Quantifying the variability of potential black carbon transport from cropland burning in Russia driven by atmospheric blocking events

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Abstract

The deposition of short-lived aerosols and pollutants on snow above the Arctic Circle transported from northern mid-latitudes have amplified the short term warming in the Arctic region. Specifically, black carbon has received a great deal of attention due to its absorptive efficiency and its fairly complex influence on the climate. Cropland burning in Russia is a large contributor to the black carbon emissions deposited directly onto the snow in the Arctic region during the spring when the impact on the snow/ice albedo is at its highest. In this study, our focus is on identifying a possible atmospheric pattern that may enhance the transport of black carbon emissions from cropland burning in Russia to the snow-covered Arctic. Specifically, atmospheric blocking events are large-scale patterns in the atmospheric pressure field that are nearly stationary and act to block migratory cyclones. The persistent low-level wind patterns associated with these mid-latitude weather patterns are likely to accelerate potential transport and increase the success of transport of black carbon emissions to the snow-covered Arctic during the spring. Our results revealed that overall, in March, the transport time of hypothetical black carbon emissions from Russian cropland burning to the Arctic snow is shorter (in some areas over 50 hours less at higher injection heights) and the success rate is also much higher (in some areas up to 100% more successful) during atmospheric blocking conditions as compared to conditions without an atmospheric blocking event. The enhanced transport of black carbon has important implications for the efficacy of deposited black carbon. Therefore, understanding these relationships could lead to possible mitigation strategies for reducing the impact of deposition of black carbon from crop residue burning in the Arctic.

1. Introduction

The deposition of short-lived aerosols and pollutants above the Arctic Circle transported from northern mid-latitude open-source biomass burning has been well documented in scientific literature (e.g. Warneke et al. 2010, Quinn et al. 2011, Sharma et al. 2013, Cheng 2014, Liu et al. 2015, Hall and Loboda 2017). Specifically, the transport of black carbon (BC) has received a great deal of attention as the deposition of BC onto Arctic snow and sea ice leads to a decrease in the snow/ice albedo, resulting in a positive feedback cycle. Although studies have indicated that biomass burning (forests, grasslands, shrubs, and croplands) and gas flaring from as far south as 40°N are dominant sources of BC within the Arctic (e.g. AMAP 2015, Evangeliou et al. 2016), the relative importance of these various sources is dependent on their seasonal patterns as the timing of the burning plays a key role in determining the absorptive efficiency of BC on the Arctic snow (Doherty et al. 2015). Most notably, the deposition of BC in the Arctic during the spring has the largest impact on the snow/ice albedo (Quinn et al. 2011). Although forest fires produce substantially more emissions than cropland fires due to higher biomass loading, the majority of forest fires occur
during the summer (Groisman et al. 2007); whereas, burning within the Russian croplands predominantly occurs within the spring and fall months (Hall et al. 2016, Hall and Loboda 2017).

The Russian croplands (\(\sim 215 \times 10^4 \text{ km}^2\); FAO-STAT 2015) stretch along most of Russia’s southern border between 40°N and 55°N. Although open-source burning is illegal in Russia (Groisman et al. 2017), it is still a widely used practice to clear fields after harvest and before the next planting (Romanenkov et al. 2014, Hall et al. 2016a). For example, cropland burning in Russia between 2001 and 2003 accounted for 31%–36% of all global cropland burning (Korontzi et al. 2006). Despite the low intensity and low injection heights (ranging between 500 m and 1500 m–see Ichoku and Kaufman 2005, Martin et al. 2010, Soja et al. 2012), several studies have identified cropland burning in northern mid-latitudes as a contributor to BC deposited in the Arctic (Koch and Hansen 2005, Stohl et al. 2006, Hegg et al. 2009, Pettus 2009). Specifically, approximately 10% of the observed spring (2003–2015) cropland active fires (7% annual) within the Russian cropland likely contributed to BC deposition on the Arctic snow from low-level transport (Hall and Loboda 2017).

