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NOTES AND CORRESPONDENCE

Recent Abrupt Intensification of the Northern Polar Vortex since 1988

By H. L. Tanaka

Institute of Geoscience, University of Tsukuba, Tsukuba, 305 Japan

Ritsuko Kanohgi

Japan Weather Association, Chiyoda-ku, Tokyo, 101 Japan

and

Tetsuzo Yasunari

Institute of Geoscience, University of Tsukuba, Tsukuba, 305 Japan

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Abstract

Walsh (1994) reported that the surface vorticity in the Central Arctic has changed its sign from negative to positive since 1988. This study is devoted to confirm the recent abrupt change in the Arctic documented by Walsh. The analysis is extended not only to the surface but also to the upper air circulation to find the vertical structure in the vorticity change.

As a result, the decreasing trend in geopotential height since 1988 is confirmed for the polar vortex throughout the troposphere. The vorticity change is thus regarded as barotropic in its structure. The surface Beaufort high has weakened associated with the strengthened upper air vortex. It is anticipated from the result that the wind-driven Beaufort gyre might undergo significant deformation, which would lead to a drastic impact on the export of sea ice to the North Atlantic Ocean through Fram Strait.

1. Introduction

The Arctic is one of the most sensitive regions on the earth to the global climate change due both to the natural variability and the anthropogenic climate forcing. The polar climate system is in a delicate balance among its subsystems of the atmospheric circulation, oceanic circulation, and sea ice motions. Therefore, the global warming, if it is real, would be detected first in the Arctic, as predicted by a series of climate model predictions (IPCC, 1990). The latest observational reports on the Arctic climate change are summarized by Walsh *et al.* (1996b), based on various sources of instrumental observations.

In the central Arctic, the annual-mean motion of the sea ice is characterized by the Beaufort gyre as seen in Fig. 1. The sea-ice motion is clockwise, and one branch of the ice drift pushes the sea ice out to the North Atlantic Ocean through Fram Strait. At the subpolar North Atlantic Ocean, the mixing of water mass leads to the deep-water formation that drives the global conveyor belt of thermohaline circulation. Hence, variations of sea-ice export have been the subject of considerable attention recently in the context of possible changes in the rates of North Atlantic Deep Water formation (*e.g.*, Aagaard and Carmack, 1989; Mysak *et al.*, 1990). Since the anticyclonic Beaufort gyre is driven mostly by the wind stress due to the low-level anticyclonic circulation, the so-called Beaufort high (see Fig. 1), long-term variations of the Beaufort high as the atmospheric subsystem draw some attention to the issues in the global change.

Recently, Walsh (1994) and Walsh *et al.* (1996a) reported significant decadal-scale changes in sea-level pressure over the Arctic, based on buoy observations for the period of the International Arc-

