocean. The most recent warming event in the 1990s spread from Fram Strait to the Lomonosov Ridge and into the Canadian Basin. Only a warming event in the 1960s can also be followed into the eastern Eurasian Basin. These two warming events are reinforced by anomalously warm flow from the Barents Sea while warming events in the 1970s and 1980s encounter average or below normal temperatures in the Barents Sea branch of the Atlantic Water. The warm Barents Sea outflow in the 1960s is caused by extensive ice cover and a melt water induced halocline in the Barents Sea that reduced heat loss from the Atlantic water. In the 1990s, however, the warm inflow from the Nordic Seas was responsible for warmer than normal flow from the Barents Sea into the Arctic Ocean. *INDEX TERMS:* 4207 Oceanography: General: Arctic and Antarctic oceanography; 4215 Oceanography: General: Climate and interannual variability (3309); 4255 Oceanography: General: Numerical modeling; 4504 Oceanography: Physical: Air/sea interactions (0312). **Citation:** Gerdes, R., M. J. Karcher, F. Kauker, U. Schauer, Causes and development of repeated Arctic Ocean warming events, *Geophys. Res. Lett.*, *30*(19), 1980, doi:10.1029/2003GL018080, 2003.

1. Introduction

[2] One of the most remarkable changes observed in the Arctic in recent years is the subsurface warming of the early 1990s [*Carmack et al.* 1995; *Grotefendt et al.*, 1998]. Associated with the warm event was an eastward shift in the boundary between Pacific origin water and Atlantic origin water from the Lomonosov Ridge to the Mendeleyev Ridge [*McLaughlin et al.*, 1996].

[3] The predominant source of variability at intermediate depths in the Arctic Ocean is the Atlantic Water [*Rudels et al.*, 1994]. There are two major pathways of Atlantic Water into the Arctic, one through Fram Strait (FS) and one through the Barents Sea (BS). The FS branch is subducted under a shallow halocline shortly after it enters the Arctic proper north of Spitsbergen and its properties are thus well conserved from its source in the West Spitsbergen Current (WSC). On the other hand, the BS branch is exposed to the atmosphere over a much longer distance and experiences strong water mass modification due to heat loss and the influx of fresh water from continental run-off and melting sea ice. The two branches join again near the St. Anna Trough, the main entranceway of modified Atlantic Water from the BS into the Arctic proper.

[4] In 1992, the subsurface temperature in the WSC at about 79°N, close to FS reached its highest value since continuous measurements were taken in that area [*Saloranta and Haugan*, 2001]. It dropped by almost 2K until 1995 with rising values again afterwards. *Saloranta and Haugan* [2001] also report earlier warm periods in the WSC when the temperature reached more than 4°C, namely around 1930, 1960, 1970 and 1984. *Saloranta and Haugan* [2001] speculate that enhanced volume transport of Atlantic Water or processes in the Arctic Ocean must have been responsible for the recent warming event in the Arctic Ocean (see *Karcher et al.* [2003a] for a discussion of the relevant literature). Since the database of the Arctic is not sufficient to clearly detect earlier warming events there, another possibility would be that the 1990s warming event was not as exceptional as originally perceived.

[5] Are the temperature maxima in the WSC time series related to Arctic warming events? Is the observed Arctic warming in the 1990s just due to decadal variability or was it a truly outstanding event? Do different warming events develop in the same fashion as the 1990s event? Which processes are important for Arctic warming events besides the supply of heat from the WSC?

2. Method

[6] In the following we shall analyse results from a numerical hindcast experiment for the period 1948–2002. The model used here is based on the MOM-2 model of the GFDL [*Pacanowski*, 1995]. The model domain includes the subpolar North Atlantic, the Nordic Seas and the Arctic Ocean. The horizontal grid distance is 0.25° in both directions of a rotated spherial grid. The vertical is resolved with 30 unevenly spaced levels. Biharmonic friction is employed while the only diffusion acting on tracers is due to the small implicit diffusion of the FCT advection scheme. The ocean model is coupled to a dynamic-thermodynamic sea ice model with viscous-plastic rheology [*Hibler*, 1979; *Harder*, 1996].

[7] The model has an open boundary at approximately 50°N where the barotropic transport is prescribed from a coarser resolution version of the model that covers the whole Atlantic [*Köberle and Gerdes*, 2003]. Forcing of the model is provided by atmospheric fields taken from the NCEP/NCAR reanalysis. Initial conditions and open boundary hydrography are taken from *Steele et al.* [2001]. More details are given in *Karcher et al.* [2003a] and *Kauker et al.* [2003].