The Russian croplands are located within Northern Eurasia, an area which accounts for 60% of the land north of 40°N (Monier et al. 2017). This vast region is often prone to extreme weather events created from the presence of large scale weather systems driven by atmospheric Rossby waves (Soja and Groisman 2018). These extreme weather events, which form a basis for this study, can result in wide-ranging impacts from extreme droughts or precipitation events to extreme temperature fluctuations in the winter. Based on previous research findings (Hall and Loboda 2017), this study set out to examine a potential low-level, long-distance transport mechanism based on these extreme weather events that could act to enhance potential transport of crop residue emissions to the Arctic snow. There are several proposed mechanisms for long-range, low-level transport of emissions from northern mid-latitudes to beyond the Arctic Circle (e.g. Stohl 2006, Wameke et al. 2010). The most well-known mechanism is related to the formation of isentropic surfaces known as the Polar Dome (Kłonecki et al. 2003). These surfaces of constant potential temperature form in the lower troposphere when the cold, stable Arctic air extends to lower latitudes during the winter and has been recorded as far south as 40°N in January (Iversen and Joranger 1985, Barrie 1986, Stohl 2006). The isentropic surfaces, however, are primarily associated with transport during the northern hemisphere winter and early spring, i.e. before the beginning of an active burning season, and thus have limited relevance for transporting biomass burning BC emissions. The typical mid-latitude cyclonic/anticyclonic circulation patterns present a more common transport mechanism that is active throughout the year including March, April, and May—the critical time period for BC deposition on snow/sea ice—and are capable of transporting BC emissions from burning with low injection heights from the Russian croplands (Hall and Loboda 2017). The clockwise (anticyclonic) and anticlockwise (cyclonic) circular winds enable the transport of BC emissions along the South–North axis and connect the areas of substantial burning during spring months to eventual deposition on the Arctic snow. However, the wind patterns associated with typical cyclonic and anticyclonic activity on average last less than 48 hours (Klein 1958, Lebedeva et al 2016) which is rarely sufficient to move BC emissions from the most productive and extensive areas of croplands in the south of Russia to the Arctic snow.

Atmospheric blocking events—large-scale patterns in the atmospheric pressure field that are nearly stationary and act to block migratory cyclones—amplify the long-range, low-level transport associated with anticyclonic and cyclonic wind patterns. These mid-latitude weather events are distributed globally with the highest northern hemisphere blocking frequencies occurring in the Atlantic region (approximately 100°W–0°E), the European region (approximately 0°–90°E) and the Central Pacific regions (approximately 160°W–180°W) (Pelly and Hoskins 2003, Barriopedro et al. 2006)—with the European region primarily overlapping the major regions of crop production in Russia. The temporal persistence within the European sector (on average 8.3–10.0 days) and large spatial scale (on average \(\sim 30\) degrees longitude) (Barriopedro et al. 2006) result in prolonged low-level sustained wind patterns that have spurred several studies focused on the ability for these blocking events to transport pollutants to regions outside of the emission source (Raatz and Shaw 1984, Witte et al. 2011). Primarily focusing on blocking highs (an atmospheric block associated with a stagnant high pressure system) the persistent anticyclonic wind field leads to either the accumulation of air pollutants within the circulating wind field or leads to the accelerated transport of pollutants along the periphery where the pressure gradients are relatively strong.

