Penetration of the 1990s warm temperature anomaly of Atlantic Water in the Canada Basin

Koji Shimada,[1] Fiona McLaughlin,[2] Eddy Carmack,[2] Andrey Proshutinsky,[3]
Shigeto Nishino,[1] and Motoyo Itoh[1]

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[1] Penetration of the 1990s warm temperature anomaly (WTA) of the Fram Strait branch of Atlantic Water (FSBW) in the Canada Basin is described using available temperature, salinity, and velocity data. The core temperatures of FSBW show distinct pathways. Over the Chukchi Borderland advective velocities of the FSBW are well-correlated with bottom topography. The resulting multifarious pathways over the Chukchi Borderland act to modulate and substantially increase the time scale of WTA spreading and advancement. Further downstream two WTA tongues are observed. One tongue followed the Beaufort Slope and, along this pathway, the core temperatures of FSBW decreased rapidly. The depth integrated value of heat content remained near constant however, suggesting enhanced vertical mixing. The second tongue debouched from the northern tip of the Northwind Ridge and spread eastward into the deep Canada Basin, suggesting a complex recirculation structure within the Beaufort Gyre. *INDEX TERMS:* 4532 Oceanography: Physical: General circulation; 4536 Oceanography: Physical: Hydrography; 4512 Oceanography: Physical: Currents. **Citation:** Shimada, K., F. McLaughlin, E. Carmack, A. Proshutinsky, S. Nishino, and M. Itoh (2004), Penetration of the 1990s warm temperature anomaly of Atlantic Water in the Canada Basin, *Geophys. Res. Lett.*, *31*, L20301, doi:10.1029/2004GL020860.

1. Introduction

[2] In 1989–90 an anomalously warm pulse of Fram Strait branch Atlantic water (FSBW) entered the Arctic Ocean and began a cyclonic journey around the deep Arctic Basin. Here we define the warm temperature anomaly (WTA) as FSBW with temperature greater than 0.8°C, based on a comparison with the Arctic Ocean Atlas climatological data from 1948–1993 (not shown) which shows the temperature maximum of FSBW is about 0.5°C in the Chukchi Borderland and is near 0.4°C in the Beaufort Sea. The temporal variation of Atlantic water near its entrance into the Arctic Ocean (Nordic Seas, Barents Sea, and Fram Strait) is well-correlated with the NAO/AO on decadal time scales [*Grotefendt et al.*, 1998; *Dickson et al.*, 2000; *Rudels and Friedrich*, 2000]. Once in the Arctic Ocean, however, oceanic processes control the circulation within individual sub-basins and along specific pathways. Thus the WTA propagation would be expected to be decoupled from direct control of atmospheric forcing.

[3] Penetration of the 1990s WTA into eastern Arctic sub-basins has been traced by both hydrographic data [cf. *Rudels et al.*, 1999a; *Schauer et al.*, 2002] and numerical simulation [cf. *Karcher et al.*, 2003]. In the western Arctic Ocean, however, only fragmental observations of the 1990s WTA have been reported. The 1990s WTA reached the Alpha/Mendeleyev Ridge by 1993, as observed from the *CCGS Henry Larsen* [*Carmack et al.*, 1995] and *USS Pargo* [*Morison et al.*, 1998]. Advancement of the WTA to the Alpha/Mendeleyev Ridge was also marked by a corresponding retreat of Pacific-origin waters away from the Lomonosov Ridge [*McLaughlin et al.*, 1996]. Progression across the region between the Mendeleyev Ridge and the southeastern Canada Basin, however, remained poorly understood. It is occupied by the highly complex Chukchi Borderland (CBL) topography, consisting of the Chukchi Plateau, Chukchi Gap, Northwind Ridge, and Northwind Abyssal Plain. Recently *McLaughlin et al.* [2004] discussed this region using 1997–98 SHEBA/JOIS data, and found two WTA tongues: one along the continental margin in the Chukchi Gap, and one on the northern flank of the Chukchi Plateau. However, the final penetration of the 1990s WTA across the CBL and into the Canada Basin appeared to take much longer than the progression across the three upstream basins. In this paper we try to fill the gap of current knowledge about the progression of the WTA in the Canada Basin using hydrographic and current meter data: we analyze temperature and salinity profile data from 1993–2000 SCICEX XCTD data; 1990–2002 hydrographic data from Fisheries and Oceans Canada's Institute of Ocean Sciences (IOS); 1992–2002 hydrographic and 1999–2000 mooring data from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC); 1992–1994 drifting buoy data from JAMSTEC and Woods Hole Oceanographic Institution (WHOI); and 2003 hydrographic data from a joint JAMSTEC, IOS and WHOI project. Here our discussion is limited to FSBW because the XCTD and drifting buoy measurements did not reach the depth of Barents Sea Branch of Atlantic Water (BSBW).

