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Black carbon aerosols in the Arctic:

Modeling cycles and evaluating radiative effects

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Abstract

Along with the predicted and observed warming of the global climate comes an even more rapid warming in the Arctic climate, an effect that has been dubbed Arctic amplification. This is due to a variety of feedbacks that make the Arctic particularly sensitive to a globally warming climate; among these is the black carbon (BC) aerosol cycle. Due to the difficulty in measuring BC aerosols in the Arctic, models remain as a crucial tool in understanding the role of BC aerosols in the Arctic climate. The most recent simulations of various Earth system models (ESMs) from the Coupled Model Intercomparison Project Phase 6 (CMIP6) are analyzed in this project in order to assess the abilities of modern ESMs to reproduce the cycles of BC aerosols in the Arctic. Firstly, observations of BC concentrations from two stations in the Arctic are used to compare the annual cycle of BC modeled in historical CMIP6 experiments. Secondly, comparisons between the pre-industrial control simulations and pre-industrial simulations with only 2014 BC emissions as inputs in CMIP6 are made.

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1 Introduction

Black carbon (BC) aerosols are simply airborne particles of soot that can originate from both natural (wildfires) and anthropogenic (incomplete fuel combustion and biomass burning) sources [1]. There are not many sources for BC aerosols in the Arctic; of the natural sources, wildfires may occur seasonally, and the largest source of BC in the Arctic is anthropogenic BC transported into the region, mostly from northern Eurasia [2]. The BC aerosol concentrations are overall very small relative to other regions. The annual cycle comes to a minimum during the summer, with increased BC aerosol concentrations during the winter and spring.

The interactions of black carbon aerosols in the climate system are many. BC absorbs incoming radiation efficiently, resulting in both a direct change of temperature within the air mass and the possibility for re-emission of long wave radiation. Relevant to the Arctic climate, however, is the ability of BC aerosols to deposit onto snow and ice, reducing the surface albedo, increasing the absorption of incoming solar radiation at the snow- and ice-covered surface, and accelerating melt [3]. Black carbon aerosols may also undergo changes in their lifetimes. They may collect other aerosols, changing the reflectivity of the exterior of the particle and thus altering the radiative impact of the particles. All of these factors significantly complicate the complete implication of an accurate representation of BC aerosol cycles in atmospheric and Earth system models, which has been hitherto difficult to accomplish [4].

The polar regions are expected to experience the most warming of any global region in a globally warming climate, and the Arctic climate is already observed to be exceeding previously predicted rates of warming. It is necessary to understand the components of the climate system in the Arctic and how they interact, as unknown or misunderstood feedbacks can lead to an accelerated warming that we as a society are not prepared to mitigate or alleviate the effects of. As Earth system modeling remains the primary, most practically viable tool for understanding the complex climate system interactions in the Arctic and how these interactions extend their reach and effect globally, it is crucial to continuously test, assess, and update models when new simulation data is available.

The latest international body of work in Earth system modeling to emerge is the simulation data available through Coupled Model Intercomparison Project Phase 6 (CMIP6), which first began with the publication of its experimental designs in 2016 [5]. The models involved in CMIP6 are Earth system models (ESMs) with coupled components (atmosphere, land, ocean, etc.), each with implemented schemes that simulate chemical and physical processes in the atmosphere that describe the evolution of atmospheric concentrations of chemical constituents and aerosols as well as how they affect radiative transfer in the Earth's atmosphere. With the implication of these schemes of more specific components of atmospheric processes, the goal is to increase the accuracy of the model; thus, it becomes doubly important to assess the accuracy of them, as otherwise only the complexity of the model is increased.

In this project report, the following hypothesis will be investigated:

> *Earth system models in the CMIP6 multi-model ensemble accurately reproduce the black carbon concentrations in the Arctic.*

This hypothesis will be the overall starting point for assessing modern models' abilities to reproduce specific components of the climate system and to check parameterizations for the success of their outcomes. Because models do not employ the more complex cycles of BC aerosols' feature changes in the atmosphere, such as the brightening of the particles due to aggregation, ESMs cannot be expected to fully reproduce the radiative effects of BC aerosols in the Arctic climate. However, testing whether the emissions, sources, and sinks interact to produce an annual cycle comparable to those that have been measured at stations in the Arctic will provide an idea as to whether the radiative effects of BC aerosols in the ESMs that are a part of CMIP6 can be comparable to those that exist in reality. If the BC aerosol cycles in the Arctic are generally not well reproduced in models, the radiative effects by BC aerosols can be assumed to be wrongly represented and the models' abilities to reproduce an accurate future climate evolution are compromised.