In addition to the development of persistent winds along the South–North axis, which allow for successful transport of BC to the Arctic, this accelerated transport of BC emissions, has important implications for the absorptive efficacy of BC and subsequent snow/ice albedo impacts. As its atmospheric residence time grows, BC becomes increasingly mixed with other atmospheric constituents leading to changes in the optical properties and atmospheric lifetime of BC (Bond et al. 2013). The exact impact of deposited BC on Arctic snow relies on information of the chemical and microphysical processes within the atmosphere; however, as a general rule, the longer a molecule remains in the atmosphere the more mixing and alterations it will undergo before it is ultimately removed via wet or dry deposition.
This study’s primary focus is on quantifying the variability in transport of potential crop residue emissions from the Russian cropland to the snow-covered Arctic based on the persistent wind patterns associated with atmospheric blocking events between 2003 and 2015. The overall aim is to establish if atmospheric blocking events; (1) improve the success rate of transport to the Arctic, which ultimately determines what fraction of the cropland burning contributes to the BC deposition in the Arctic; and (2) accelerate the transport time, which is crucial for understanding the potential increase in potency of BC depositions on Arctic snow.

2. Data and methods

2.1. Low-level transport model data

Emissions transport modeling most frequently involves atmospheric transport models (e.g. NOAA’s Hybrid Single Particle Lagrangian Integrated Trajectory model (HYSPLIT; Stein et al 2015), Stohl et al 2007, Larkin et al 2012) which can represent the complex mixing of particles within the atmosphere and estimate the fall out rate of specific pollutants based on the atmospheric properties. The precision and accuracy of these modeling approaches, however, strongly depends not only on the ability of the model to accurately represent atmospheric processes but also on the emission estimates ingested by the model. Unfortunately, current methods for mapping burned area in croplands and, subsequently, emission calculations are plagued with uncertainties (Hall et al 2016a, Hall and Loboda 2017), therefore cannot be expected to produce anything resembling a reasonable assessment. As a result, the complex modeling environments cannot deliver estimates that are realistically more refined than the likelihood of a successful transport for a hypothetical amount of emissions under the influence of prevailing winds. Thus, in this study, we use a previously published (Hall and Loboda 2017) simplified transport model driven by global reanalysis meteorology to track the trajectory and speed of a hypothetical parcel of BC emissions originating from the Russian cropland as indicated by satellite active fire detections.

The transport model ingests wind direction, wind speed, and precipitation derived from the European Centre for Medium-Range Weather Forecasts’ daily, 0.75° ERA-Interim Reanalysis product (Berrisford et al 2011) to identify potential BC source regions within the Russian cropland between 2003 and 2015 that are likely to contribute to the deposition of hypothetical BC emission parcels on the Arctic snow (defined as above 60°N). Snow cover melt and establishment dates were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) MOD/MYD10C1 Collection 6 snow cover product at climate modelling grid (0.05°) resolution (Hall et al 2016b). The MODIS active fire (MCD14ML; Giglio et al 2003) Collection 6 dataset along with a crop mask created using a composite of the cropland and cropland/ natural vegetation mosaic layers from the 500 m Level 3 1GBP classification scheme within the MODIS land cover dataset (MCD12Q1; Friedl et al 2010) were used to identify the hourly starting burning locations within the Russian cropland. The algorithm was designed to record the low-level transport trajectories of hypothetical BC emission parcels from cropland burning locations to the Arctic snow within 96 hours—reflecting the atmospheric lifetime of BC and transport cutoffs used in a previous study (Larkin et al 2012). These trajectories were tracked at five pressure levels to account for the reported differences in crop burning injection heights: 1000 mb ( ~110 m altitude), 975 mb ( ~323 m altitude), 950 mb (~540 m altitude), 925 mb (~762 m altitude), and 900 mb (~914 m altitude). A transport trajectory was determined to be successful if the emission parcel reached the snow-covered Arctic within 96 hours, whereas an unsuccessful trajectory was recorded if the emission parcel either encountered precipitation while not over snow—assuming total washout of BC from the atmosphere—or the parcel did not reach the Arctic snow within 96 hours. The only exception to this was if precipitation was encountered while over snow-covered ground in the Arctic—i.e. wet deposition. The transport trajectories and corresponding transport time were used to develop the following metrics: time to successful deposition (hours) and percent success, which is defined as the percentage of successful transport events. For more details on the transport algorithm, see Hall and Loboda (2017).

