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The effect of the 2020 COVID-19 lockdown on atmospheric black carbon levels in northeastern Greenland

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HIGHLIGHTS

• DEHM model and aethalometer used to assess effect of lockdown on Villum BC levels.
• DEHM model simulated a 10% reduction in BC at Villum during April–May 2020.
• Similar reductions are expected throughout the Arctic region (between 7% and 11%).
• The aethalometer showed no response to the lockdown due to inherent BC variability.

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ABSTRACT

The outbreak of SARS-CoV-2 and subsequent spread of the disease COVID-19 became classified as a pandemic in March of 2020, leading to global safety measures introduced to limit the impact of the virus. This combination of safety measures has become commonly referred to as ‘lockdown’. The associated industry and lifestyle changes led to reductions in the anthropogenic emission of atmospheric pollutants such as black carbon (BC), which is transported from the mid-latitudes into the Arctic during the winter and spring. Measurements of BC and other anthropogenic pollutants are of increasing importance in the Arctic due to the rapid warming observed there in the past few decades. It is believed that BC has a significant role in this warming, and so understanding the Arctic’s response to reduced BC emissions at lower latitudes will provide insight into how future changes might mitigate further warming. Reductions in BC have been reported worldwide, and so in this study, the impact of these reductions on BC concentrations at the High Arctic site Villum Research Station was investigated. The effect was examined from March 2020, around when global lockdowns began, to June 2020, when the Arctic haze period ended and BC levels were once again low. Firstly, the Danish Eulerian Hemispheric Model (DEHM) was used to assess this impact on BC concentrations by adjusting global anthropogenic pollution emission inventories to simulate those observed during the lockdown period and comparing the results to a similar model run with standard emission inventories. Secondly, equivalent BC data from an aethalometer at Villum Research Station were analysed, comparing the concentrations during the lockdown period to both aethalometer data from previous years and DEHM results from the lockdown period. It was found that when adjusted DEHM emission inventories were introduced from the 1st of March, the model predicted a reduction in BC concentrations beginning on the 10th of March and reached a 10% reduction by the 1st of April. This reduction fluctuated around 10% until the end of the Arctic haze period. Aethalometer data did not show any significant change from previous years, and no concentration reduction could be concluded from its comparison with DEHM results. This is likely because the predicted reduction of 10% is smaller than both the inter-annual and intra-annual variability of measured BC concentrations at Villum.

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1. Introduction

Black carbon (BC) is a type of fine particulate carbon formed from the incomplete combustion of fossil fuels or biomass. It has been shown to have significant implications for both human health and climate change, and BC emission reductions have been recognised as a promising focus to combat short-term global warming (Bond et al., 2013; IPCC et al., 2013). BC aerosols can have complex direct and indirect climate effects, and these were investigated thoroughly in a 2013 study led by the International Global Atmospheric Chemistry (IGAC) project (Bond et al., 2013). One key result from this study is the total BC climate forcing, which was found to be around twice that of previous estimates. For example, the Fifth Assessment Report from the IPCC in 2013 evaluated total BC radiative forcing as 0.64 Wm$^{-2}$ (IPCC et al., 2013), whereas the study from IGAC proposed the value 1.1 Wm$^{-2}$. This would place BC as the second-highest anthropogenic climate forcer after CO$_2$. BC is also a short-lived climate forcer (SLCF) with an atmospheric lifetime of between a few days and a few weeks, commonly 4–8 days (Bond et al., 2013; Park et al., 2005). This means that the response to a change in emissions would be reflected quickly in atmospheric BC levels. Through unfortunate circumstances, this response was able to be assessed in 2020 when the worldwide outbreak of COVID-19 forced global lifestyle changes that resulted in reduced anthropogenic emissions.