2 Methods

[2]:
```python
from imports import (pd, np, xr, mpl, plt, cy, ccrs, pya)
import functions as fu
```

Technical tools include the JupyterLab interface Jupyter notebooks for ease of reproducibility. Packages used for the Python programming language include `pandas`, `numpy`, `xarray`, `matplotlib`, `cartopy`, and `pyaerocom` (defined with abbreviations in the supplementary `imports.py` file). A supplementary file is included with the functions used in this report entitled `functions.py`. Climate Data Operators (CDO) [6] were used for merging model output data in advance of reading with `xarray` in some cases.

[3]:
```python
fu.plotaodobs()
```

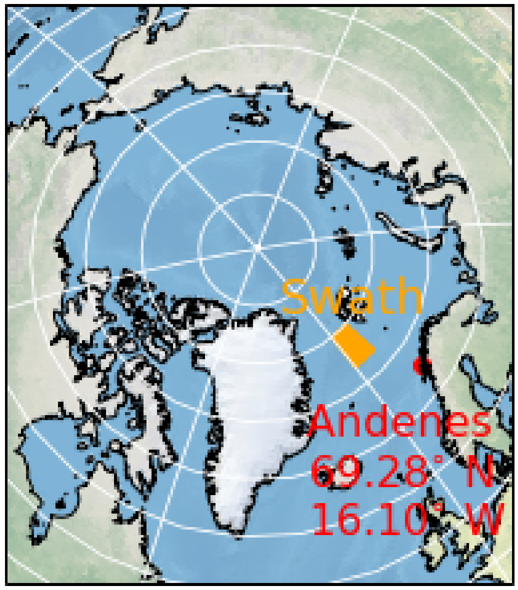

Figure 1: Positions of swath where satellite-retrieved AOD is compared to modeled AOD, and position of sun photometer-measured AOD is compared to satellite-based AOD.

In this project, CMIP6 data is compared against both remote and in-situ observations of aerosol parameters in the Arctic. To begin with, Along Track Scanning Radiometers (ATSR) and Advanced ATSR (AATSR) data products [7] for aerosol optical depth at the 550 nm wavelength (AOD) are compared with those of ground-based sun photometers, and then with model output for the corresponding AOD in a swath of ice-free ocean (a dark surface as a retrieval area for the satellite-based AOD measurement provides the least amount of error introduced from bright, ice-covered surfaces). The swath is chosen to include many pixels in order to average over a larger area and reduce the effect of random variability from choosing single points. Both the position of the sun photometer and the swath used for this are shown in *Figure 1*. This allows for a comparison of the total AOD between models and observations to allow for an idea of how accurately the models represent radiative processes' interactions with aerosols. The AOD contribution by BC is compared to the overall AOD as well in order to estimate the importance and contribution of BC to the overall effect of aerosols on modeled climate systems. The common period between 2002-2011 was used. CDO was used to compute the statistical measures for this period in this way.

In order to compare modeled BC cycles in the Arctic, measurements from two campaigns for BC aerosol sampling from two stations are used: Alert, Canada (2011-2012) and Summit, Greenland (2010), available through the EBAS data portal. Due to the difficult nature of collecting samples and in-situ observations in the Arctic region, there are no longer time series available with which to compare the observed interannual variability of BC cycles with those of the models. The CMIP6 experiment used for this comparison is the historical simulation made using historical emissions as input, and ran to model the historical state of the Earth's climate; the decade from 2005-2014 was used to calculate the mean annual cycle for these two points.

[4]:
```
fu.plotbcobs()
```

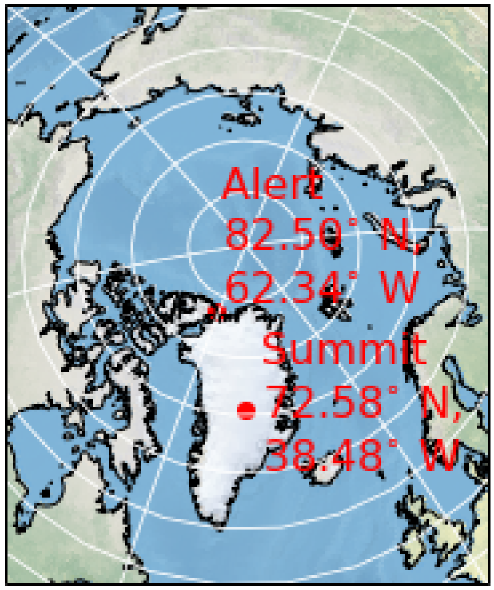

Figure 2: Positions of the two BC concentration measurement datasets available in EBAS.