2.2. Atmospheric blocking

The University of Missouri Center of Blocking Studies atmospheric blocking index dataset (1968–present day) was used to analyze the impacts of atmospheric blocking events on the transport time and success rate to the Arctic between 2003 and 2015 (Lupo et al 2008). This blocking index defined a blocking event as having a minimum duration of five days, a horizontal extent of over 30 degrees longitude, an amplitude of at least 5 degrees latitude, and the northern hemisphere atmospheric block must begin poleward of 35°N. The dataset contains several variables, including time and dates of blocking onset and decay, longitude of block onset, and blocking size (Lupo and Smith 1995). Although the analysis focuses on Russian croplands, the larger spatial area (0°E–175°E) was chosen to extend the western edge of the analysis field to account for atmospheric blocks that may occur over Central and Eastern Europe and contribute to the development of sustained wind fields, which are the focal point of the presented study. Daily blocking layers were created from the blocking dates, starting longitude (degrees), and block size (km). The existing blocking indices do not, however, specify the starting latitude for any blocking events; thus, a central starting latitude
of 60°N was assumed for all blocks—a common assumption since these phenomena are primarily mid-latitude weather patterns (Pelly and Hoskins 2003, Tyrlis and Hoskins 2008). The daily blocked masks were created between the two longitudes and all latitudes between 35°N and 85°N and rounded to the nearest 0.75° grid cell to match the resolution of the ERA-Interim Reanalysis product.

Because this study aims to quantify the impact of blocking on potential transport, we examine two ‘pure’ atmospheric states—‘blocked’ and ‘nonblocked’—and disregard conditions of partial temporal overlap between the two. Specifically, we consider transport to occur under ‘blocked’ conditions if the emission source grid cell remains completely within the spatial extent of the atmospheric block for the duration of transport to the Arctic snow up to 96 hours from the release of the hypothetical emission parcel, which is determined by the date, and time stamp of the active fire detections. Similarly, nonblocked conditions represent only those cases where the emission source grid cell remains outside (spatially and temporally) of the influence from any atmospheric blocking events. Figure 1 illustrates the criteria required in selecting ‘pure’ blocked and nonblocked cropland burning grid cells.

Analysis of the Lupo et al. (2008) blocking index between 2003 and 2015 revealed that the highest concentration of blocking events occurred between 30°E and 90°E (see figure S1 available at stacks.iop.org/ERL/13/055010/mmedia), corresponding to an area containing approximately 80% of the Russian cropland region. Based on the recorded blocking durations, monthly counts found March and April contained blocks with durations up to 15 days, whilst May included a number of blocks with durations between 15 and 30 days (figure S2). The persistent wind associated with these longer duration blocking events, especially in May, is likely to have a large influence on the long-range transport of BC emissions to the Arctic during the most vulnerable period for sea ice melt.

3. Results

Our analysis revealed a fairly complex spatial and temporal relationship between atmospheric blocking events and the transport time (hours) and the success (%) of reaching the snow-covered Arctic. Specifically, the ability for a blocking event to enhance emission transport from the Russian croplands to the Arctic varies both by month and by the location of the blocking event in relation to the fire activity. However, in general, during the spring (March, April, and May) transport of hypothetical BC emissions parcels to the Arctic snow under blocking conditions was faster and more successful than under nonblocking conditions. Although analysis was carried out over all months and injection heights (see supplementary tables S1 and S2), based on the importance of BC deposition on the Arctic snow during the spring, the following results will be focused on March, April and May for the two extremes in the range of analyzed injection heights (900 mb will be illustrated and 1000 mb included in the text). To quantify the spatial variability under blocked and nonblocked conditions, mapped outputs of average transport time, the percent success for each starting grid cell, and the number of fire occurrences in each successful cropland burning grid cell was performed (figures 2–4). Difference maps (nonblock minus block) were also included to highlight the difference between nonblocked conditions and blocked conditions in the three metrics—the legends were normalized to highlight the advantages for transport under blocked and non-blocked conditions in red and blue, respectively. Only
grid cells that contained values in both blocked and nonblocked maps were subtracted.