In March 2020, the World Health Organisation declared the outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which causes coronavirus disease 2019 (COVID-19), a pandemic (WHO, 2020). Social distancing measures, quarantines and curfews were implemented worldwide to limit the spread of the disease. This included closing businesses and public spaces, and restricting travel, forcing many people to work from home in a state that became commonly referred to as “lockdown”. Though the health and socioeconomic effects have been devastating, there have also been noticeable improvements in air quality across the world that are attributed to the reduction in traffic and industrial activities (Adams, 2020; Bauwens et al., 2020; Berman and Ebisu, 2020; Dantas, Siciliano, França, da Silva and Arbillá, 2020; Evangeliiou et al., 2021; He et al., 2020; Kerimray et al., 2020; Le Quéré et al., 2020; Otmani et al., 2020; Shakoor et al., 2020; Xu et al., 2020). For example, Evangeliiou et al. (2021) investigated BC emissions in Europe during the lockdown period, using in situ measurements of BC concentration from 17 measurement stations in Europe, and modelled BC emissions using both the FLEXPART Lagrangian particle dispersion model and the FLEXPART + Bayesian inversion framework. They then compared these modelled data to both emissions before the lockdown began and in previous years to calculate the BC emission anomaly. They determined that BC emissions in Europe decreased overall by 11% during the lockdown period, compared to before the lockdown began. This reduction was not observed in previous years (2015–2019), and so it can be attributed to the COVID-19 lockdown.

One area of immense interest in the field of climate change is the Arctic, where the temperature is rising at twice the global rate in a phenomenon known as Arctic amplification (IPCC et al., 2013). This is leading to glacial and ice sheet melt and rising sea levels (King et al., 2020; Slater et al., 2020), so it is imperative that we understand the causes and effects of this phenomenon. There are very few local sources of anthropogenic emissions in the Arctic, but anthropogenic aerosols are still present in the Arctic atmosphere due to long-range transport from the mid-latitudes. Specifically, during the winter and spring, the polar dome expands and the transport of anthropogenic pollutants into the Arctic results in a phenomenon known as Arctic haze. Its constituents include sulfate, particulate organic matter, ammonium, nitrate, BC and dust (Heidam et al., 2004; Li and Barrie, 1993; Quinn et al., 2002, 2007). Source regions for the Arctic Haze are the northern areas of Europe, Russia, China and North America, though northern Eurasia is understood to be the dominant source region (Heidam et al., 2004; Hirdman et al., 2010; Sobhani et al., 2018; Stohl, 2006). Therefore, BC concentrations can be used as a proxy to assess the impact in the High Arctic of reduced anthropogenic emissions in these mid-latitude source regions.

In this study, we have assessed the impact of the worldwide lockdown period in the spring and summer of 2020 on BC levels measured at Villum Research Station (Villum) in northeastern Greenland. This was accomplished using a dual approach. Firstly, the Danish Eulerian Hemispheric Model (DEHM) was used to assess the impact of the lockdown using emission inventories that were adjusted to reflect the reduced emissions in the source regions during this time, and then evaluating BC concentrations at Villum. These were compared to a similar model run with standard emission inventories to give a direct prediction of the effect that should be observed at Villum. Secondly, in situ BC concentration measurements using an aethalometer were examined and compared to both the concentrations predicted by DEHM as well as BC concentration measurements from previous years.

2. Methods

2.1. Measurement site

Measurements were taken at Villum Research Station (Villum) at Station Nord in North Greenland (81°36′N, 16°40′W, 24 m above sea level), between August 2017 and August 2020. Modelling data were also extracted from the DEHM model at the grid cell that contains Villum to compare the results. Villum is located on Princess Ingeborg Peninsula, around 2.5 km southeast of the military base Station Nord, and its location in Greenland is shown in Fig. 1. The proximity of the air measurement laboratory to the military base results in only a minor contribution of anthropogenic pollution, as the site is located such that it is upwind of the military base for the majority of the time, and it is otherwise very isolated. Events of local pollution are typically distinguishable considering the high resolution of anthropogenic pollution proxies, such as BC itself.

2.2. Modelling using DEHM

DEHM was used to assess the effect of emission reductions in the BC source regions for Villum. DEHM is a three-dimensional atmospheric chemistry transport model used to study long-range transport of air.

