The Role of Cyclone Activity in the Interannual Variability of the Summertime Beaufort High

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Abstract

The Beaufort High (BH) is a well-known climatological feature of the Arctic with close ties to sea ice variability. Here, an objective cyclone-tracking algorithm was utilized to link the summertime interannual variability of the BH to cyclone migration pattern and its intensity. The results indicated that rather than the in situ change of anticyclone in the region, the variability of BH is influenced more by passive effects of cyclone activity with its center near the North Pole. The effect of cyclones is twofold. One is the effect of more intense cyclones entering the peripheral region of the BH where three times as many cyclones below 980 hPa reach the Arctic for years in which BH is weak. The other is intensification of cyclones forming within the Arctic contributing to an average difference of 4.9 hPa between years with strong and weak BH. We argue that along with the in-situ change in the BH, such peripheral cyclone activity spreads into the BH region strongly affecting the observed interannual variability.

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1. Introduction

A prominent feature of the summertime mean sea level pressure (SLP) field over the western Arctic Ocean is the existence of a permanent anticyclone along the coast of Alaska centered over the Chukchi/Beaufort Sea commonly referred to as the Beaufort High (BH) (Walsh 1978; Serreze and Barrett 2011). Surface winds associated with the BH are closely related to the mean circulation of the Arctic Ocean and sea ice; i.e., the Beaufort Gyre. In summer, the strength and structure of the Beaufort Gyre lead to transport of sea ice across the Arctic Ocean, thus contributing to the recent marked decrease in sea ice distribution (Stammerjohn et al. 2012; Stroeve et al. 2012). Such rapid transport of sea ice is related to the dipole anomaly pattern in which the BH acts as one of the action centers (Watanabe et al. 2006; Wang et al. 2009). There have been a number of studies documenting the properties and long-term variability of the BH. Serreze and Barrett (2011) studied the climatological features of the BH based on observational data. Their study showed that the BH could be interpreted as a surface manifestation of an amplified western North American ridge at 500 hPa. They also found that a stronger BH is accompanied by a deeper Aleutian Low. Moore (2012) found a decadal and recent amplification of the summer BH that began in the late 1980s and have related it to the warming of the troposphere in the western Pacific and a reduction of baroclinicity in the northern flank of the BH.

Given the importance of BH for the teleconnection patterns over the Arctic and the transportation of sea ice in summer, there is a great deal of interest in the mechanism underlying the interannual variability of the BH. While surface sea ice distribution, low-level clouds, and the resultant radiation balance play roles in the variability of the BH, it shows a distinct characteristic in its relation to the surrounding low-pressure systems and cyclone migration patterns.

Rather than focusing on the intrinsic interannual variability of the BH, we present an alternate view where the passive influence of synoptic cyclones toward the BH is addressed using a Lagrangian cyclone-tracking algorithm. Examining individual cyclone tracks has a distinct advantage over taking the seasonal mean. First, cyclone tracks can explain a particular negative anomaly in the SLP as either a shift in cyclone migration or as a change in cyclone density. Second, while specific features in the synoptic timescale are lost in the seasonal or monthly average, Lagrangian cyclone track analysis can present a more detailed view, how the seasonal mean field is created as a manifestation of individual cyclones. We present the method used for cyclone track analysis in Section 2. The results of cyclone track analysis based on strong and weak BH years are presented in Section 3, and Section 4 presents our closing discussion.

2. Data and methods

The primary data used in this study consisted of the SLP obtained from the Climate Forecast System Version 2 (CFSv2) reanalysis dataset (Saha et al. 2010). The data have a resolution of $0.5^\circ \times 0.5^\circ$ on a fixed latitude – longitude grid. Six-hourly data from January 1979 to December 2013 were used.