2. Penetration of the WTA

[4] The temperature maximum (core) of FSBW lies in the potential density range of $\sigma_\theta = 27.90 - 28.00$. Here we use maps of potential temperature on density $\sigma_\theta = 27.90$ because confounding effects associated with thermohaline interleaving are relatively small on this surface [cf. *Carmack et al.*, 1998]. The advancement of WTA penetration over five time

[1]Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan.
[2]Institute of Ocean Sciences, Sidney, British Columbia, Canada.
[3]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

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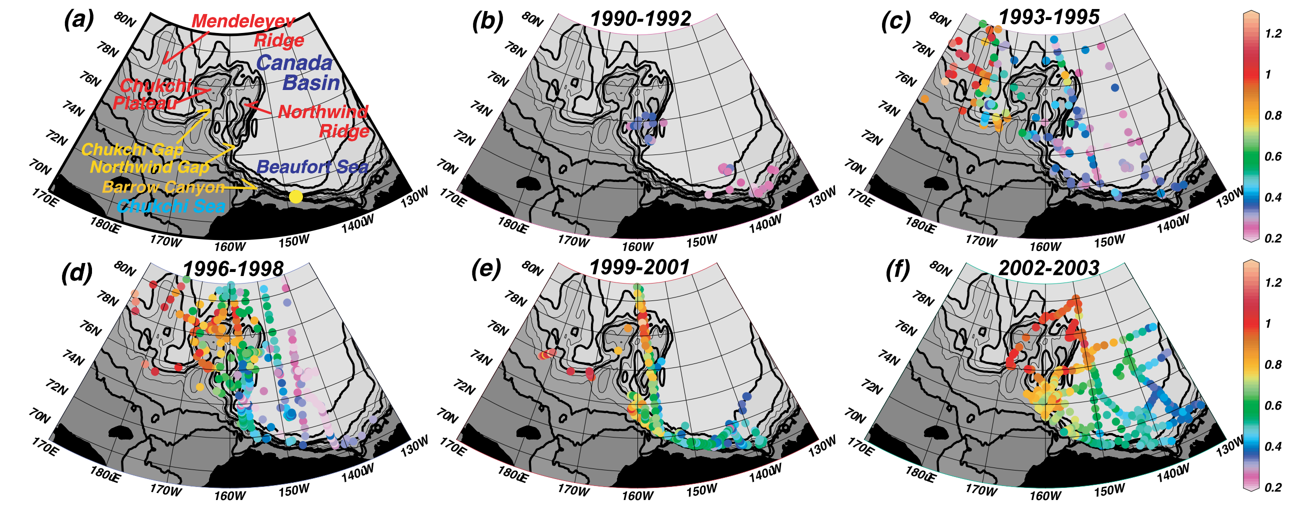

Figure 1. Study area and temporal sequences of potential temperature on the density surface $\sigma_\theta = 27.90$. Yellow circle in Figure 1a denotes the mooring location used in Figure 3.