The package `pyaerocom` is used to retrieve BC concentration measurements for Summit and Alert from the EBAS database. The reader is initialized and the EBAS data for Summit and Alert are retrieved, and then cleaned for outliers and invalid measurement flags. They are then converted into monthly mean values (with Alert having two years' worth of measurements averaged into one annual cycle).

[5]:
```
pya.const.BASEDIR = '/home/notebook/shared-ns1000k/inputs/pyaerocom-testdata/'
reader = pya.io.ReadEbas()
data = reader.read(vars_to_retrieve='conceqbc',␣
 ↪station_names={'Alert','Summit'})

##For Summit
summit = data.to_station_data('Summit',remove_invalid_flags=True)
summit.remove_outliers(var_name='conceqbc')
summitbc = summit.conceqbc #take only the concentration of BC
_summitbc = summitbc.groupby(summitbc.index.month).mean() #calculate the␣
 ↪monthly mean
```

```python
##For Alert, the time unit is not recognized by pyaerocom, so it must be found␣
↪in another way:
stations = []
ts_type='hourly'
station_name = 'Alert'
for meta_idx, meta in data.metadata.items():
    if meta['station_name'] == station_name and meta['ts_type'] == ts_type:
        stations.append(data.to_station_data(meta_idx))
stat = pya.helpers.merge_station_data(stations,␣
↪var_name='conceqbc',remove_invalid_flags=True)
stat.remove_outliers(var_name='conceqbc')
alertbc = stat.conceqbc #take only the concentration of BC
_alertbc = alertbc.groupby(alertbc.index.month).mean() #calculate the monthly␣
↪mean
```

```
Initiating directories for pyaerocom test dataset
Retrieving EBAS files for variables
['conceqbc']
Reading files 1-2 of 9 (ReadEbas) | 09:52:53 (delta = 0 s')
Reading files 2-3 of 9 (ReadEbas) | 09:52:53 (delta = 0 s')
Reading files 3-4 of 9 (ReadEbas) | 09:52:53 (delta = 0 s')
Reading files 4-5 of 9 (ReadEbas) | 09:52:53 (delta = 0 s')
Reading files 5-6 of 9 (ReadEbas) | 09:52:54 (delta = 0 s')
Reading files 6-7 of 9 (ReadEbas) | 09:52:54 (delta = 0 s')
Reading files 7-8 of 9 (ReadEbas) | 09:52:56 (delta = 2 s')
Reading files 8-9 of 9 (ReadEbas) | 09:52:56 (delta = 0 s')
Reading files 9-10 of 9 (ReadEbas) | 09:52:58 (delta = 2 s')
```

Two CMIP6 experiments were also used for another component of this report: the pre-industrial (PI) control simulation using only the steady pre-industrial state of the atmospheric composition, and the PI with only modern (2014) BC emissions implemented as forcing (PI-BC). The difference between the two climates, that is, the climate state from PI-BC minus that of PI, is useful in order to analyze the impact of solely increased BC levels in the atmosphere. The differences in AOD and temperature between the two experiments are calculated by subtracting the seasonal mean PI states from the seasonal mean states of the PI-BC.

3 Results

First, a comparison of the Andenes sun photometer-measured monthly mean AOD reveals a less-than-ideal agreement between satellite and sun photometer data with a large spread (R^2 of 0.69), but with no bias and a correlation coefficient of 0.95.