3. Propagation of Warm Signals

[8] The model reproduces the main features of the *Saloranta and Haugan* [2001] WSC temperature time series (Figure 1). The model results indicate a marked temperature

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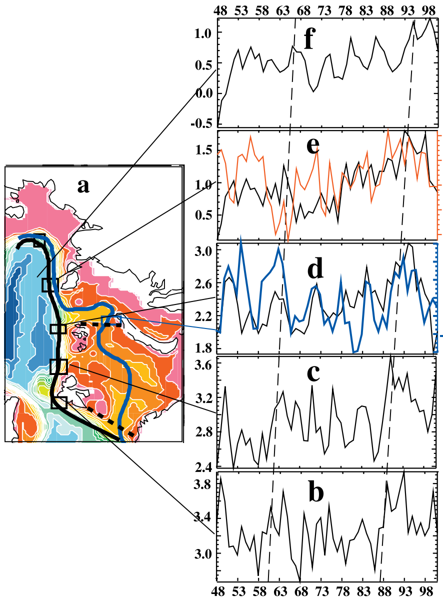

Figure 1. Model topography in the eastern Arctic (a). Boxes indicate the averaging areas for the temperature (in °C) time series in 350 m depths (b) in the WSC, (c) north of Svalbard, (d) Franz Josef Land, (e) Severnaya Zemlya, and (f) Laptev Sea. The blue line in (d) is the mean temperature of the water below 100 m depth leaving the BS north of Nowaya Zemlya. The red line in (e) is the long-slope velocity (in cm/s) in 350 m depth north of Severnaya Zemlya. Dashed straight lines indicate the propagation of selected temperature maxima from the WSC to the Laptev Sea. The thick dotted lines on the map indicate the Barents Sea Opening (BSO) and Franz-Josef-Land section used in Figure 2.

maximum in the mid-1960s, preceding the *Saloranta and Haugan* [2001] time series.

[9] Figure 1 illustrates the propagation of warm signals by means of temperature time series from stations along the continental slope of the Eurasian Basin (EB). A clear propagation is visible for the 1990s signal that arrives north of the Laptev Sea approximately five years after it appeared first in the WSC. A second peak of this warm signal arrives north of the Laptev Sea in 1999 while it originated in FS around 1994. Note that temperatures were decreasing by 0.8K north of the Laptev Sea between 1999 and 2002. This is consistent with observations that show a drop of 0.8K in the core temperature of the Atlantic Water between 1995 (probably from the first warming signal in the 1990s) and 2002 [*Polyakov et al.*, 2003].

[10] Earlier warming events in the Arctic Ocean do not show the pronounced long distance propagation of the 1990s event. Only the mid-1960s signal can be traced from FS to the eastern EB. The 1970s and 1980s warming events apparently just affect the boundary current region west of the St. Anna Trough. Atlantic Water temperatures generally drop considerably between Franz Josef Land and Severnaya Zemlya.

4. The Role of the Barents Sea Branch

[11] At its entrance to the Arctic Ocean, the BS branch of the Atlantic Water is much colder than the FS branch and reduces the average temperature east of the St. Anna Trough (Figure 1). The BS branch exhibits interannual to decadal variability in temperature and volume transport [*Karcher et al.*, 2003a]. The modelled temperature of the inflow into the BS shows pronounced decadal variability with positive temperature anomalies in the early 1960s, the mid-1970s, the early 1980s (weak), and in the early 1990s in good agreement with the observed variability [*Loeng*, 1991].

[12] The heat transport into the Arctic Ocean (calculated relative to 0°C) between Franz Josef Land and the northern tip of Novaya Zemlya (Figure 2 is anomalously high in the early 1960s and again in the mid-1990s. High temperatures and low volume transports of the BS branch water (as in the 1960s and the 1990s) mean less cooling of the Atlantic Water in the boundary current north of the Barents and Kara seas.

[13] The variability of the heat fluxes at inflow and outflow sections is not well correlated (Figure 2). Apparently, the heat transport from the BS into the interior Arctic Ocean is significantly affected by the conditions in the BS. The temperature time series north of Novaya Zemlya (Figure 1) is a good indicator for the outflow properties from the St. Anna Trough. It contains distinct maxima in the mid-1960s and in the early 1990s that are 0.5 to 0.8K above the background value of around −0.2°C. Between 1965 and 1996, *Schauer et al.* [2002a] find a similar increase in temperature in the lower layer in the St. Anna Trough from which the BS Branch Water is fed.

