Marine cold air outbreaks in the Russian Arctic: climatology, interannual variability, dependence on sea-ice concentration

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Abstract. In this study, we evaluated the climatology and interannual variability of marine cold-air outbreaks (MCAOs) in the Russian Arctic marginal seas (from the Barents to Chukchi seas). We used a simple index for identifying MCAOs based on the vertical potential temperature gradient between the sea surface and the 800 hPa level. We calculated the index using 6-hourly Era-Interim data for the 1979–2018 period. Given the index, we evaluated spatial and temporal variability of weak, medium, and strong MCAOs frequency as well as their dependence on sea-ice concentration using non-parametric tests. The most intense MCAOs were found in the Barents and Kara seas. The annual cycle maximum for the western Russian Arctic (WRA) were found in wintertime, while it was revealed in mid-late autumn for the eastern Russian Arctic (ERA). In the WRA, we found a statistically significant decrease in amount of strong MCAOs in winter and late autumn and a general strengthening of MCAOs in spring. Meanwhile, over the ERA region, increase of moderate and weak cold-air intrusions during October and November was revealed.

1. Introduction

Marine cold-air outbreaks (MCAOs) are large-scale relatively rapid departures of cold, polar air masses over warm, ice-free waters in lower latitudes. MCAOs favor intensive heat exchange between the ocean and the atmosphere — in particular, the sum of sensible and latent heat fluxes in MCAO can be greater than 500 W/m$^2$ [1]. Inhomogeneity of the underlying surface during transition of air mass from the open sea surface through the shoreline or ice edge directly affects as well the physical properties of clouds and its structural organization [2].

MCAOs, being sources of atmospheric convective system development [3], result in high vertical and horizontal temperature gradients and wind gusts which may lead to polar lows formation [4, 5] and arctic front intensification and regeneration. In its turn, polar lows and arctic fronts have considerable environmental and socio-economic impacts, that are essential for the developing regions of the Russian North. Thus, understanding the climatological characteristics of MCAOs and their dependence on sea-ice conditions is essential for minimizing risks associated with MCAOs impacts. The issues of MCAO characteristics changes under various future scenarios, especially taking into account sea-ice retreat and shifts in global circulation patterns such as North Atlantic Oscillation (NAO) and AO (Arctic Oscillation), is still understudied [6, 7].
In this study, we evaluated the climatology and interannual variability of MCAOs in the Russian Arctic marginal seas for the last four decades. The paper is organized as follows: section 2 describes the data used and defines the MCAO index. Section 3 demonstrates trends and interannual variability of MCAOs. Section 4 summarizes the results and indicates future work motivated by this study.

2. Data and methods
Several criteria have been suggested for MCAO identification (e.g. [6, 8, 9]). In this study, we identified MCAOs based on index $M$ [10] that was calculated as follows:

$$M = \theta_{skt} - \theta_{800}$$  \hspace{1cm} (1)

where $\theta_{skt}$ is the potential skin temperature, defined as $\theta_{skt} = T_{skt} \left( \frac{p_o}{p_{msl}} \right) R/c_p$, $R/c_p$ equals to 0.288, $T_{skt}$ is the skin temperature (sea surface temperature (SST) over open ocean), $p_o$ equals to 1000 hPa and $p_{msl}$ is the mean sea level pressure; $\theta_{800}$ denotes potential temperature at 800 hPa. To avoid excessive variations of sea level pressure due to the high extratropical cyclonic activity in the region under consideration, $\theta_{skt}$ was used instead of skin temperature. $M$-index is similar to one developed by Kolstad and Bracegirdle [6] and can be looked at as a simple stability parameter similar to Brunt–Väisälä frequency.

For calculating index $M$, we used 6-hourly data form the ERA-Interim reanalysis [11] that comes with the horizontal resolution 0.75×0.75 degree for the 1979–2018 period. The ERA-Interim reanalysis was proved to reliably reproduce the Arctic climate parameters [12].

We defined MCAOs as oceanic regions where $M>0$. All MCAOs were then clustered by spatial connectivity with condition to contain not less than 8 neighboring grid-cells. Furthermore, all events were classified according to their intensity [13] as weak (0<$M$≤3 K), moderate (3<$M$≤6 K) and strong ($M$>6 K). All cells with negative $M$ were excluded.