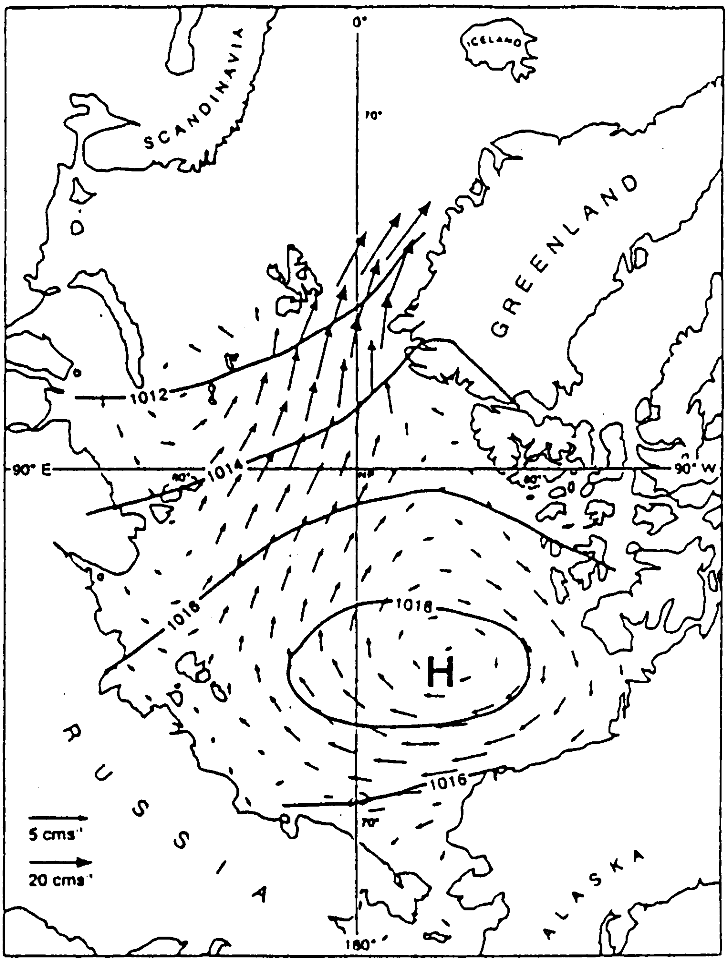

Fig. 1. Mean annual ice drift and mean annual surface pressure (courtesy by R. Colony). The Beaufort high is marked by H.

tic Buoy Program (1979–1994). They showed that sea-level pressure over the central Arctic (70°–90°N) has decreased noticeably since 1988. Correspondingly, the mean anticyclone over the Arctic Ocean has weakened, and vorticity at sea level in the Central Arctic has changed its sign from negative (anticyclonic) to positive (cyclonic) since the winter 1988/89. If this trend continues, the oceanic Beaufort gyre might change its direction of circulation to counter-clockwise, and then the sea-ice supply through Fram Strait to the North Atlantic Ocean would change significantly, possibly causing a considerable impact on the global climate.

Walsh *et al.* presented the pressure patterns only at the sea level. Changes in the upper-air circulation, if any in association with the changes in the sea level, are of significant importance, but no information has been provided thus far. Walsh *et al.* computed the mean vorticity based on the gradient wind over the central Arctic Ocean estimated from the surface pressure data. In Walsh (1994), the mean vorticity is computed over the polar cap of 80°–90°N by means of the finite-differenced numerator of the Laplacian. The computation is repeated in Walsh *et al.* (1996a) over an area of similar size centerd at (84°N, 125°E). Since the computation is a rather rough approximation to vorticity, further analysis is desired for confirmation using a direct computation of vorticity from the wind field.

The purpose of this study is to confirm the recent abrupt intensification of vorticity over the Arctic Ocean after 1988 as documented by Walsh (1994) and Walsh *et al.* (1996a). Their simplified vorticity index is compared with the direct computation of vorticity based on the wind field. In this study, the analysis is extended not only to the surface but also to the upper-air circulation in order to identify the vertical structure in the vorticity change.

2. Data and computational method

The global analysis data obtained from the U.S. National Meteorological Center (NMC) have been edited for monthly means during a period from January 1981 to December 1994 over the region for 50°–90°N. The analysis data comprise meteorological variables of horizontal wind $\mathbf{v} = (u, v)$, temperature

T, and geopotential height Z on the 2.5° × 2.5° (lon. × lat.) grids at the standard pressure levels of 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, and 50 hPa.

The analysis region for the computation of vorticity in this study is a polar cap over 80°–90°N, as in Walsh (1994). The area-mean vorticity $\bar{\zeta}$ computed over the polar cap is evaluated from the u-component of wind vector based on Stokes' theorem.

$$\bar{\zeta} = \frac{C}{A} = \frac{1}{A}\oint \vec{v} \cdot d\vec{l} = \frac{l}{An}\sum_{i=1}^{n} u_i, \qquad (1)$$

where C is circulation, A is the area of the polar cap, l is the length of the periphery. The upper-air polar vortex is associated with the westerlies ($u > 0$). Therefore, the circumpolar vorticity is in general positive: *i.e.*, cyclonic. In the Arctic, the zonal mean easterlies ($u < 0$) are occasionally observed near the surface. It is these easterlies that are associated with the anticyclonic circumpolar vorticity.