Cyclone tracks and statistics were calculated using an algorithm developed by the University of Melbourne (Murray and Simmonds 1991a; Murray and Simmonds 1991b; Simmonds and Murray 1999). The basic methodology involves conversion of the data to a polar stereographic grid and calculation of the Laplacian of pressure ($\nabla^2 p$) for each grid point at each time step for the whole northern hemisphere to identify the location and strength of a potential low. The position of the cyclone is refined by iteration to the center of the ellipsoid showing the best fit to the local pressure surface. To remove spurious results due to topography and identify a closed cyclone system, a topographical filter was applied as well as diffusive filtering of $2^\circ$ latitude radius. Then, the identified cyclones were tested by a concavity criterion that requires the Laplacian value to exceed 0.2 hPa m$^{-2}$ over a radius of $2^\circ$ latitude. A tracking algorithm was employed to connect cyclones in each time step to each other, taking into account the steering velocity. All combinations of cyclones within a potential region were calculated to find the maximum sum of probability determining the matching for a particular group, and unmatched cyclones were marked as cyclogenesis or cyclolysis depending on the time evolution. The algorithm does not account for merging of cyclones. To remove noise, we analyzed only cyclones lasting more than 1 day. In addition, the location of the cyclone center and its pressure among other variables are summarized into multiple cyclone statistics, such as the mean cyclone track density and cyclone depth.

3. Results

Figure 1 shows the basic structure of the summertime BH and its variability. Figure 1a shows the climatological SLP and intra-seasonal standard deviation for the JJA season averaged over the
period 1979–2013. Upon calculating the standard deviation, a 3–6 day band-pass filter is applied following Blackmon et al. (1976) to quantify the contribution of transient eddies. The filter is applied to the original SLP data and the standard deviation is taken over the whole JJA season.

The BH showed an elongated structure along the coastline of Alaska with its center near 74°N, 220°E reaching a strength of 1014 hPa. Another notable structure is the low-pressure center near the North Pole with a value of 1010 hPa. This contrast of high- and low-pressure systems characterizes the summertime Arctic pressure field where cyclone activity is strongest in the central Arctic Ocean and diminishes toward the BH region. This was also evident in the intraseasonal standard deviation field where the largest value was located south of the climatological low-pressure center midway to the BH region. The standard deviation field also shows a trail of signal along the Eurasian continent and along the western coast of Greenland indicating the contribution of migratory cyclones. There is also a signal over Greenland, but it is considered to be an artifact resulting from the reduction of surface pressure over the ice sheet to the sea level. The cyclone-tracking algorithm in use takes topography into account and such variability over Greenland is ignored.

To quantify the interannual variability of the BH signature, an area average of SLP was taken for the region 70°N–80°N, 160°E–250°E. The time series showed a relatively weak BH in the 1990s, followed by a positive trend. This was consistent with the recent positive trend of summer BH reported by Moore (2012).

Figure 2 shows the composite analysis of SLP for 10 years in which BH index is larger (less) than +0.5 (−0.5) standard deviation. Unit is in hPa.

Figure 3 shows the regression of BH signature on the cyclone track variability and cyclone depth. The cyclone track quantifies the number of cyclone migration paths in a particular grid, with the largest values in notable storm track regions, such as the North Atlantic. Figure 3a shows a band of negative regression value in the Arctic region slanted more towards the Alaskan coastline but not reaching the BH region, which coincided with the region of large SLP variability shown in Fig. 1a. Negative regression in this case means that a strong BH corresponds to fewer cyclones in the region and vice versa. This indicates that the cyclone migration pattern in this peripheral region of the BH has a strong effect on the interannual variability of the BH. It should be noted that cyclones tend to diminish in this peripheral region and do not directly enter the BH region to influence the variability. Regression on the cyclone depth showed a similar negative signal centered near 85°N, 170°E (Fig. 3b). The cyclone depth statistics correspond to the depth of each cyclone system averaged over the JJA season. Figure 3 shows that BH interannual variability is influenced by cyclone activity where a strong BH corresponds to a diminished cyclone track density just north of the BH region, and also by intensification of cyclones in the North Pole region.

This can be interpreted as an effect of more cyclone activity in the peripheral region of the BH passively reducing the pressure of the BH, thus influencing the interannual variability. Conversely, in the years in which the BH was strong, the lack of such cyclone activity allowed the BH to strengthen. Through such processes, we argue that the BH interannual variability is passively governed by the cyclone activity in the peripheral region of the BH.