Fig. 1. The location of Villum Research Station (Villum) in northeastern Greenland.
pollution in the Northern Hemisphere (Brandt et al., 2012; Christensen, 1997; Eckhardt et al., 2015; Heidam et al., 2004; Massling et al., 2015). DEHM has been used in the field of Arctic air pollution for many years and in many published articles, and has contributed to many of the assessments in the AMAP program since the first assessment in 1998. In Massling et al. (2015) and Eckhardt et al. (2015), details of the Arctic BC output from DEHM are shown as examples.

In this study, the model was set up with two nested model domains with 300 × 300 grid points. A mother domain was used with a resolution of 75 km × 75 km at 60° N, covering the whole northern hemisphere, and a nested domain was also used covering the Arctic down to approximately 50° N with resolution of 25 km × 25 km. The North Pole was used as the centre for both model domains. In the vertical dimension, there are 29 unequally distributed layers that extend up to 100 hPa, approximately 15 km above MSL, with the finest resolution in the atmospheric boundary layer. DEHM is driven by meteorological input from the numerical weather prediction model WRF v4.1 (Skamarock et al., 2008). The spatial setup of the WRF model system is identical to the setup of the DEHM model system, both horizontally and vertically, meaning that the 2D and 3D WRF data do not need to be interpolated spatially to the DEHM grid points. The WRF model is driven by global data from the ERA5 reanalysis from ECMWF (Hersbach et al., 2018). The WRF data were archived with 1-h resolution and interpolated temporally inside the DEHM model.

The basic chemical scheme in DEHM includes 68 different species. It is based on the scheme by Strand and Hov (Strand and Hov, 1994), and has been extended with a detailed description of ammonia chemistry and a Volatility Basis Set (VBS) scheme to describe the formation of Secondary Organic Aerosols (SOA). Reactions concerning the wet-phase production of sulfate have also been included. The setup describes concentration fields for 59 photochemical compounds (including NOx, SOx, VOC, NHx, CO, O3 etc.), 12 species for the SOA scheme and several classes of particulate matter, of which one class is related to BC. This class is comprised of two BC components: freshly emitted BC, for which the particles are treated as hydrophobic, and aged, coated BC, for which the particles are treated as hygroscopic. The transformation from freshly emitted BC to aged BC depends on the OH concentration (Liu et al., 2011). Both BC species are assumed as a single bulk representation with a particle diameter of 0.33 μm. The anthropogenic emissions used are from Eclipse v6b with a 0.5° × 0.5° resolution (Klimont et al., 2017). Emissions from the EMEP (European Monitoring and Evaluation Programme) expert database are used for the areas over Europe with 0.1° × 0.1° resolution (see https://www.ceip.at/). Biomass burning emissions are obtained from the Global Fire Assimilation System (GFAS) from ECMWF (Kaiser et al., 2012), which has a horizontal resolution of a 0.1° × 0.1° on a daily time basis. The dry deposition velocity is calculated by using the resistance method, and the parameterisation of wet deposition is based on a simple scavenging ratio formulation with in-cloud and below-cloud scavenging coefficients for both gas and particulate phase.

In this study, three DEHM runs were performed to simulate BC levels at Villum during the period between the 1st of January and the June 30, 2020. Firstly, a standard run with the default emission inventories used for DEHM (no changes reflecting the lockdown): “DEHM basic”. Secondly, the same run but with contributions from biomass burning artificially turned off, to assess their impact: “DEHM noBB”. Finally, a run in which emission inventories have been altered from the 1st of March to reflect the COVID-19 lockdown conditions (with biomass burning included): “DEHM COVID”; specifically, reductions were used as described in Barré et al. (2020), part of the Copernicus Atmospheric Monitoring Service (CAMS). In this study, predictions were made for reductions in NOx, noting that “its short lifetime combined with localized emission sources make NOx an excellent proxy for detecting emission reductions, from both surface and satellite measurements” (Barré et al., 2020). Individual emission reduction percentages were obtained for European countries, and the average values of these were used for countries outside of Europe where these data were not available: manufacturing industry emissions were reduced by 15.5%, road traffic by 54% and aviation by 94%.