periods, from 1990 to 2003, is shown in Figure 1. In 1990–1992 there was no evidence of anomalously warm FSBW in the region of study although, admittedly, the data are sparse. During 1993–1995 the WTA extended past the Mendeleyev Ridge [cf. *Carmack et al.*, 1995], with the nose of the WTA ($\theta \sim 0.8°C$) extending to the western side of Chukchi Gap. The WTA is also found at a two stations on the northern flank of the Northwind Ridge. Still, no warm FSBW was identified in the Canada Basin east of the Northwind Ridge or along the Beaufort Sea slope. During 1996–1998 the WTA covered much of the CBL, but not the southern half of the Northwind Ridge. The nose of WTA ($\theta \sim 0.6°C$) at this time approached - but did not go beyond - Barrow Canyon. This signal must therefore have arrived via the Chukchi Gap, along the northern slope of the Chukchi Sea, because it was clearly not present along the eastern flank of the Northwind Ridge south of 76°N. In this period some fraction of the WTA also spread eastward from the northern tip of the Northwind Ridge, a feature consistent with geochemical measurements made during SCICEX96 [*Smith et al.*, 1999; *Smethie et al.*, 2000]. During 1999–2001 the WTA, now with $\theta \sim 1°C$, was observed along the continental slope south of the Northwind Ridge. Temperatures on the eastern flank of the Northwind Ridge south of 76°N, however, remain colder than 1°C. Thus any warm FSBW seen on the Beaufort Slope in this period must also have entered via the southern route, i.e., through the Chukchi Gap. During 2002–2003, a WTA greater than 1°C was finally observed on the eastern flank of the Northwind Ridge south of 76°N. This implies that the northern penetration pathway around the northern slope of the Chukchi Plateau and Northwind Ridge into the Beaufort Slope via the eastern flank of the Northwind Ridge opened during this period. Therefore, in the southern Canada Basin, temperatures in the FSBW continued to increase monotonically into the 2000's, even though conditions in the upstream region had already turned into a cooling phase [*Karcher et al.*, 2003].

[5] Different advective time scales of the two pathways around the CBL (one a 'shortcut' along the northern slope of the Chukchi Sea and the other a much longer excursion around the outer rims of the Chukchi Plateau and Northwind Ridge), jointly modulate the penetration of the WTA into the Beaufort Sea. Recirculation of FSBW in the Northwind Abyssal Plain is another possible route that could retard the penetration of the WTA. Thus, the complex circulation pattern over CBL causes the WTA to arrive at different times in the Beaufort Sea. It also means that changes in the Canada Basin do not necessarily occur on the same time scale as in the three upstream basins or with atmospheric variations such as AO/NAO. There remains uncertainty as to the mechanism of WTA penetration. Interleaving is one possible mechanism [*Carmack et al.*, 1998; *Rudels et al.*, 1999b]. However theoretical estimates of signal propagation speed (effective diffusivity [see *Walsh and Carmack*, 2002, 2003]) do not agree with the estimates based on the changes in temperature and salinity properties described above.

[6] On the Beaufort slope east of Barrow Canyon, warming in 2002–2003 was not clearly observed as might be expected from observations upstream in 1999–2002. This might lead a conclusion that WTA penetration along the Beaufort slope is interrupted near Barrow Canyon. However the vertically integrated temperature from 200–1000 m (Figure 2) clearly shows a warm tongue spreading eastward past Barrow Canyon and onto the Canadian Beaufort slope. The discrepancy between temperature maximum (Figure 1f) and integrated temperature over FSBW (Figure 2) suggests that although the total heat content in FSBW does not change along the Beaufort slope, temperatures at the temperature maximum decreased due to intense vertical mixing that likely occurs in Barrow Canyon. Measurements from a year-long (2001–2002) current meter moored at 303 m on the Beaufort slope showed an annual mean velocity near the core of FSBW that was eastward at 4.86 cm/s (standard deviation of 8.65 cm/s), clearly sufficient to explain advection of the WTA (Figure 3).