The results in this study will be compared with the vorticity index evaluated by Walsh (1994) by means of the finite-differenced numerator of the Laplacian: *i.e.*, the center pressure at the North Pole minus the mean pressures at four points surrounding the center point. The analysis data in this study contain basic meteorological variables at all vertical levels. Thus vorticity computed in this study is straightforward in theory, although the wind data are the products of a data-assimilation cycle with sparse observing stations surrounding the Arctic Ocean. In contrast, Walsh's vorticity index is evaluated from the direct buoy observations, although the vorticity computation contains rough approximations as mentioned above. The comparison of these two types of vorticity may allow us further analysis of the upper-air circulation if those two reasonably agree with each other.

3. Variations in height field

First, variations in geopotential height before and after the abrupt change around 1988 are analyzed. Figure 2a illustrates 1000-hPa height for the 5-year average from 1981 to 1985 representing the pressure field near the surface before the abrupt change around 1988. The prominent features of the mean field are the two distinct low-pressure centers over the oceans associated with the Aleutian low in the Northern Pacific Ocean and the Icelandic low in the Northern Atlantic Ocean. The Beaufort high is located just over the Beaufort Sea extending from East Siberia to Northern Canada between these two low-pressure centers. A closed contour (140 m) around the high is detectable over the Beaufort Sea within the high-pressure belt connecting the two continents. The Siberian high is evident at the western end of the high-pressure belt, but there is no apparent high-pressure center at the other end in North America. The 1000-hPa pattern is almost identical with the sea-level pressure analyzed by Walsh for 1979–1986.

Figure 2b illustrates the same height pattern, but for the 5-year average from 1989 to 1993 after the abrupt change around 1988. The closed contour of 140 m as evident in Fig. 2a is missing over the Beaufort Sea, although the high-pressure belt still exists with a weak high-pressure center near Mackenzie river. The intensities of the Aleutian low and Siberian high are unchanged, but the Icelandic low has strengthened to some extent.

The difference between Fig. 2a and 2b is illustrated in Fig. 2c, subtracting the former from the latter. A decreasing trend is evident over the entire Arctic except over Greenland. The center of the decreasing trend (see the −40-m contour) is located over the middle of the Arctic Ocean. The overall pattern of the decreasing trend is almost identical with Fig. 2 of Walsh *et al.* (1996a). The 99 % significance level based on their t-test roughly corresponds to the 30-m contour in Fig. 2c of this study. As they discussed, the increasing trend over Greenland may be an artifact of changes in analysis procedures and/or the extrapolation to sea level. Similarly, the large difference over the Tibetan Plateau may be an artifact of changes in the extrapolation. Compared with the results by Walsh *et al.* (1996a), we confirm that the present study based on the NMC global analyses reproduces the overall characteristics of the sea-level pressure changes based on the buoy observations. Hence, we now have a basis to pursue further the long-term trend of the upper-air circulation field using the NMC global analyses. We note that the analysis regions of the polar cap and its shifted version in Walsh *et al.* (1996a) are chosen for the area of the largest difference before and after 1988. Therefore, the region does not necessarily coincide with the location of the Beaufort High, as may be compared for Figs. 2a and 2c.

Figure 3 illustrates the same patterns as Fig. 2, but for the 500-hPa height before and after the abrupt change around 1988 and the difference between the two. The minimum of the 5-year mean height over the Arctic is about 5250 m before 1988, whereas the corresponding minimum is about 5200 m after 1988. The decreasing trend of the 500-hPa height is most evident over the Arctic Ocean in Fig. 3c, as indicated by the −60-m contour around the North Pole. The center of the decreasing trend at the 500-hPa level approximately coincides with that at the 1000-hPa level, which implies that the polar vortex over the Arctic Ocean is intensified throughout the troposphere.