2.3. Instrumentation

BC concentrations were measured using a MAGEE AE33 aethalometer, which has been operating at Villum since August 2017. The aethalometer is an absorption photometer that continuously draws air through a filter and measures the transmission of light through the filter spot containing the sampled aerosol. By comparing this transmission to a reference filter spot, the attenuation of light due to the presence of atmospheric particles is ascertained. The AE33 model features a “dual-spot” setup, which automatically corrects for filter loading effects (Drinovec et al., 2015). It measures simultaneously at seven wavelengths (370, 470, 520, 590, 660, 880, and 950 nm), and a 1-min time resolution was used in this study. The raw absorption data from the aethalometer were converted to equivalent black carbon (eBC) concentrations using the standard mass absorption cross-section (MAC) value of 7.77 m² g⁻¹ at 880 nm (Drinovec et al., 2015). Data were quality controlled to remove events identified as local pollution from the military base using an automated algorithm followed by manual inspection. It has been found that the aethalometer overestimates absorption coefficients in Arctic sites compared to collocated absorption photometers such as the MAAP and PSAP (Backman et al., 2017). In order to account for this, an Arctic harmonisation factor of 3.45 was used, as proposed by Backman et al. (2017). However, it was converted to suit the AE33, as it uses a different filter type to the instrument that it was originally calculated for (the AE31) (Backman et al., 2017; Weingartner et al., 2003). This harmonisation is commonly used for Arctic datasets (Schacht et al., 2019; Schmeisser et al., 2018; Zanatta et al., 2018). It should be noted that at Villum and generally in the Arctic, we see high values of Single Scattering Albedo (SSA), meaning that aerosols tend to be much more scattering than absorbing. It is estimated that the aethalometer typically has a 2% cross-sensitivity to scattering aerosols, though it can depend on chemical composition and size of the observed aerosol particles, potentially reaching 5% (Drinovec et al., 2015; Weingartner et al., 2003). With the high SSA found in the Arctic, this could induce an overestimation of the absorption coefficients of up to 10–40% in the aethalometer data, though with the typical SSA and a 2% cross-sensitivity, the overestimation is thought to be around 15%. The Arctic harmonisation factor will include the average value of this overestimation, but the variability due to this sensitivity will still induce a residual uncertainty. The corrected eBC levels agree well with the calculated levels from DEHM, as shown in Fig. 2a. There is also a collocated Digital DHA 80 high-volume sampler at Villum, and weekly samples from this instrument were analysed in a Sunset Laboratory thermo-optical OC/EC instrument with autosampler. The analysis was done according to the EUSAAR-2 protocol assuring harmonisation of the methods for analysis of EC across Europe (Cavalli et al., 2010). The measurements are carried out continuously at Villum since 2008. Further details on the measurements are reported in Massling et al. (2015). Weekly elemental carbon (EC) concentrations from August 2017 to August 2018 are shown against eBC concentrations from the aethalometer in Fig. 2b, showing a strong agreement. BC and EC are defined by separate measurement techniques, but are known to refer to a similar fraction of the carbonaceous aerosol (Petzold et al., 2013), so this agreement supports and validates the aethalometer correction method.

3. Results

DEHM has been previously shown to recreate the large-scale seasonal fluctuations of BC at Villum very well (Massling et al., 2015). It is shown again here in Fig. 2a, in which monthly averages of BC modelled by DEHM for the grid cell containing Villum (from a DEHM run spanning 1990–2020) are compared against measured aethalometer data at Villum. It can be seen that the Arctic haze period with elevated BC levels in
the winter and spring is reproduced well; though there is disagreement between DEHM and observations in the haze period from late 2017 to mid-2018, a tighter agreement is seen in subsequent years. DEHM seems to show an overestimation of BC concentrations in the summer, between the Arctic haze periods. These relatively high concentrations in summer are predominantly from biomass burning contributions, and so this discrepancy can be attributed to uncertainties in biomass burning emissions.