These observations raise questions regarding the origin and intensity of these cyclones. Figure 3a shows a band of negative signal extending from the northern North Atlantic and North Pacific signifying a cyclone migrating from the mid-latitudes. Figure 4 shows the ensemble of cyclone tracks stratified for strong and weak BH years. Cyclone tracks entering the Arctic region are color-coded to signify the migration pattern. For ease of visualization, we draw only the 1000 strongest cyclones based on its northwards.

Figure 3 shows the regression of BH signature on the cyclone track density and b) cyclone depth. Cyclone track density is shown as the number of cyclone tracks per grid, and cyclone depth is shown in hPa.
weak BH years, respectively. This corresponds to cyclones stronger than 1001.16 hPa and 1001.87 hPa depicted for the strong and weak BH years. The minimum central pressure is shown to be larger (less) than +0.5 (−0.5) standard deviation. Each line indicates the migration of each cyclone center and green lines indicate those passing through the Arctic region (north of 70°N). Only the 1000 strongest cyclones based on its minimum central pressure is shown.

First, the number of cyclones near the North Pole where the climatological low pressure is located (Fig. 1a) is less dense in Figs. 4a, b, consistent with the results shown in Fig. 3a. Second, the cyclones entering the Arctic Circle originated from four distinct regions—the North Atlantic, from the coastline of the Eurasian continent, from the North Pacific through the Bering strait, and finally the Canadian archipelago passing directly north along the western coastline of Greenland. More cyclones enter the Arctic via the North Atlantic and Bering Strait. However, cyclones born in the Arctic cannot be dismissed. It should also be noted that cyclones are denser in the mid-latitudes for the strong BH case signifying that cyclones are less likely to enter the Arctic Circle.

Figure 5 summarizes the number of cyclones originating in each region and their intensity. Figures 5a, c correspond to 10 years in which BH was strong, while Figs. 5b, d correspond to weak BH years. In addition, Figs. 5a, b show the statistics of mid-latitude cyclones entering the Arctic, whereas Figs. 5c, d show the case for cyclones born in the Arctic that do not leave throughout their lifetime. Cyclone intensity is represented by the minimum pressure reached within the Arctic Circle and each longitudinal section is defined as follows: North Atlantic, 330°E−64°E; Eurasia, 64°E−150°E; North Pacific, 150°E−240°E; and Canadian archipelago, 240°E – 320°E. For each longitudinal section, cyclones originating in the mid-latitudes (30°N−70°N) and migrating toward the Arctic as defined by area north of 70°N were selected.

Figures 5a, b show that the number of intense cyclones (< 980 hPa) was markedly larger for the weak BH years. While the total numbers of cyclones for strong and weak BH years were 884 and 848, respectively, the numbers of cyclones with minimum pressure < 980 hPa were 65 and 74, respectively. This shows that stronger cyclones are entering the Arctic region for weak BH years.

Within each regional category, the average minimum pressure of cyclones was mostly comparable between the strong and weak BH years, indicating that the change in migration pattern is the driving mechanism for mid-latitude cyclones affecting the Arctic region. For cyclones stronger than 980 hPa, there is marked difference in the number of cyclones entering from the Bering strait, as well as the Canadian archipelago. Figure 4 also shows such change in migration pattern in the northern Pacific and the Hudson Bay, where cyclones are densely confined in these regions for the strong BH years, and more migratory in the weak BH years.

On the other hand, cyclones born in the Arctic show large differences in intensity related to BH signature, with an average minimum pressure of 996.8 hPa for the strong BH years but 991.9 hPa for weak BH years, a difference of 4.9 hPa. Thus, the passive effect of cyclones on the BH is twofold. The first is an increased number of cyclones entering the Arctic, most notably from the Canadian peninsula, and the other is the intensity of cyclones forming in the Arctic.