[14] The positive temperature anomalies leaving the BS in the mid-1960s and in the 1990s clearly contribute to the simulated temperature anomaly that was carried in the FS branch into the eastern parts of the EB at the same time. On the other hand, the 1970s signal is only enhanced by a small contribution from the BS. In the early phase of the 1980s

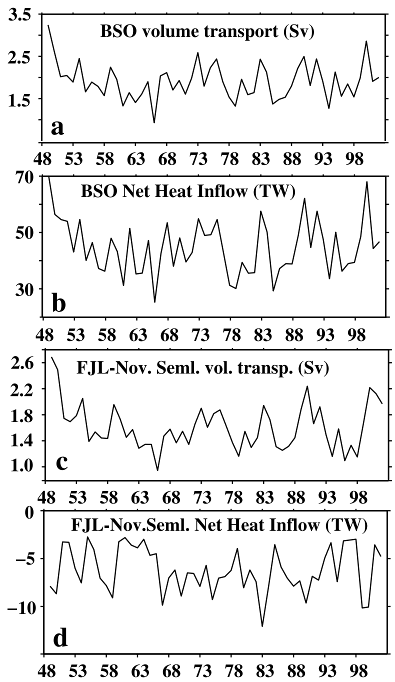

Figure 2. Winter centered annual mean values for the oceanic transport of volume (a) and heat (b) through the BSO and between Franz Josef Land and Novaya Zemlya ((c) and (d), respectively).

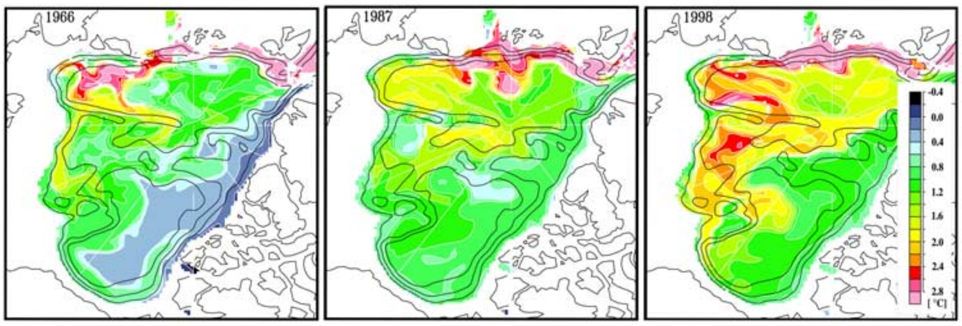

Figure 3. Monthly mean March potential temperature at the depth of the temperature maximum, (a) 1966, (b) 1987, and (c) 1998.

anomaly, the outflow from the BS is anomalously cold, it is only in the years 1985 and 1986 that the BS outflow is slightly warmer than normal.

5. Spatial Structure of the Atlantic Water Distribution

[15] Another source of apparent temperature fluctuations are shifts in the position of the core of the Atlantic Water. We show representative examples of temperature distributions at the depth of the intermediate temperature maximum in Figure 3. All cases show the separation of the FS branch from the shelf break near the St. Anna Trough where the BS branch enters the Arctic proper [*Gerdes and Schauer*, 1997]. The modelled temperature anomalies are aligned with constant depth lines in most cases, indicating that the transient heat transport is constrained by topography. However, the example of March 1966 (Figure 3a) that represents the height of the 1960s warming episode shows that large patches of warm water can leave the boundary and propagate into the interior of the basin. Several filaments generate small scale fronts in the eastern EB that make point wise comparison with observations almost impossible.

[16] While the 1960s warming event affected the eastern EB, the mid 1980s warming (Figure 3b) was halted near Severnaya Zemlya. Large boluses of warm water leave the boundary and propagate into the interior of the basin. This is consistent with observations by *Schauer et al.* [2002b] who found isolated lenses of predominately FS water on a section through the EB. The formation and shedding of warm lenses from the boundary current destroys predictability and can spread warming signals over large areas in the interior of the EB. Misinterpretation of the travel time of warming events can occur when a scheme of fixed pathways along the continental slope and the ridges is adopted for the temperature anomalies.

[17] At the peak of the most recent warming event, the warm signal spreads in a well defined along slope current (Figure 3c). This is in good agreement with observations from the 1990s warm event [*Karcher et al.*, 2003a]. Temperatures of around 2.5°C can be found between the Laptev Sea slope and the Pole as well as in the Makarov Basin.