4. Variations in vorticity field

Figure 4 illustrates the time series of 24-month running mean vorticity averaged over the polar cap,

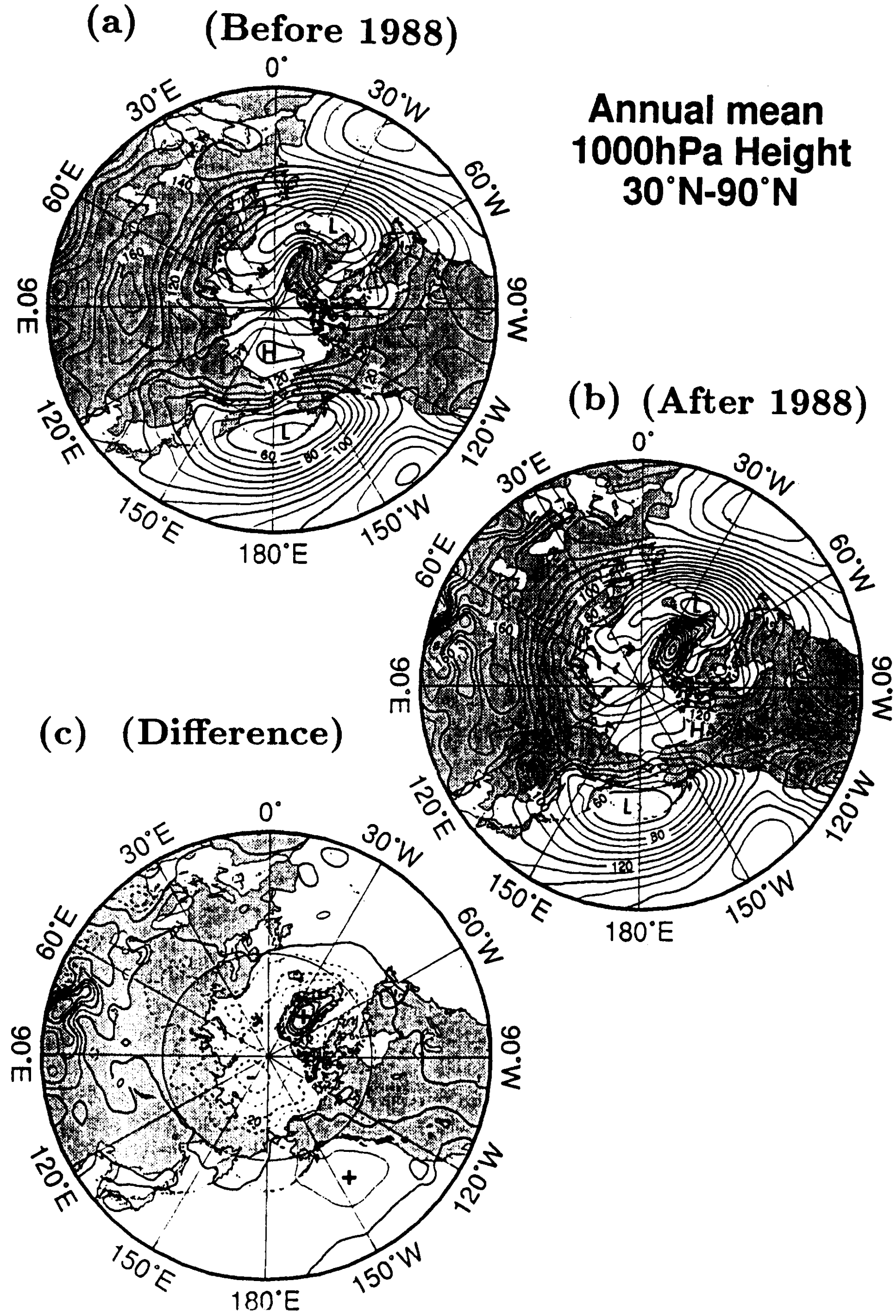

Fig. 2. Annual mean 1000-hPa height (a) averaged for 5 years (1981–1985) before the abrupt change around 1988, (b) averaged for 5 years (1989–1993) after 1988, and (c) the difference between the two mean heights, (b)–(a).