3. Direct Measurement of Circulation Pathway Over Chukchi Borderland

[7] Next we examine the properties of topographically steered currents over the CBL using direct measurement

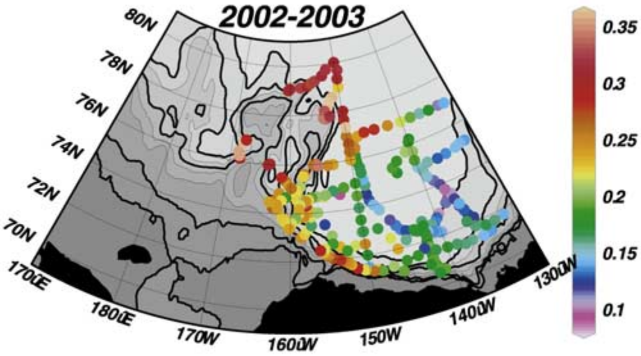

Figure 2. Vertically integrated potential temperature between 200 m and 1000 m during 2002–2003.

velocity data at 58 m, 106 m, 154 m, 202 m, and 250 m from the 1992–1994 Ice Ocean Environmental Buoy (IOEB). Although the deepest measurement depth did not reach the depth of the temperature maximum of FSBW, temperatures at 250 m depth are well-correlated with temperature on $\sigma_\theta = 27.90$ in the CBL region and the spatial pattern of temperature at 250 m depth is similar to that on $\sigma_\theta = 27.90$ (not shown). Thus we speculate that the circulation pattern at 250 m approximates the circulation pattern of the core of FSBW. Oceanic velocities are reconstructed using a box filter with 50 km radius in order to eliminate mesoscale eddies. The velocity field indicated two branches of FSBW appeared west of the CBL: one coming from the Mendeleyev Ridge via the northern Chukchi Slope, and the other entering the CBL region at the northwestern tip of the Chukchi Plateau. This data also infers that the FSBW pathway bifurcates after crossing the Mendeleyev Ridge and before arrival to the CBL region. Although there have been investigations on the dynamics of

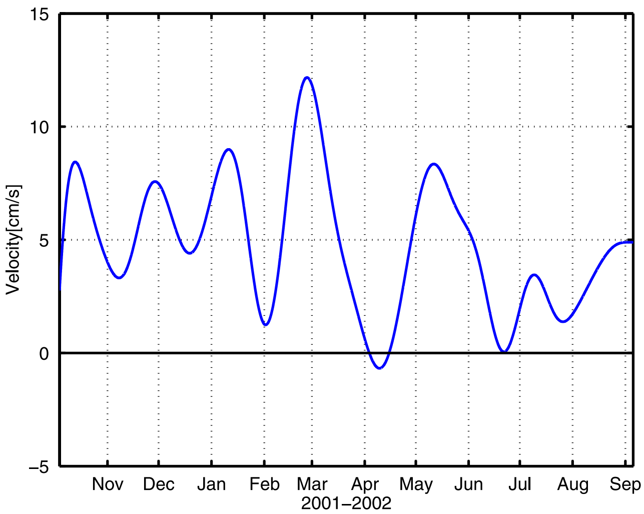

Figure 3. A year-long record of a current meter data (Aanderaa RCM7) during 2001–2002 at 303 m depth on the Beaufort Slope (71°13.34′N, 148°19.39′W, bottom depth 503 m). The plotted velocity is the amplitude of the first empirical orthogonal function (EOF), which explains 93% of variation. The direction of the first mode is 83 degree from north in clockwise.

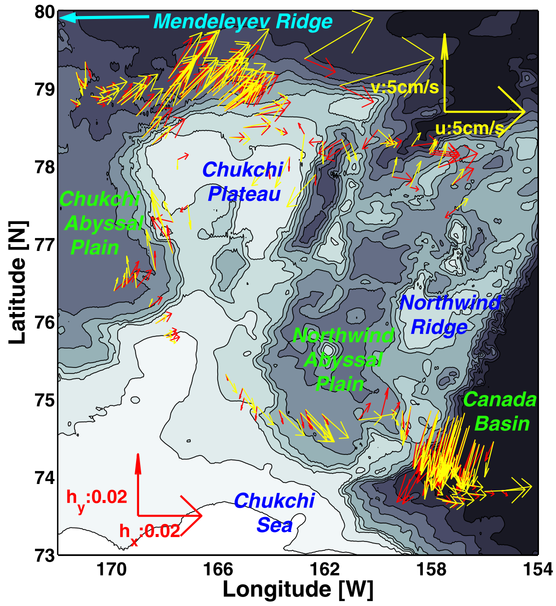

Figure 4. Velocities at 250 m depth [yellow color] and topographic vectors as described by (dh/dy, $-dh/dx$) [red color], where h is total depth.