Fig. 3 shows a comparison of BC data from the three different DEHM runs (“DEHM basic”, “DEHM noBB” and “DEHM COVID”) alongside aethalometer eBC measurements, with both (a) weekly and (b) daily means. Upon first inspection, the three runs look very similar, implying a minor effect of the lockdown. The relative change in BC in the lockdown run compared to the standard run is included in Fig. 3b, which better illustrates the results. In the DEHM COVID run, we see a decline in BC concentration that begins on the 10th of March, reaching around 10% by the start of April. This reduction then fluctuates around this level until the Arctic haze period ends. The mean absolute BC reduction between DEHM basic and DEHM COVID from the 10th of March until the 1st of June (when BC concentrations have fallen to unpolluted levels, signalling the end of the haze period) is 1.3 ng m$^{-3}$, corresponding to a mean relative reduction of 9.1%. The mean reduction between DEHM basic and DEHM COVID from the 1st of April until the 1st of June, spanning only the period when the reduction has stabilised, is 1.2 ng m$^{-3}$, or 10.3%. No significant biomass burning contribution is seen until late June.

Modelled BC results for the full nested domain are shown in Fig. 4, demonstrating both the absolute concentrations of BC in the DEHM basic run and the relative reduction between the DEHM basic and DEHM COVID runs. These results are the means over the two-month period from the 1st of April until the 1st of June, during which a stable BC reduction was observed at Villum. The comparably pristine Arctic conditions can be seen in Fig. 4a, especially in the area close to Villum. Fig. 4b illustrates the extent of the impact from the global lockdown period during this time. Part of Europe lies in the nested domain, and the model shows that there is significant spatial variation across the continent. For example, notable reductions in BC concentration are seen in the UK, France and the Netherlands, but parts of Scandinavia and Eastern Europe exhibit markedly lower reductions. The spatial variation is much lower in the Arctic region due to the lack of emission sources, meaning that the concentrations are almost entirely due to long-range transport from mid-latitudes. Over this two-month period, we see a similar response across the Arctic, with a mean BC reduction of between 7% and 11%. Local weather conditions will cause some variation on smaller scales both geospatially and temporally, however, due to the cold Arctic temperatures, the local boundary layer conditions are relatively stable. The uniformity of this mean BC reduction over the Arctic region also implies that it is not overly sensitive to local weather events, which might otherwise cause small-scale variations.

The aethalometer eBC values are substantially higher compared to those modelled by DEHM in all three model runs. As can be seen in the daily data (Fig. 3b), much of the structure and patterns are reproduced well, but the concentrations in the local peaks are generally higher in the aethalometer data than simulated by DEHM. This discrepancy is often much larger than the 10% reduction between model runs, indicating that the impact of the lockdown can neither be confirmed nor denied by comparing the observed and modelled data. However, the fine structure is recreated, implying that DEHM was generally reproducing the correct events and transport patterns, albeit not matching the absolute values of the observed peaks. Finally, three years of aethalometer data (August 2017–August 2020) were compared to assess any noticeable differences or anomalies in 2020. Fig. 5 shows eBC data for the three years that the aethalometer has been operating at Villum. The Arctic haze period can clearly be identified, but there is a very high inter-annual variability. Similar to the comparison to DEHM, this variability makes it difficult to extract any direct influence of the lockdown based on the experimental results from the aethalometer measurements.

4. Discussion

During the 2020 lockdown period, we observed a resulting decrease in BC after 10 days in the DEHM model runs, which is highly compatible with the findings by Stohl (2006), in which the transport time of aerosols into the Arctic (and hence the response time of Arctic atmospheric
constituents to emission changes at mid-latitudes) was found to be between a few days and a few weeks. The anthropogenic emission reductions used in DEHM over the COVID-19 lockdown period resulted in a reduction in BC concentrations at Villum of around 10%. We can compare this value to studies of anthropogenic emission reductions at mid-latitudes to assess the impact of these reductions. Specifically, it is important to consider the key source regions of BC in the High Arctic, known to be northern Eurasia (Hirdman et al., 2010; Sobhani et al., 2018; Stohl, 2006). Specifically, Sobhani et al. (2018) determined that in an average year, Europe and China are the largest contributors to surface-level BC concentrations: ~46% and ~25% of BC, respectively (Sobhani et al., 2018). Therefore, the study by Evangeliou et al. (2021) is of particular relevance, in which they used in situ data from 17 European stations in a Bayesian inversion framework in order to investigate the impact of the lockdown on BC emissions in Europe. Overall, BC emission concentrations were found to be reduced by an average of 11% across Europe. However, there was significant variation across Europe: BC emissions were reduced in Western Europe, Southern Europe and Northern Europe by 32%, 42% and 29%, respectively (compared to the previous five years), whereas Eastern Europe exhibited enhanced BC emissions by around 10%. This increase in Eastern Europe is attributed to the temperature in 2020 being lower than in the previous five years, leading to increased use of residential wood combustion, amplified by the need for the population to spend more time at home. This high spatial variation indicates that Arctic BC reductions may be particularly sensitive to transport pathways from Europe.