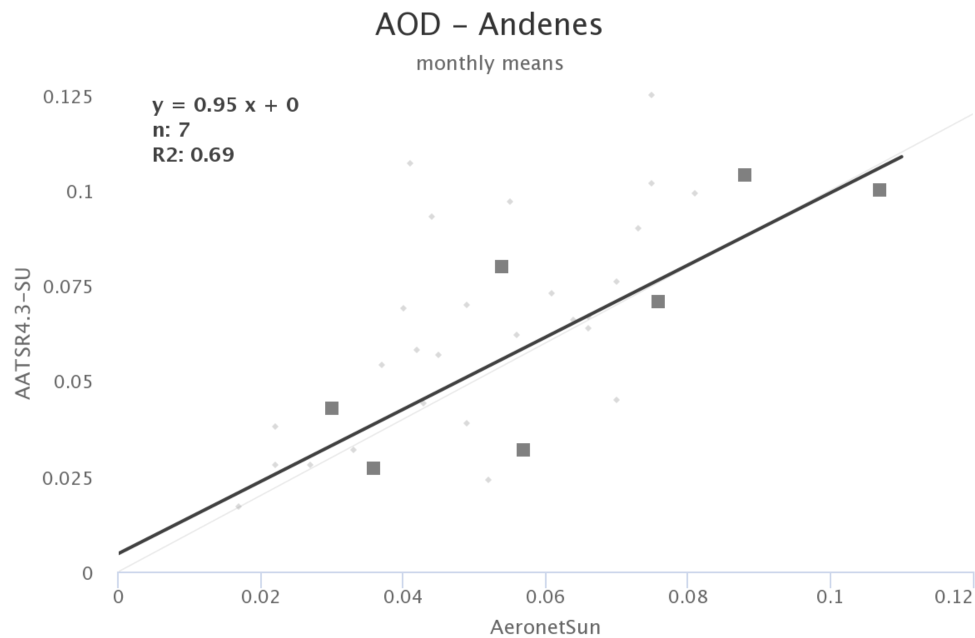

Figure 3: Scatter plot of collocated AOD measured by sun photometer at Andenes (AeronetSun) and by ATSR. Retrieved from: aerocom-evaluation.met.no

It may be that comparing satellite retrieval data with sun photometry at Andenes, a single point on the coast, will be difficult to achieve agreement with due to the presence of land, snow, and ice, as well as due to the low number of data points, which is not ideal for a statistical measure of the accuracy of ATSR and AATSR data products for AOD. However, with a higher number of data points, satellite retrieval over a swath of ocean without ice and is likely to produce a better result.

With this in consideration, we continue with a comparison of mean annual cycles from CMIP6 models (here, the following models are available: NorESM2-LM, UKESM1-0-LL, CNRM-ESM2, CESM2, and CanESM5) with AOD results available to the mean annual cycles measured from ATSR and AATSR in the swath of ocean between 0°-10° E and 74°-78° N, for the period 2002-2011:

[6]:
```
fu.retrieve_aod_data()
```

```
/opt/conda/lib/python3.7/site-packages/xarray/core/nanops.py:140:
RuntimeWarning: Mean of empty slice
  return np.nanmean(a, axis=axis, dtype=dtype)
```

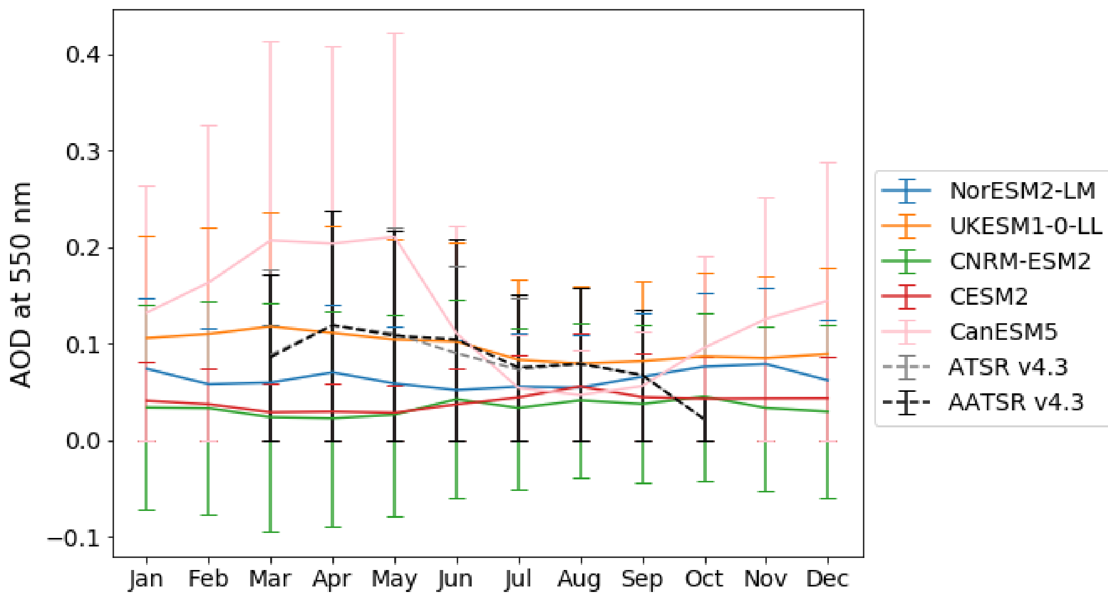

Figure 4: Modeled and satellite-observed monthly mean AOD and standard deviation bars within the swath of ocean between the years 2002 and 2011.