driving force for the steered currents [e.g., *Holloway*, 1992; *Nazarenko et al.*, 1998], the mechanism is still unclear.

[8] The dominating effect of CBL topography on WTA progression is illustrated by comparing IOEB velocity data with the slope of the underlying topography. The International Bathymetric Chart of the Arctic Ocean (IBCAO) is used in the following analysis and the same spatial filter was also applied to the topographic data for consistency with the velocity data. Figure 4 shows the velocities at 250 m versus topographic vectors as described by (dh/dy, $-dh/dx$), where h is total depth. Topographical steering of currents is clearly demonstrated: the relation (Figure 5) is given by

$$(u, v) = 79.3 \times (dh/dy, -dh/dx) + 0.18$$

with a correlation coefficient of 0.89.

4. Summary

[9] The penetration of the 1990s WTA into the Canada Basin is described. The circulation of warm FSBW is strongly constrained by sea floor topography. In particular, over the complex topography of the CBL the circulation was well-correlated with steepness of sea floor topography. CBL topography allows two major pathways of FSBW: one along the northern slope of the Chukchi Sea, and the other along the outer rim of the Chukchi Plateau and Northwind Ridge. The difference between the transit distances of these two pathways can modify the downstream response timescale of upstream variability. Within the Canada Basin east of the Northwind Ridge, two pathways into the basin are observed: one is an extension of the flow along the northern slope of the Chukchi Sea along the Beaufort Shelf slope; the other is the debouching of flow eastward from the northern tip of the Northwind Ridge into the central basin. Along the Beaufort slope temperatures at temperature maximum of FSBW decrease, while the heat content of the FSBW

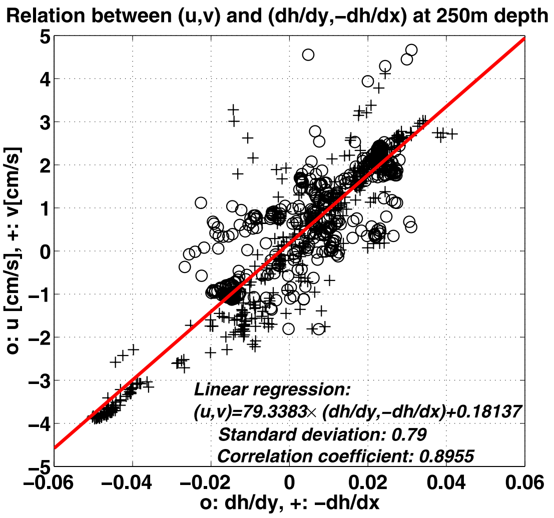

Figure 5. Scatter plot for the relation between horizontal velocities and the topographic vector shown in Figure 4.

remains constant, showing that WTA penetration in the Canada Basin is further compounded by active vertical mixing along the slope and within submarine canyons.

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E. Carmack and F. McLaughlin, Institute of Ocean Sciences, Sidney, British Columbia, Canada V8L 4B2. (carmacke@pac.dfo-mpo.gc.ca; mclaughlinf@pac.dfo-mpo.gc.ca)

M. Itoh, S. Nishino, and K. Shimada, Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology, 2-15 Natsushima, Yokosuka 237-0061, Japan. (motoyo@jamstec.go.jp; nishinos@jamstec.go.jp; shimadak@jamstec.go.jp)

A. Proshutinsky, Woods Hole Oceanographic Institution, MS #29, 360 Woods Hole Road, Woods Hole, MA 02543, USA. (aproshutinsky@whoi.edu)