Disappearance of Pacific Water in the northwestern Fram Strait

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[1] Water of Pacific origin, entering the Arctic Ocean through the Bering Strait, exits the Arctic Ocean through the Canadian Archipelago and the Fram Strait. The amount and timing of Pacific Water export through these gates depend on the upper circulation of the Arctic Ocean and react accordingly on changes. Nutrient and hydrographic data from four cruises to the area north of the Fram Strait in 1984, 1990, 1997, and 2004 show that substantial changes have occurred lately in the amount of Pacific Waters delivered to the Fram Strait and hence further to the Atlantic Ocean. While the data from 1984, 1990, and 1997 all showed considerable amounts of Pacific Water above the shelf and slope northeast of Greenland, this strong signal had completely vanished in 2004. The arrival of a previously not observed cold halocline layer at the area can be recognized in 1997. **Citation:** Falck, E., G. Kattner, and G. Budéus (2005), Disappearance of Pacific Water in the northwestern Fram Strait, *Geophys. Res. Lett.*, *32*, L14619, doi:10.1029/2005GL023400.

1. Introduction

[2] Extraordinary changes in the Arctic Ocean have been reported during the recent decades such as warming of the Atlantic Layer and changes in the position of the boundary between halocline waters from the Eurasian and the Canadian Basin (see *Morison et al.* [2000] for a summary). The Pacific Water, that enters the Arctic Ocean trough the Bering Strait, is found at and near the surface, and its distribution should therefore be influenced by changes in atmospheric forcing. *Steele et al.* [2004] presented possible pathways for Pacific halocline waters during different states of the Artic Oscillation (AO). They postulate a more efficient transport of waters of Pacific origin toward the Fram Strait if the AO index is more frequently in its positive state, whereas in a persistent negative AO state, the Pacific Water contribution to this outflow should decrease substantially.

[3] *Jones et al.* [1998] showed that the relationship between nitrate and phosphate is appropriate to distinguish between water of Pacific and Atlantic origin in the Arctic, which is not always possible by use of salinity and temperature. They found that, in the surface layer, Pacific Water was dominant in the Canadian Basin, but significant amounts were also present in the area north of Greenland, which might exit through the Fram Strait. This was confirmed by *Falck* [2001] showing that the shelf off northeast Greenland was covered by nearly undiluted Pacific Water down to the depth of the winter mixed layer. Pacific Water extending from the coast of Greenland to nearly halfway across the Fram Strait along 79°N for the years 1997–1999 was reported by *Jones et al.* [2003].

[4] The Polar Water ($T < 0°C$, $S < 34.5$), which exits the Arctic through the Fram Strait, actually consists of several distinct water masses, which might be of either Pacific of Atlantic origin, including the surface as well as the halocline waters. Different halocline types can be identified: Upper Halocline Water (UHW) of Pacific origin formed in the Canadian Basin is associated with a nutrient maximum and a corresponding salinity of about 33.1 [*Jones and Anderson*, 1986]. Both the Alaskan Coastal Water and the Bering Sea Water (BSW) also produce summer haloclines that can be traced in the Canadian Basin above the UHW [*Steele et al.*, 2004]. In the Eurasian Basin, Lower Halocline Water (LHW) is formed from waters of Atlantic origin, which, when entering the Canadian Basin, lies below the UHW. A cold halocline layer (CHL) may be found above the LHW [*Steele and Boyd*, 1998]. *Rudels et al.* [2004] distinguish between these two types of Atlantic derived halocline waters as the Fram Strait branch halocline water and the Barents Sea branch halocline water.

[5] Here we present data on the contribution of these different water masses to the Polar Water outflow from an area northeast of Greenland just at the northern boundary of the Fram Strait. The fate of the Pacific Water has implications for the freshwater balance and hence global overturning. It is therefore most important to improve our knowledge about the water masses exiting the Arctic Ocean towards the Atlantic.