Frequencies ($f$) of strong, moderate, and weak MCAOs ($f_s$, $f_m$, and $f_w$, respectively) were calculated for each month for two regions, namely the Kara and Barents Seas (so called western Russian Arctic or WRA: 66°N-84°N; 10°E-120°E) and the Eastern Siberian and Chukchi Seas regions (so called eastern Russian Arctic or ERA: 66°N-84°N; 120°E-160°W). The frequency for each category was calculated as the ratio between number of reports with MCAO of this category to all reports per month. The intrannual and interannual variability of $f$ was also calculated for two smaller domains — 30°E-50°E/70°N-75°N for the WRA and 67°N-73°N/170°E-160°W for the ERA (WRA$_D$ and ERA$_D$, respectively). For these domains, we also calculated monthly means of M-index averaged over cells with positive $M$ only ($M_{mean}$). Trends of MCAO characteristics were calculated using the non-parametric Theil-Sen estimator, which is insensitive to outliers. Its significance was estimated using Mann-Kendall rank correlation.

To quantify the effects of ice concentration patterns on MCAOs, monthly mean data of sea ice concentration was calculated using the Ice Data Center Sea Ice Trends and Climatologies from satellite observations SMMR and SSM/I-SSMIS, version 3 [14]. The dataset provides information for the polar region on a 25 km × 25 km grid for the period 1978–2018 years. The data was bilinearly interpolated to the 0.75×0.75-degree grid. The coefficient of regression of MCAO frequency on sea-ice concentration was calculated using the Theil-Sen estimator for the aforementioned small domains and its significance was estimated based on the Mann-Kendall test.

3. Results
3.1 Inter-annual and seasonal variability
There are two main routes of invasion of polar air masses in the Northern Hemisphere [15]. The first flow is directed from the Siberian Arctic to East Asia with a dissipation over the northern basin of the Pacific Ocean. The second flow is from the Arctic across the North American continent to the northern Atlantic Ocean with a weakening over the North Atlantic Seas. This defines the contrast in the intensity of MCAOs that originate over the Russian Arctic seas. Larger sensible and latent heat fluxes that are
transferred from warm Atlantic current towards the Barents Sea basin lead to greater ocean-atmosphere vertical and horizontal temperature gradients [15]. In contrast to the ERA seas, which are less affected by warmer ocean waters due to a very narrow Bering strait, the Barents Sea is marked preference for significant MCAOs.

Prevailing of cyclone activity in the WRA compare to the ERA [16] favors greater frequency of MCAOs over the Barents and Kara seas that is few times higher than over the Eastern Seas (figure 1). In particular, over the WRA (figure 1a), $f_S$ is around 5-7% and $f_W$ is near 10%. In turn, over the ERA (figure 1b), $f_W$ is around 1-2%, while strong events lack during some years. Moreover, $M_{\text{mean}}$ has no prominent annual cycle in the ERA and shows non-linear relationship with MCAOs frequency.

A negative trend for MCAOs characteristics is found for the WRA (table 1) that is especially pronounced for $f_S$. This is in line with the study [17], where a declining trend for MCAO-index were determined for the Fram Strait region. In contrast, a positive trend is revealed for the ERA, that is statistically significant for $f_M$ and $f_W$ (table 1).

Because of relatively high difference between wintertime sea surface temperatures over ice-free Arctic seas and air temperature, strong MCAO events over the Barents and Kara Seas often happen during winter season (figure 1c), while summertime MCAOs are uncommon [13]. While the maximum of MCAO events over the WRA happen during the wintertime and reaches up to 20%, over the ERA (figure 1d) the maximum number of MCAOs is shifted towards mid-autumn. During winter and spring, this region is fully covered with ice and does not provide strong vertical and horizontal temperature gradients needed for MCAO development.

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**Figure 1.** Upper panels show variability of annual-means of MCAOs characteristics. Lower panels depict seasonal cycle of MCAOs frequency of occurrence (%) averaged over the (a, c) WRA (solid lines) and (b, d) ERA (dotted lines). Blue lines stay for $f_W$, green for $f_M$, red for $f_S$; black dotted lines show $M_{\text{mean}}$ mean MCAO index, averaged over cells with positive M only.
Table 1. The Theil-Sen slope regression coefficients for annual-mean MCAO characteristics (in % decade$^{-1}$ for $f_i$ and in K decade$^{-1}$ for $M_{mean}$) for the ERA$D$ and WRA$D$ regions for the 1979–2018 period. Significant trends (at 95% level) are shown with the bold font.

|        | $f_W$ | $f_M$ | $f_S$ | $M_{mean}$ |
|--------|-------|-------|-------|------------|
| WRA$D$ | 0.003 | -0.09 | -0.74 | -0.12      |
| ERA$D$ | 0.17  | 0.01  | 0.002 | -0.03      |