80°–90°N, during 1981 through 1994 for the 1000-, 850-, 500-, and 200-hPa levels. The 95 % confidence interval of the mean, evaluated from the unsmoothed time series over the entire analysis period, is hatched in the figure. The result for 1000 hPa indicates a remarkable increase in the mean vorticity from near-zero to positive about $2\times10^{-6}(s^{-1})$ after 1988. This implies that within the polar cap the low-level anticyclonic circulation is disappearing in the annual mean. The result is consistent with the recent tendency documented by Walsh (1994) for the sea-level pressure, although his result shows significantly negative vorticity before 1988. In Walsh *et al.* (1996a) the computation of circumpolar vorticity is repeated for a slightly shifted area centered at (84°N, 125°E). The basic features are not altered, though the abrupt change of vorticity around 1988 from negative to positive values becomes even

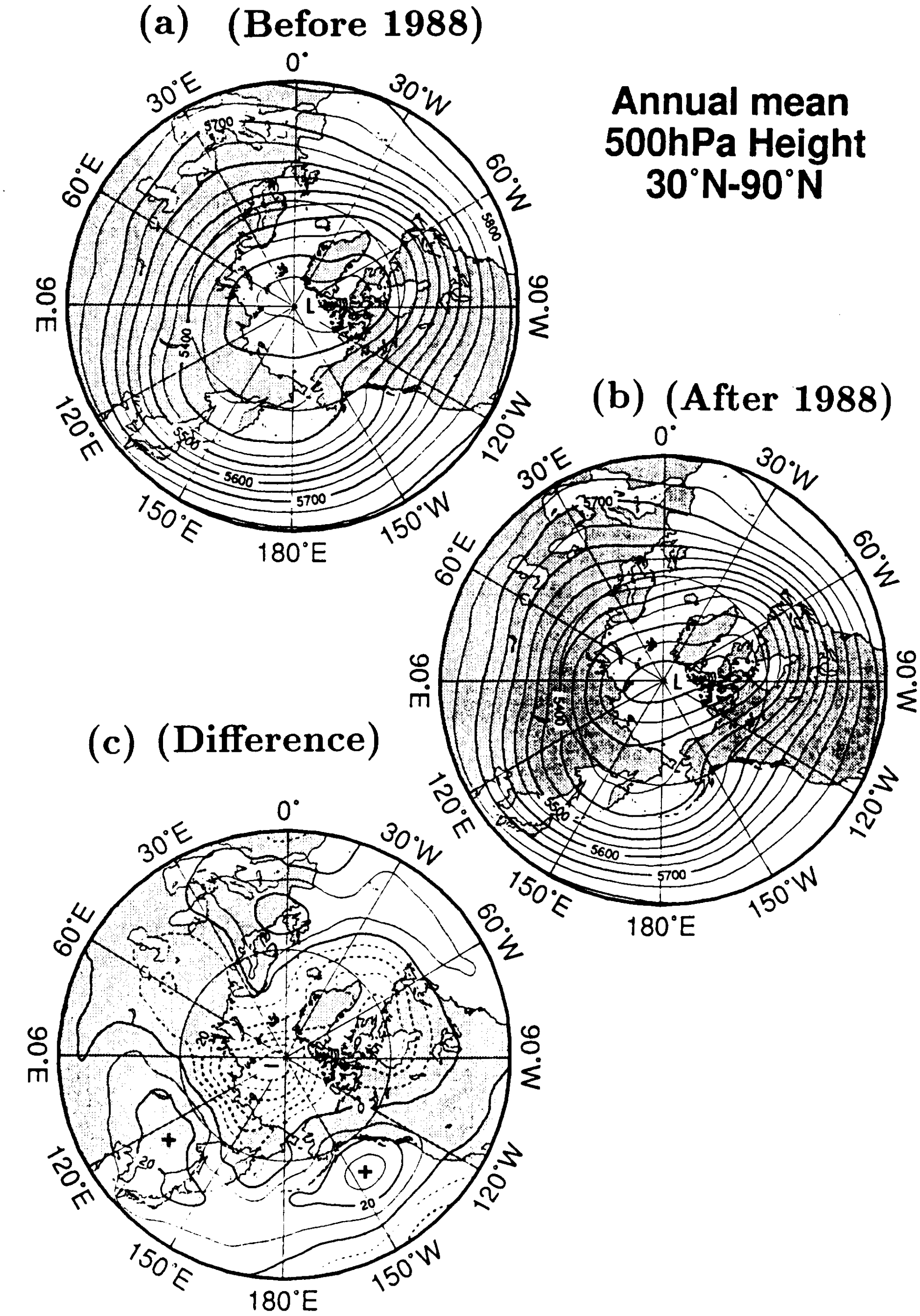

Fig. 3. As in Fig. 2, but for the mean 500-hPa height.

clearer.