2. Data and Methods

[6] Nitrate, phosphate, and silicate data, in combination with temperature and salinity obtained from four cruises with the research icebreaker *Polarstern* to the area north of the Fram Strait (ARKII/3 1984, ARK VII/2 1990, ARK XIII/3 1997, and ARK XX/2 2004) were used to identify the different water masses present in the upper 200 m of the water column and to investigate their origin. The sampling positions are shown in Figure 1. Water samples were taken with a rosette sampler equipped with Niskin bottles and a CTD probe (Neil Brown in 1984, Salzgitter Bathy-Sonde in 1990, and Seabird 911+ in 1997 and 2004). Nutrients were measured with an Autoanalyzer (Bran and Luebbe) according to seawater standard methods [*Kattner and Becker*, 1991].

[7] The *Jones et al.* [1998] nitrate-phosphate relationship was applied to distinguish Pacific derived waters from Atlantic derived waters. A nitrate versus phosphate diagram comprising all data is shown in Figure 2. The two lines indicate "pure" Atlantic Water and "pure" Pacific Water, and are based on measurements from the St. Anna Trough and the Chukchi shelf break region, respectively

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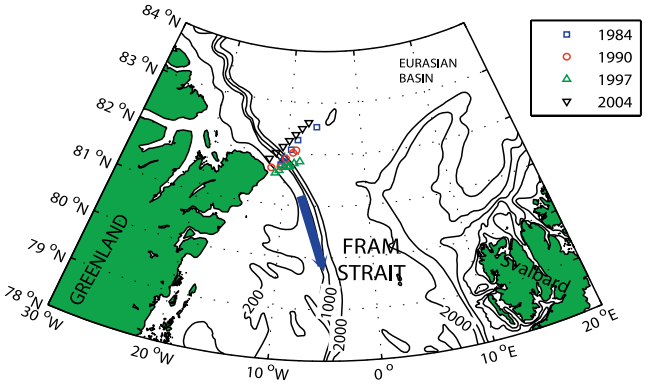

Figure 1. Map of the Fram Strait with station positions for 1984, 1990, 1997, and 2004. Thin lines show the bathymetry, in meters. Blue arrow show the East Greenland Current.

[*Jones et al.*, 1998]. There are different reasons for uncertainties in the calculated source water fractions, such as local denitrification, nitrogen fixation, choice of source water lines, and measurements error, which are discussed by *Jones et al.* [2003]. This results in a deviation of points from the pure source water lines of roughly ±10%. Data points to the right of the Pacific source water line and to the left of the Atlantic source water line are taken to represent pure Pacific Water and pure Atlantic Water, respectively, and data points between the two lines as mixtures between the two source waters. The percentages calculated with this method only represent the relative amounts between Pacific and Atlantic Water. The contribution of nutrients to the two source waters by mixing with freshwater that originates from precipitation, river run-off, and sea ice meltwater has a nitrate-phosphate relation similar to Atlantic Water but has been reported to be relatively insignificant to these calculations [*Jones et al.*, 1998]. Also during times of biological production an apparent Atlantic Water fraction will result when nitrate is totally depleted and inorganic phosphate continuous to be used together with other sources of nitrogen, as seen clearly in some of the data from 1990 in Figure 2.

[8] Since the UHW will be mixed to variable degrees with LHW on its path toward the Fram Strait, it will generally lie to the left of the Pacific Water line and the LHW to the right of the Atlantic Water line in the nitrate-phosphate diagram, how far off depends on the mixing history before reaching the Fram Strait. It is therefore not possible to ascertain the presence of UHW by the nitrate-phosphate method, since it can not be distinguished from any mixture of Atlantic and Pacific Waters. The UHW is better recognized, when passing through the Fram Strait, by its higher silicate concentrations compared to those of the LHW.