3.2 Regional analysis

Figure 2 shows trends of MCAOs of different intensity for certain months over the WRA. For weak events, positive trend coefficients are prominent for the period from December to April. Meanwhile, for both moderate and especially strong events, a statistically significant decrease is revealed for cold season (down to -5% per decade in December and January). These trends in MCAOs can lead to pronounced changes in weather regimes. The decrease of strong and moderate MCAOs and increase of weak MCAOs are likely associated with the steady year-to-year so-called ‘atlantification’ or increased inflow of warm waters from the Atlantic ocean to the Atlantic Arctic region [1] together with air temperature increase in the Arctic [18-20], which results in smaller contrast in air-sea temperature and enlarged areas where sea ice cannot form [21]. Sea-ice retreat results in appearance of regions with positive trends near sea-ice edge.

Figure 2. Linear trends (Theil-Sen regression slope) of weak (left column), moderate (middle column) and strong (right column) MCAOs frequency, in % per decade, over the WRA region for months October–December-January–March during the 1979–2018 period. Black points show significant trends (at 95% level).
Because MCAO events are prevailed in the rear of cyclones [9, 10, 22], interannual variability of MCAO events, especially strong ones, is tied to cyclonic long-term variability. Number of cyclones over the WRA region significantly declines during winter season over the recent 30 years [23], which favors a decrease in MCAOs over the same area (table 1, figure 3). Meanwhile, during the spring-summer season, the cyclone frequency has positive trends over the central-northern part of the Barents Sea, which comprehends with intensification of spring MCAOs in this region.

For Eastern seas (figure 4), sea-ice concentration is substantially higher compared to the WRA region [24]. Thus, noticeable trends of MCAOs can be found only over a small area close to the Bering Strait. Trends are significant only during months from September to December. An increase (3-4% per decade) of weak events in autumn and a decrease of strong events are revealed (less than 1% per decade). The overall number of MCAOs over the ERA has increased because of increase of cyclonic activity [23, 25] and sea-ice retreat [24], while the decrease of strong events is likely linked to the air temperature increase.

**Figure 3** Same as Figure 2 but for the ERA region for months from September to December.

Figure 4 shows the regressions of MCAOs on sea-ice coverage for the WRA region. The seasonal movement of sea-ice edge is traceable with sharp changes of regression coefficient values. In general, for weak MCAOs, negative regression coefficients are revealed for all the months from November to
April. Both moderate and strong MCAOs have significant positive regression on sea-ice concentration during autumn and winter season, and negative during spring. For the ERA basin (not shown), regression coefficients are negative for all types of MCAOs, with slight positive values only over the Chukchi sea for moderate and strong events and over almost all eastern seas for weak MCAO events in early spring.

**Figure 4.** The same as Figure 2, but for coefficient of regression of MCAO frequency on sea-ice concentration (%).

### 4. Conclusion

In this study, based on the ERA-Interim reanalysis data, we found that MCAO characteristics vary broadly from western to eastern Russian Arctic seas. Thus, cold intrusions primarily exist closer to the Atlantic region, namely in the Barents and Kara seas, with peaks during wintertime. Over the ERA region, the frequency of MCAOs is overall much smaller and has seasonal maximum in mid-late autumn. We found an overall weakening of MCAOs in winter and late autumn and strengthening in spring in the WRA region. Meanwhile, over the ERA region, increase of frequency of moderate and weak cold-air intrusions during October and November was revealed. These changes are likely connected with changes in dynamic and thermodynamic characteristics of the Arctic, namely, changes in cyclone activity [23, 25] and changes of air and sea surface temperature. In particular, Kolstad et al. [6] found that changes in atmospheric temperature play greater role in both seasonal cycle and inter-annual variability of MCAOs in comparison to SST fluctuations. Sea-ice retreat plays the
major role as well. Specifically, positive coefficients of regression of MCAO frequency on sea-ice concentration over the WRA region were found being positive in winter and negative in spring.

Understanding the climatological characteristics of MCAOs is essential for studying the processes that determine energy exchange in high-latitude regions between ocean and atmosphere, and the processes that lead to convective clouds developments. An observed increase of convective clouds and convective precipitation in the Russian Arctic [2, 27-29] may be associated with long-term changes in MCAOs frequency. Further analysis needs to be done for a better understanding of the connection between MCAOs and convection development over the Arctic including convective self-aggregation process [2]. Such analysis should be performed using numerical simulations; however, numerical modelling itself is not yet able to provide reliable reproduction and prediction of small-scale processes associated with MCAOs [30]. In particular, models do not correctly reproduce radiation fluxes and cloud characteristics in the Arctic [31, 32], which is presumably due to incorrect reproduction of clouds in the MCAOs.

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