4. Discussion and conclusion

This study was performed to examine the influence of cyclone activity on the interannual variability of the summertime BH from a Lagrangian perspective utilizing cyclone track analysis. The main finding was that the BH interannual variability is governed more by cyclone activity in the peripheral region spreading into the BH region than in situ variability of the anticyclone. The numbers of mid-latitude cyclones entering the Arctic from the Atlantic Ocean, Eurasian continent, and the Canadian peninsula increase when BH activity is weak and vice versa. On the other hand, the intensity of cyclones forming within the Arctic also influences the BH, where more intense cyclone formation in the peripheral region corresponds to a weaker BH.

Our findings were consistent with previous studies, but provided more detailed descriptions. Zhang et al. (2004) reported increased cyclones entering the Arctic from the mid-latitude in summer, and Moore (2012) reported that the summertime BH showed a strong positive trend accompanied by reduced baroclinicity over the northern Beaufort Sea. While these studies argued that cyclogenesys is the reason for the former observation, our results showed that a shift in cyclone migration pattern and their number and intensity also plays a role.

Taken together, our findings correspond to a stronger/weaker summertime Northern hemispheric Annular Mode (NAM) related to a weaker/stronger BH (Ogi et al. 2005). Taking the leading mode of the SLP field north of 30°N as an index of NAM, it is found that the BH index has a significant negative correlation of −0.73 in the JJA season. Stronger NAM favors more mid-latitude cyclones entering the high latitudes, so this is consistent with the results shown in Fig. 4. Further study is required to evaluate the regional asymmetries and the relationship of cyclone migration patterns against the NAM pattern.

One can argue the possibility that a strong or weak BH may affect the Arctic cyclone activity and prevent or allow the cyclones from entering the Arctic. Such is the case for mid-latitude Bonin high where a stable high pressure strongly governors the migration pattern of cyclones. However, the summer BH is more transient in nature with the whole region being covered in a low pressure system regularly. Figure 6 shows the lag correlation between the SLP averaged over the BH region and the region north of 80°N, showing a strong negative correlation.
The correlation is taken using the original SLP dataset for the whole JJA season and averaged over the strong and weak BH years. It can be seen that in both cases, there is a slant towards the SLP lagging the North Pole region by 1–2 days, indicating that the pressure variability in the peripheral region governing the BH is indeed strong.

Also, according to Fig. 5, the number of cyclones entering the BH region from the mid-latitudes was comparable in each region. If there was an effect of BH deflecting the cyclones away from the Arctic, there should be a marked reduction in the number of cyclones especially ones originating from the Bering Strait, which is not the case. Nevertheless, the interaction between a high pressure system and migrating cyclones is difficult to decouple, and further studies possibly including model sensitivity experiments is required.

These results provide insight into not only the source of the interannual variability of the BH but also its climatological significance. The BH is different from other climatological high-pressure regions, such as the subtropical highs (i.e., the Azores High or the Bonin High), which are maintained through a meridional Hadley circulation. In contrast to the mid-latitudes, there is no strong meridional circulation that maintains the ridge or a strong westerly mean flow. From the perspective of cyclone tracking, the BH region can be seen as a cyclolysis region of cyclones migrating from the North Atlantic, Eurasia, or the Canadian archipelago.

The findings of the present study suggest that the interannual variability and long-term trend in the BH and the Arctic should be examined more closely through comprehensive activities and its boundary conditions. In a model study, Orsolini and Sorteberg (2009) projected that increased greenhouse gas levels would result in increases in the number of cyclones in the Arctic due to changes in the meridional temperature gradient between Northern Eurasia and the Arctic Ocean, and this effect may already be visible in this study. The Arctic sea ice may act as a similar boundary condition toward migrating cyclones, creating a long-term trend in the BH and the Arctic Basin as a whole.

On the other hand, study by Simmonds and Rudeva (2012) states that deep cyclones such as the great cyclone of August 2012 are not governed by lower level boundaries but more closely tied to the local baroclinicity and tropopause polar vortex. The effect of large scale migration pattern of cyclones and their strengthening in the Arctic domain should be discussed not only by cyclones defined in the surface SLP but with their interaction between cyclones defined in the upper level.

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SOLA: https://www.jstage.jst.go.jp/browse/sola

Fig. 6. Lag correlation between the SLP averaged over the BH region and the region north of 80°N. Correlation is taken for the JJA season, and averaged over the strong/weak BH years.