3. Interannual Variability

[9] Vertical sections of Pacific Water content (in %) and silicate concentrations from the four cruises are shown in Figure 3 together with temperature and salinity. In 1984 and 1990, a surface layer of 50–75 m contained almost undiluted Pacific Water (~100%). The layer was shallower above the shelf break than further offshore above the slope. Salinity (S) was less than 32.5 throughout the layer. In the lower part S was close to 32.5 and temperatures near the freezing point, indicative of the depth of the winter convection (Figure 4). Below the rather homogeneous remnants of the winter mixed layer, both temperature and salinity increased throughout the halocline layer, and the fractions of Pacific Water decreased. Zero Pacific Water content was found at depths with S of about 34–34.5. A subsurface layer with maximum silicate values of 18.5 μmol L^{-1} was found at depths between 60 and 75 m in the southern part of the transect in 1984, with a corresponding S ~ 33.2 and a Pacific Water fraction of ~65%. In 1990, the highest silicate concentrations were, however, found above the base of the winter mixed layer. Here silicate was between 17.7 and 18.9 μmol L^{-1}, temperatures were near the freezing point, and S was just below 32.5 at depths of 50–60 m. In the halocline below, at depths with S between 32.5 and 33.5, silicate values of 15–17 μmol L^{-1} were still indicative of Pacific origin. In 1984, one sampling station was also performed above the deep Lena Trough showing that the lateral extent of the pure Pacific Water did not stretch this far north, but was mainly confined to a boundary current along the coast. The T-S structure was also different for this station, although a reduced Pacific Water signal (~60%) was still present at the surface and a silicate maximum of 13.0 μmol L^{-1} (at S = 33.3) was seen at 80 m, but with a Pacific Water fraction of only 35%. Comparing 1984 with 1990, the distribution of Pacific Water looks rather similar, and one would not expect that any great changes had taken place during the intervening years.

[10] In 1997, a surface layer with undiluted Pacific Water was also present, but shallower than in 1984 and 1990, reaching only down to about 25–40 m. Beside the difference in the vertical distribution of Pacific Water fractions, also other changes were evident in the water mass composition of the upper 200 m. The surface layer, being almost homogeneous in temperature and salinity, was considerably fresher than in 1984 and 1990. The salinity in this layer ranged from 31.1 above the shelf break to 31.7 at the northernmost station with temperatures close to the freezing point. Below the surface layer the salinity steadily increased but not the temperature. The temperature remained near the freezing point to well below 100 m for most of the stations. This is the signature of the CHL, which was found only in the Makarov Basin during SCICEX'95 [*Steele and Boyd*, 1998] but in 1991 and 2001 it was also observed in the

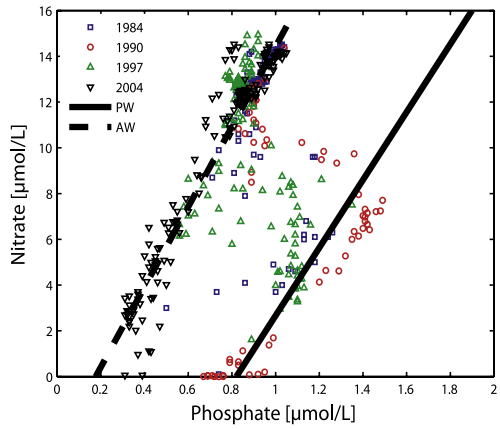

Figure 2. Nitrate-phosphate relationships for 1984, 1990, 1997, and 2004. The lines represent the nitrate-phosphate relationship of Pacific (PW) and Atlantic Water (AW).