6. An Outstanding Event in the 1990s

[18] The comparison of the temperature distributions for the two most pronounced warming events in the model simulation in Figure 3 shows that the 1990s warming spreads much further to the east and also covers a far larger area overall. The heat flux through FS into the Arctic remains on a high level over several years in the 1990s [*Karcher et al.*, 2003a] such that the integrated amount of heat entering the Arctic is truly exceptional. While low heat losses over the Nordic Seas are responsible for the high temperatures in the WSC, the large heat transports are also due to enhanced velocities in the FS branch (Figure 1e). North of Severnaya Zemlya, the eastward velocity exhibits an increasing trend from the early 1960s onwards with velocities three times as high in the early 1990s as in the mid-1960s.

[19] During the 1990s, the temperature signal was carried very efficiently by a coherent boundary current that extended all the way from FS to the Lomonosov Ridge. The 1960s warming event, on the other hand, did not penetrate as far as the 1990s event because the boundary current differed in speed and definition from the more recent event. As a consequence of the converging heat, the temperature anomaly spread off-slope in the eastern part of the EB.

[20] The 1990s warming was the latest in a series of warming events since 1970. Because of the isolation of the Atlantic layer by the Arctic halocline, the heat brought into the Arctic Ocean is neither released to the atmosphere nor used to melt sea ice. The heat must eventually exit the Arctic Ocean through the passages towards lower latitudes. Due to the renewal time of 10–15 years of the Atlantic layer in the EB and more than 18.5 years for its extensions into other Arctic Ocean basins [*Smethie et al.*, 2000], a substantial part of the heat input during earlier warming events has not yet left the Arctic Ocean. The 1990s warming, in this

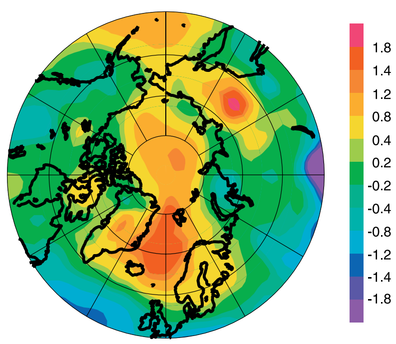

Figure 4. Anomaly of the surface pressure in 1959–1965 from the 50 year mean. Contour interval is 0.3 hPa.

sense, build upon the earlier warming events of the last decades.

7. Atmospheric Forcing of the 1960s and 1990s Warming Episodes

[21] The Arctic Ocean warming event of the mid-1990s was the result of increasingly positive states of the NAO. Warmer air temperatures over the Nordic Seas and the BS resulted in higher temperatures in the WSC and in the BS. The strengthening circulation in the EB forced by the cyclonic wind stresses provided effective eastward transport [*Karcher et al.*, 2003a].

[22] Apparently, the causes of the 1960s warming event are different as that event occurred during a phase of low NAO index. The average surface pressure field for 1959–1965 was characterized by anomalously high pressure over the Nordic Seas and the central Arctic (Figure 4). The pressure distribution implies increased flow of Atlantic origin through FS but reduced flow into the BS (Figure 2). It also indicates stronger than normal sea ice transport from the Nansen Basin and the northern Kara Sea into the BS. A large part of the ice melts within the BS. In the first half of the 1960s we find a net ice import of 300 km^3/yr [*Karcher et al.*, 2003b]. The melt water stabilizes the water column in the BS and deep mixing becomes restricted to the southernmost areas of the BS. This generates a situation where the Atlantic Water flowing into the BS is shielded from the atmosphere and looses less heat than during normal winters. Despite anomalously low air temperatures over the BS, the outflow of modified Atlantic Water through the St.Anna Trough was thus very warm [*Karcher et al.*, 2003b].

8. Conclusion

[23] With a hindcast simulation we reproduced the observed temperature time series in the West Spitsbergen Current. Each temperature maximum in the WSC is associated with a warming of the Atlantic layer in the western Nansen Basin. Only a warming in the 1960s and the warming event of the 1990s had larger scale consequences in the whole Eurasian Basin and, in case of the 1990s warming, the Makarov and Canadian basins.

[24] The mechanisms of the warming episodes differ: The 1990s episode is due to a large heat flux through Fram Strait, high current speeds in the FS branch and anomalously warm Barents Sea outflow. The later was caused by advection of anomalously warm water from the Nordic Seas. The 1960s episode also profited from an exceptionally warm contribution from the BS. The cause of the warm outflow through the St.Anna Trough was, however, completely different from that of the 1990s: Isolation of the Atlantic Water from the atmosphere by extensive sea ice cover and a melt water induced halocline curtailed the heat losses in the BS.

[25] Knowing the development of earlier events, we can state that the 1990s event was exceptional in the total warmth and the extent of the warming. Remnants of this warming are still present in the Arctic and are expected to leave the Arctic through FS in the coming years.

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