Similar studies have not yet been published for Asia, but we can use related studies to inform us of similar emission reductions in these other important source regions. Shakoor et al. (2020) investigated environmental pollutant levels during the lockdown period in China in five provinces that were severely affected by the lockdown: Hubei, Beijing, Shanghai, Guangdong, and Zhejiang. BC is not reported, but NO_2 and PM2.5 concentrations were found to be reduced overall by 38.98% and 17.78%, respectively. In a different study, Xu et al. (2020) measured BC concentrations in the megacity Hangzhou, China, and found an average reduction of 44%, from 2.30 to 1.29 μg m^{-3}. If this is typical for Chinese megacities, it implies that there was not a high contribution from this source region to the concentration of BC observed at Villum during this time.

However, we cannot identify this reduction in the aethalometer measurements, as the predicted reduction is less than the inter-annual variation of BC concentrations at Villum. In general, we measured higher BC levels with the aethalometer compared to those simulated by DEHM, though the high variation signifies that these aethalometer results are not conclusive on their own. The polar dome itself is also known to be variable between years, and therefore a single year of data cannot conclusively be used to determine the impact of reduced mid-latitude emissions. However, similar measurements from other Arctic sites could help to evaluate these influences. The emission reductions caused by the COVID-19 lockdown may provide insight into the future of the Arctic atmosphere, because through these unprecedented circumstances, we are able to directly measure the effect of abruptly reduced anthropogenic pollution. Further studies will also help to investigate the source regions and transport patterns into the Arctic, and it will therefore be highly beneficial to know the scale of these changes at other Arctic sites.
5. Conclusions

The impact of the worldwide COVID-19 lockdown on black carbon levels in the High Arctic was assessed in this study, using both the Danish Eulerian Hemispheric Model and in situ aethalometer measurements at Villum Research Station. Reductions in emissions from industry (15.5%) on average, traffic (54%) and aviation (94%) were introduced in DEHM on the March 1, 2020 and it was found that DEHM predicted a response time of 10 days before these changes would be observed at the High Arctic station Villum. Compared to the default model run (“DEHM basic”), the model run with emissions altered to simulate the lockdown (“DEHM COVID”) exhibited a reduction of BC concentrations at Villum. This reduction reached around 10% by the beginning of April, and then fluctuated around this value until the Arctic hazy period ended. This value is similar to emission reductions found in Europe during the lockdown (Evangeliou et al., 2021). Measurements of eBC at Villum using an aethalometer do not show a noticeable reduction over the lockdown period, though a change of 10% cannot be confirmed nor denied due to the inherent variability in Arctic BC concentrations. Further study of emissions at mid-latitudes during the COVID-19 lockdown period will allow more accurate emission inventories to be used in DEHM and similar models. Further measurements of atmospheric pollutants across several Arctic sites during this time will also help to evaluate the impact of these reductions. Together, these may give insight into the response of the Arctic atmosphere to changes at mid-latitudes, and how future changes may shape the Arctic climate.

Data availability

All data is available upon request. Please contact the corresponding author at dath@envs.au.dk.

CRediT authorship contribution statement

Daniel Charles Thomas: Conceptualization, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. Jesper H. Christensen: Conceptualization, Formal analysis, Methodology, Writing – review & editing, Visualization. Andreas Massling: Conceptualization, Writing – review & editing, Supervision, Project administration. Jakob Boyd Pernov: Conceptualization, Writing – review & editing, Visualization. Henrik Skov: Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the interests reported in this paper.

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