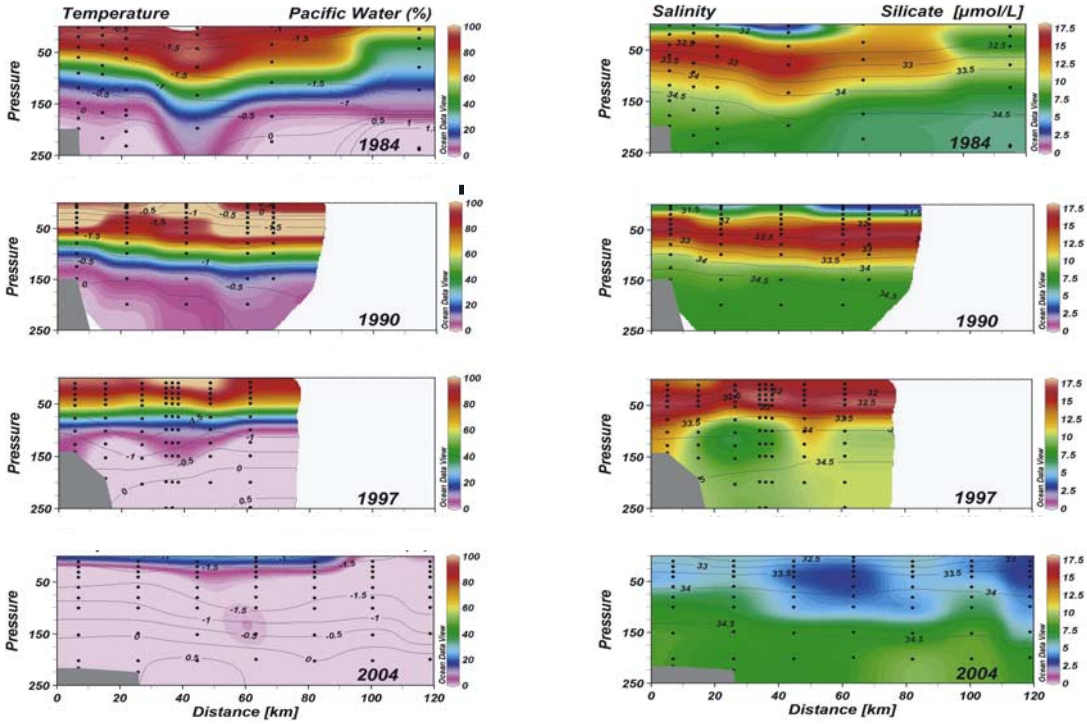

Figure 3. Vertical sections of Pacific Water (in %) and silicate (µmol L^{-1}) shown with colour scales and temperature and salinity shown as contour lines. Dots indicate sampling depths. All of the four sections start near the shelf break, as indicated by the grey area in the lower left corner of each panel, and are directed in a north-easterly direction.

Amundsen Basin [*Björk et al.*, 2002]. The highest silicate value, measured in 1997, was 20.4 µmol L^{-1} at one station at 40 m (S = 32.85). At the other stations maximum values were between 17.3 and 19.4 µmol L^{-1} (32.5 < S < 32.8; 75–100% Pacific Water). These silicate maxima were located just below the surface layer, at 50 m at both ends of the transect but shallower (30–40 m) in the middle due to an intruding core of water with a relative minimum in silicate (and other nutrients) not seen in the 1984 and 1990 data. This minimum was found where the signature of the CHL was most pronounced. Following *Rudels et al.* [2004] this would be the signal of the Fram Strait branch halocline water, exiting the Fram Strait much closer to the Greenland coast than in the earlier years.

[11] Great contrasts to these earlier measurements were observed in 2004, where neither a surface layer of pure Pacific Water nor any UHW was present. The five southernmost stations showed a very thin summer surface layer of only 10–20 m with fresher (S < 32.5) and slightly warmer water than the neighbouring stations. Evidence of water that might have been in contact with Pacific influenced water (Pacific Water fractions of 20 to 30% at 10 m) was only found in this very thin layer.

4. Discussion

[12] A surface layer of about 50 m of pure Pacific Water is present above the slope in both 1984 and 1990. The freshening and shoaling of this surface layer, as seen in the data from 1997, is similar to changes in the water mass characteristics and structure of the upper layer in the Lincoln Sea in the early 1990s [*Newton and Sotirin*, 1997] which could indicate that these changes took place upstream. A further change in the Pacific Water circulation within the Arctic Ocean occurred sometime after 1997 resulting in an almost complete disappearance of Pacific Water in the Fram Strait detected first during our 2004 survey.

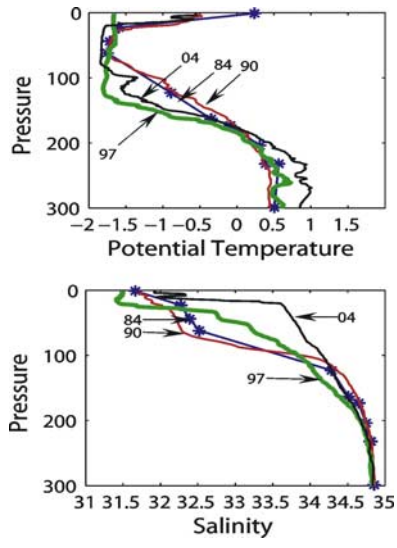

Figure 4. Vertical profiles from 0 to 300 m of potential temperature and salinity for one selected station each year. Each of these profiles is representative for most of the stations in that year. 1984 (blue line) is bottle data and the bottle depths are marked with stars, 1990 (red), 1997 (olive), and 2004 (black) are CTD measurements.