A tendency similar to that at the 1000-hPa level is seen at the upper levels of 850, 500, and even 200 hPa. Since the westerlies are stronger at the upper levels, the running-mean vorticity is increasingly positive, *i.e.*, cyclonic, throughout the analysis period. The abrupt increase in vorticity around 1988 is detectable throughout the troposphere. The result suggests that the cyclonic polar vortex has been intensified throughout the troposphere from 1988.

5. Concluding remarks

This study is devoted to confirming the recent abrupt change in surface pressure in the Arctic before and after 1988, as documented by Walsh (1994) and Walsh *et al.* (1996a). We have analyzed the time series not only near the surface but also for the upper circulation.

First, the 5-year averages of 1000-hPa height are compared before and after the abrupt change. The result shows a significant decrease in height (about

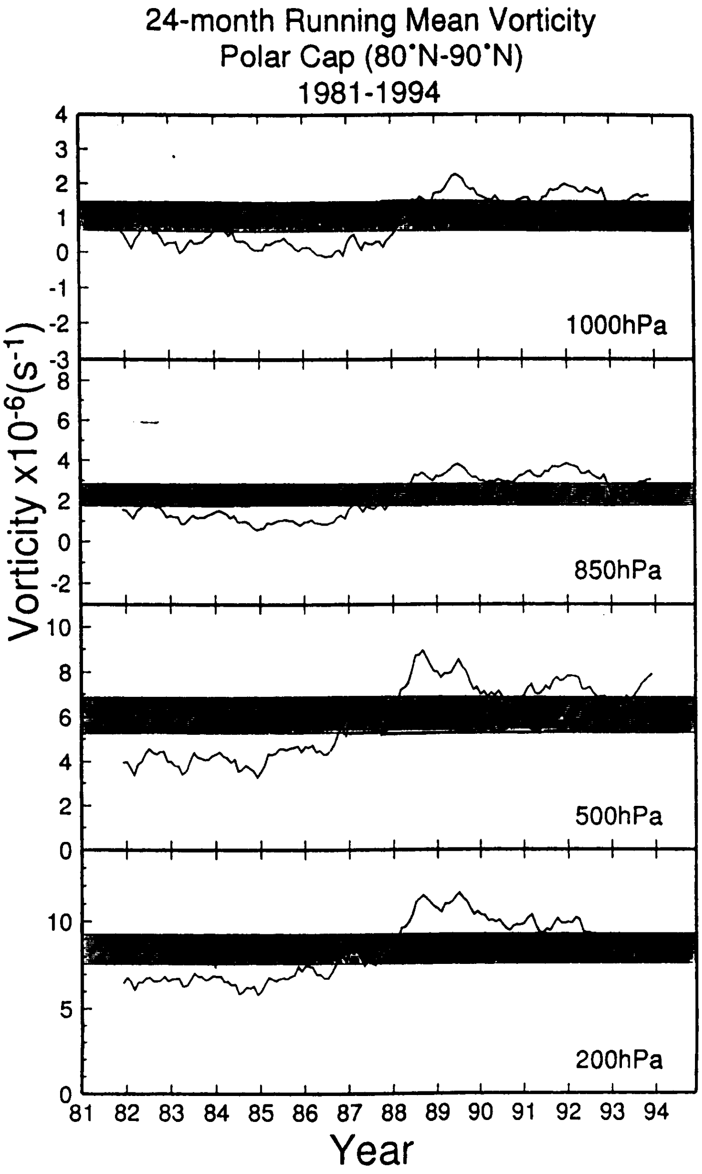

Fig. 4. Time series of 24-month running mean of vorticity over the polar cap, 80°–90°N during 1981 through 1994 for pressure levels at 1000, 850, 500, and 200 hPa. The 95 % confidence interval of the mean during the analysis period is hatched in the figure.