The difference maps indicate that overall blocking events are more successful and are quicker at transporting potential BC emissions to the snow-covered Arctic during March and May, regardless of injection height. Although the lower injection heights are associated with longer transport times and decreased success rates as compared to the higher injection heights. Overall, in March, the transport time to the Arctic is shorter (in some areas over 50 hours less at higher injection heights) and the success rate is also much higher during blocked conditions (figure 2). Although the number of fire occurrences within these regions is fairly low (<15 active fires per month on average between 2003 and 2015) they are associated with areas containing the highest wheat yields in the Russian cropland (predominantly between the southern tip of Russia and Moscow; yield data compiled by USDA Foreign Agricultural Service, Mark Lindeman pers.comm.). Therefore, these fires could possibly contain higher volumes of crop residue leading to a higher amount of emitted BC. At the lowest injection height, the success percentage was still much higher during blocked conditions and the transport was still quicker as compared to nonblocked conditions; however, the magnitude of the time difference was lower.

During May, transport under blocked conditions is also generally more successful and quicker than under nonblocked conditions; however, unlike March there is considerable spatial variability (figure 4). The area in blue, centered on 90°E in both the transport and active fire difference maps shows that those areas contain not only more cropland fires during nonblocked conditions but the potential emissions are also transported to the Arctic faster during nonblocks. This result has implications on the BC deposition in the Arctic, as nonblocked conditions are more prevalent than blocked conditions. At the lowest injection height, the percent success decreased overall with two exceptions. The region centered on 90°E is still present but not as pronounced, while the north-west corner (approximately 55°N, 45°E) still showed differences of over 50% in successful transport under blocking conditions.

April is the notable exception with slower transport times in the western region of European Russia (centered on 55°N, 40°E) and less successful transport in the region centered on 80°E (figure 3) under blocking conditions. These two sections are most distinct at higher injection heights but can still be identified at the lowest injection height. Further analysis revealed a large portion of the successfully transported fires in the western region of European Russia under blocking conditions were driven by a single blocking event in April 2006. This moderate blocking event lasted 10 days with a spatial extent between approximately 10°E and 45°E. There were two other blocking events during April 2006; however, they were located further east, starting at 60°E and 100°E respectively. The location of this blocking event in relation to the fire activity created an ideal example of the gradation of transport times caused by the circulating wind patterns associated with the blocked high pressure system (figure 5).

Table 1. Difference in mean transport time to the snow-covered Arctic. Negative values indicate transport to the snow-covered Arctic was on average quicker under blocking conditions, whereas the positive values indicate nonblocked conditions were quicker.

| Month     | Latitude  | 900 mb | 925 mb | 950 mb | 975 mb | 1000 mb |
|-----------|-----------|--------|--------|--------|--------|---------|
| March     | 45°N–50°N | −17    | −16    | +9     | +3     | −       |
|           | 50°N–55°N | −12    | −14    | −15    | −18    | −11     |
|           | 55°N–60°N | −23    | −23    | −20    | −20    | −11     |
|           | 45°N–50°N | +19    | +6     | +16    | +24    | −       |
| April     | 50°N–55°N | +4     | +4     | +4     | +3     | +7      |
|           | 55°N–60°N | +8     | +8     | +7     | +5     | +1      |
|           | 45°N–50°N | −23    | −20    | −13    | −17    | −       |
| May       | 50°N–55°N | +8     | +6     | +2     | +2     | +2      |
|           | 55°N–60°N | −1     | −2     | −1     | +1     | +6      |