[13] The maximum silicate values in 1984, 1990, and 1997 were similar for all three years, but the corresponding salinities were different. A clear silicate maximum was found in the UHW below the surface layer in 1984 and in 1997, although salinities were slightly below 33 in 1997. In 1990, the silicate maximum lay within the lower part of the remnants of the winter mixed layer (where $S \leq 32.5$), and not in the UHW layer. The reason for these differences may be seasonal and interannual variations of silicate concentrations in the different water masses leaving the Chukchi Sea shelf, and differences in the path and time until reaching the Fram Strait. Both the 1984 and 1990 sections show very low silicate values at the very surface, which are the result of biological production, but below the biological active layer the high silicate values of Pacific derived water is clearly present. In 2004, the low silicate values extend down through the whole column of polar waters and can not be caused by biological uptake alone.

[14] In 1984 and 1990 our data show a strong signal of Pacific Water in the surface and the upper halocline north of the Fram Strait, which most probably have passed north of Ellesmere Island some years previously. This is in contrast to *Steele et al.* [2004], who suspected that the Lincoln Sea had very little Pacific Water influence during much of the 1980s. They related this to the negative AO state, since the area north of Ellesmere Island is then influenced by sea ice from mid-Siberia. During the highly positive AO state in the 1990s similarities are seen for the waters in both the Lincoln Sea and north of the Fram Strait. The gradual decline of the BSW temperature maximum in the Lincoln Sea after 1994 was thought to be a result of shifting back again of the Transpolar Drift Stream origin towards the New Siberian Islands and away from the Chukchi Sea source in the later 1990s. A relaxation back towards less Pacific influence in the Ellesmere region was then expected to follow [*Steele et al.*, 2004]. A strong reduction in the Pacific Water contribution to the Fram Strait has indeed taken place during the last couple of years.

5. Conclusion

[15] In this paper we have mainly focused on the Pacific Water signal delivered to the entrance of the Fram Strait and its variations over the past twenty years. We assume that the observed changes are due to a modification of the circulation pattern and not of the sources themselves. The data from 1984 and 1990 show that the waters reaching the Fram Strait along the Greenland coast, from the surface to the Atlantic layer, have arrived from the Canadian Basin. Farther offshore there is a transition to water mass characteristics of the Eurasian Basin. While the surface and upper halocline waters still had a strong Pacific Water signal in 1997, most of the stations showed a "new" water mass below the UHW, recognized as the CHL. At some time between 1997 and 2004 a significant change in the flow pattern of Pacific Water in the Arctic Ocean has taken place. The most reasonable explanation is a change in the position of the Transpolar Drift Stream [*Proshutinsky and Johnson*, 1997], cutting off the route to the Fram Strait for the Pacific Water.

[16] Although our time series does not well resolve interannual changes, we find no indications for a direct relation between the presence of Pacific Water north of the Fram Strait and the Arctic Oscillation. A strong shift of the axis of the Transpolar Drift Stream toward the Canadian Archipelago in later years would explain why only waters from the Eurasian Basin are now present in the area north of the Fram Strait. From our findings we conclude that the Pacific Water must at the present either be stored in the Beaufort Gyre and/or drained through the passages of the Canadian Archipelago. It is now important to monitor how long it takes before the Pacific Water again exits the Fram Strait and to compare the Pacific Water outflow through the Fram Strait and the Canadian Archipelago.

[17] **Acknowledgments.** We thank the various CTD and autoanalyzer groups for their assistance during the cruises and the captain and crew of the RV Polarstern for professional support. Figure 3 was produced using Ocean Data View [*Schlitzer*, 2004].

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