−40 m) over the central Arctic Ocean. The overall pattern of the decreasing trend is almost identical with the result by Walsh *et al.* (1996a) analyzed from the buoy observations. Therefore, we have a basis to pursue further analysis of the abrupt change in the upper levels using the NMC global analyses. The result for the 500-hPa level indicates a similar decreasing trend over the Arctic Ocean, reaching nearly −70 m around the North Pole.

The intensified polar vortex after 1988 is further confirmed by the time series of vorticity over the polar cap (80°–90°N). In this study, similar tendencies of increasing vorticity are analyzed at 850-, 500-, and even 200-hPa levels. The vertical structure of the vorticity change is thus regarded as barotropic. It may be concluded that the weakening surface Beaufort high is associated with the intensifying polar vortex in the upper air. It is anticipated from the result that the wind-driven Beaufort gyre might undergo significant deformation due to the weakening Beaufort high. The consequence would be a profound impact on the export of sea ice to the North Atlantic Ocean through Fram Strait.

According to previous studies, similar discontinuous change occurred in the intensity of the Aleutian low before and after 1977. The Aleutian low intensified after 1977, but was weakened after 1988 (see, Kashiwabara, 1988; Chen *et al.*, 1992; Trenberth and Hurrell, 1994). Likewise, an interesting discontinuous shift was reported for the sea-ice area within the Sea of Okhotsk by Tachibana *et al.* (1996a). The sea-ice area increased abruptly after 1977 in the southern part of the Sea of Okhotsk and decreased after 1988.

It may be interesting to note that these abrupt changes at high latitudes occurred simultaneously with the outbreak of extreme weather. During January 1977, the polar vortex over the North Pole was replaced by an abnormaly persistent anticyclone (see Miyakoda *et al.*, 1983). A remarkable warming occurred in Alaska during the following decade (see Jones, 1988), linked with the weakened polar vortex after 1977. Another extreme event was reported in 1989, showing a record breaking cold spell in January followed by a record breaking warm spell in February in Alaska (see Tanaka and Milkovich, 1990; Tan and Curry, 1993). The cold spell in January at Barter Island, Alaska indicated a temperature anomaly of two times the negative standard deviation, and that of the warm spell in February reached four times the positive standard deviation (see Walsh and Chapman, 1990). Those extreme events are both associated with formations of extraordinary blocking high.

Further analysis is necessary to understand the régime shift between different climate states and its relation to the outbreak of the extreme events.

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北極圏の極渦の1988年以降の強化に関する解析的研究

田中 博
(筑波大学地球科学系)
叶木律子
(日本気象協会調査部)
安成哲三
(筑波大学地球科学系)

北極海上の渦度が1988年を境に、負(高気圧性)から正(低気圧性)に転じたことがWalsh (1994)により報告されている。本研究ではWalshが解析した近年のこのような渦度の急変を再検討し、その急変がどのような鉛直構造になっているのかを調べた。

解析の結果、北極海上の高度場が1988年以降対流圏で一様に低下し、それに伴い極渦の渦度が一様に増大していることが明らかになった。つまり、大気上層の極渦の強化に伴い下層のボーフォート高気圧が衰退しているという事実が確認された。本研究の結果によると、ボーフォート高気圧による海氷の風成循環に異変が生じ、フラム海峡を経て北大西洋に運ばれる海氷の量が変化し、北大西洋の大規模熱塩循環に多大な影響を与えることが危惧される。