To further analyze the latitudinal variability within the transport times during blocked and nonblocked conditions, statistical analysis was carried out comparing the average transport times at the following latitude bands: 45°–50°N, 50°–55°N, 55°–60°N at each of the five injection heights (pressure levels). Quantifying the difference in the mean transport time between blocked and nonblocked conditions found that, in general, when successful transport occurs under blocked conditions it is not only faster but the magnitude of the difference is greater than when faster transport occur under nonblocked conditions (table 1). The main exception occurs in April between 45°N and 50°N. This difference is likely the result of the April 2006 blocking event, which skewed the transport time results—the transport followed the anticyclonic circulation pattern effectively lengthening the transport trajectory (see figure 5 and the accompanying text above).

4. Discussion

4.1. Atmospheric blocking index uncertainty

The original Lejenä and Økland (1983) index, henceforth known as L&O83, forms the basis for the derivations of the most commonly used blocking indices. For this study, the Lupo et al (2008) blocking index dataset is used and this too is based off a modified version of the L&O83 index. These blocking indices calculate the geopotential height gradient surrounding a static central latitude (60°N) for each longitude. A key drawback of this type of blocking index is the inability to determine the North-South extent of the blocking event (Diao et al 2006). In recent years,
Figure 2. 900 mb March 2003–2015: The average transport time (top), percent success (middle) and successful active fires (bottom) are highlighted for all blocks (a), nonblocks (b) and difference (c) maps. Only grid cells which contained values in both block and nonblock maps were differenced. The difference map color bars have been created so that red grid cells indicate transport under blocked conditions was either quicker, more successful or contained higher fire loads compared to the blue color indicating that transport was quicker, more successful or had higher fuel load under nonblocked conditions.
Figure 3. 900 mb April 2003–2015. The average transport time (top), percent success (middle) and successful active fires (bottom) are highlighted for all blocks (a), nonblocks (b) and difference (c) maps. Only grid cells which contained values in both block and nonblock maps were differenced. The difference map color bars have been created so that red grid cells indicate transport under blocked conditions was either quicker, more successful or contained higher fire loads compared to the blue color indicating that transport was quicker, more successful or had higher fuel load under nonblocked conditions.
Figure 4. 900 mb May 2003–2015: The average transport time (top), percent success (middle) and successful active fires (bottom) are highlighted for all blocks (a), nonblocks (b) and difference (c) maps. Only grid cells which contained values in both block and nonblock maps were differenced. The difference map color bars have been created so that red grid cells indicate transport under blocked conditions was either quicker, more successful or contained higher fire loads compared to the blue color indicating that transport was quicker, more successful or had higher fuel load under nonblocked conditions.
development of new blocking indices has been underway to try capture the latitude of the blocking events (e.g. Pelly and Hoskins 2003, Scherrer et al. 2006). Although there is a lack of latitudinal information, the Lupo et al. (2008) index was utilized in this study as the fundamental blocking equations are widely accepted in the scientific literature.

At present, there are numerous blocking indices all with slight variations in the blocking criteria, equations and underlying datasets (Diao et al. 2006). Because blocking events are important atmospheric phenomena, which can have a wide range of impacts on both people and the environment, there is an urgent need to create a consistent blocking index methodological framework (Barnes et al. 2012). Depending on the scientific question, the importance of identifying the North-South extent of the blocking event is crucial. As shown in the results of this study, the geographic location of the blocking event in relation to the fire activity in April 2006, led to large variability in the transport time to the Arctic. Therefore, identifying the latitudinal extent of the blocking event is an important task in relation to understanding the potential impacts on emission transport.

4.2. Contribution to the broader Northern Eurasia and Arctic science agenda

The unique characteristics of the Arctic region has spurred a resurgence in Arctic science research as the amplified regional warming is leading to a range of biophysical and socio-economic impacts. The Arctic is not an isolated, desolate region but rather an integrated, dynamic ecosystem which supports both local and global climatic structures. At the local level, the Arctic landscape supports an abundance of wildlife and local human populations. The sea ice, coastal zones, wetlands, and estuaries are all crucial habitats for local and migratory animals and important hunting grounds for native populations. At the global level, the Arctic is responsible for helping moderate the global temperature through atmospheric and oceanic circulation transporting warmer air from the tropics to the colder Polar Regions. These crucial functions within the Arctic region are under attack from the amplified regional warming effects. At present, the loss of snow cover and sea ice has led to a number of devastating local effects; however, with the projected rise in temperatures from current climate models (Stocker et al. 2013) these could eventually be experienced on a global scale. This reality of large scale snow cover and sea ice loss has led to...
a rise in the number of international interdisciplinary initiatives focused specifically on addressing various issues within the Arctic environment. For example, the Northern Eurasian Earth Science Partnership Initiative (NEESPI; http://neespi.org/) was designed to improve the understanding of the interactions between the atmosphere, the terrestrial ecosystem, and human dynamics in Northern Eurasia with a particular focus on climate impacts. Following the conclusion of NEESPI, the Northern Eurasian Future Initiative (NEFI; Groisman et al. 2017, Monier et al. 2017) was established with several key research areas including a focus on extreme events and Arctic warming.

This study fits well within the framework of both NEESPI and NEFI through exploring potential mechanisms for accelerated transport of cropland BC emissions from Russia to the snow in the Arctic. Specifically, this study identified that atmospheric blocking events can influence the likelihood of transport and accelerate the transport of pollutants to the snow-covered Arctic from Russian cropland burning based on the persistent wind patterns in comparison to nonblocked conditions under all injection heights; however, there is both spatial and temporal variability across the Russian croplands. Based on the mean differences in the transport data under blocks and non-blocks, it is clear that blocking events can substantially enhance the transport to the Arctic. This accelerated transport has large implications for the potency of deposited BC on the snow and potentially sea ice in the Arctic. The transport of pollutants via atmospheric blocking events are not limited to cropland emissions. With changes in wildfire activity, lengthening of the fire season (e.g. Flannigan et al. 2009), and the increase in gas flaring (e.g. Worldbank 2016) at mid- and high northern latitudes, it is crucial to educate the broad public (with a special focus on prescribed burners and policy-makers) on the potential impact of burning during these blocking events. With the increased frequency of block occurrence over such a vast section of the Russian cropland and the proclivity for long duration blocks in May, identifying these areas associated with enhanced transport provides a focal point for possible mitigation strategies aimed at reducing the impact of BC deposition from northern mid-latitude biomass burning in the Arctic.

5. Conclusion

This study quantifies the contribution of large-scale, quasi-stationary meteorological blocking events to the transport of potential BC emissions from cropland burning in Russia to the snow in the Arctic. It was determined that they do influence the success and, in many cases, the timing for these emissions to be transported and deposited on the Arctic snow. Specifically, it was identified that blocking events, particularly during March and May, led to the accelerated transport (in some areas over 50 hours less) and increased success rates (in some areas up to 100% more successful) to the Arctic snow at almost all injection heights. The majority of the BC emission source locations that experienced accelerated transport to the Arctic snow occurred in European Russia which contains more than 80% of all Russian cropped area and where the wheat yield values are the highest. Therefore, the accelerated transport of hypothetical BC emissions is likely to occur from cropland burning on fields with higher volumes of crop residue, thus influencing the quantity and potency of BC emissions deposited on the Arctic snow and sea ice during spring.

Finally, further work needs to be undertaken to not only improve blocking indices through including the latitudinal extent of the blocking event, but to also ensure these datasets are publicly available and are consistently used in scientific studies. In addition, improvements are needed to accurately represent the spatial and temporal cropland emission fluxes and once successful, more sophisticated modelling approaches can be undertaken to develop a more nuanced understanding of how the accelerated transport under blocking conditions might impact the efficacy of the deposited BC emissions on the Arctic snow.

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