Observed AOD is not able to be measured between November and February, when there is no sunlight available for passive sensing. It is also possible that the rapidly decreasing daylight hours cause the measurements for March and October to be affected. The most clearly surprising result is the representation of a negative AOD in CNRM-ESM2; however, this is most likely due to the calculation of standard deviation assuming a normal distribution, which may not be the case, as the real populations are most likely skewed. This can result from taking the absolute values of deviations overall, which may be high positive deviations and low negative deviations.

In the next step, the measured BC cycles retrieved from EBAS are plotted alongside monthly mean values of BC loading (column-integrated concentration) from the corresponding grid box in CESM2, CESM2-WACCM, IPSL-CM6A-LR, and GFDL-CM4. The modeled monthly means are calculated from the period 2010-2014.

[7]:
```
fu.plot_bc_obsvsmodel(_summitbc,_alertbc)
```

```
/opt/conda/lib/python3.7/site-packages/xarray/conventions.py:494:
SerializationWarning: variable 'loadbc' has multiple fill values {1e+20, 1e+20},
decoding all values to NaN.
  use_cftime=use_cftime,
```

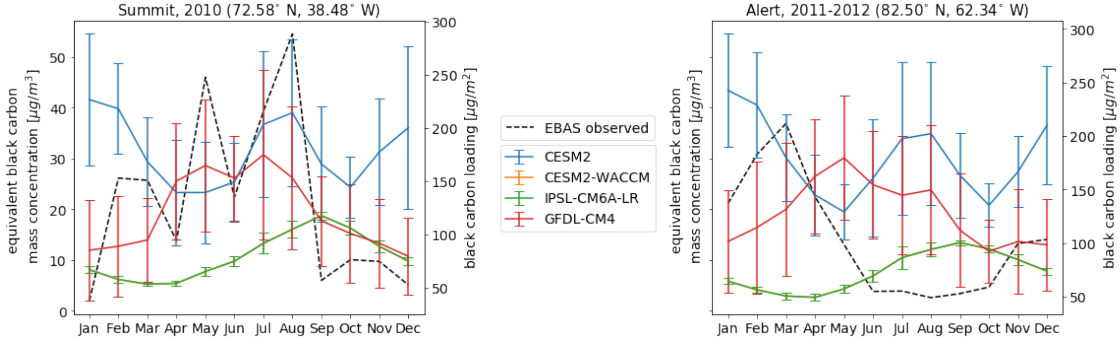

Figure 5: Modeled and measured monthly mean BC with standard deviation bars. The left axis is the measured BC concentration measured at the surface (EBAS observed, dashed lines); the right axis is the BC loading in model output.

From the CMIP6 multi-model ensemble, the models with available BC loading output data are NorESM2-LM, UKESM1-0-LL, and CNRM-ESM2. The CDO operations used to perform these calculations are found in the supplementary file, `NeGIcourse_2019_aiden_supp_cdocommands.ipynb`. `xarray` is used to take the differences from the two experiments, allowing the impact introduced by increased BC aerosol emissions to be investigated. The global and Arctic mean temperature differences between the PI-BC and PI experiments are included in *Table 1*:

Model:	NorESM2-LM	UKESM1-0-LL	CNRM-ESM2
Global mean surface temperature:	-0.0041 K	+0.0096 K	-0.0416 K
Mean surface temperature north of 67° N:	-0.0708 K	-0.0016 K	-0.1701 K

Table 1: Field mean surface temperature differences between PI-BC and PI experiments in CMIP6. A positive difference indicates that increased BC aerosol emissions introduce a warming response.

In Figures 6 and 7, surface temperature differences (ΔT) and differences in AOD at 550 nm (ΔAOD), respectively, are presented for the winter and summer seasons.

[7]:
```
fu.plot_pibc_tas()
```

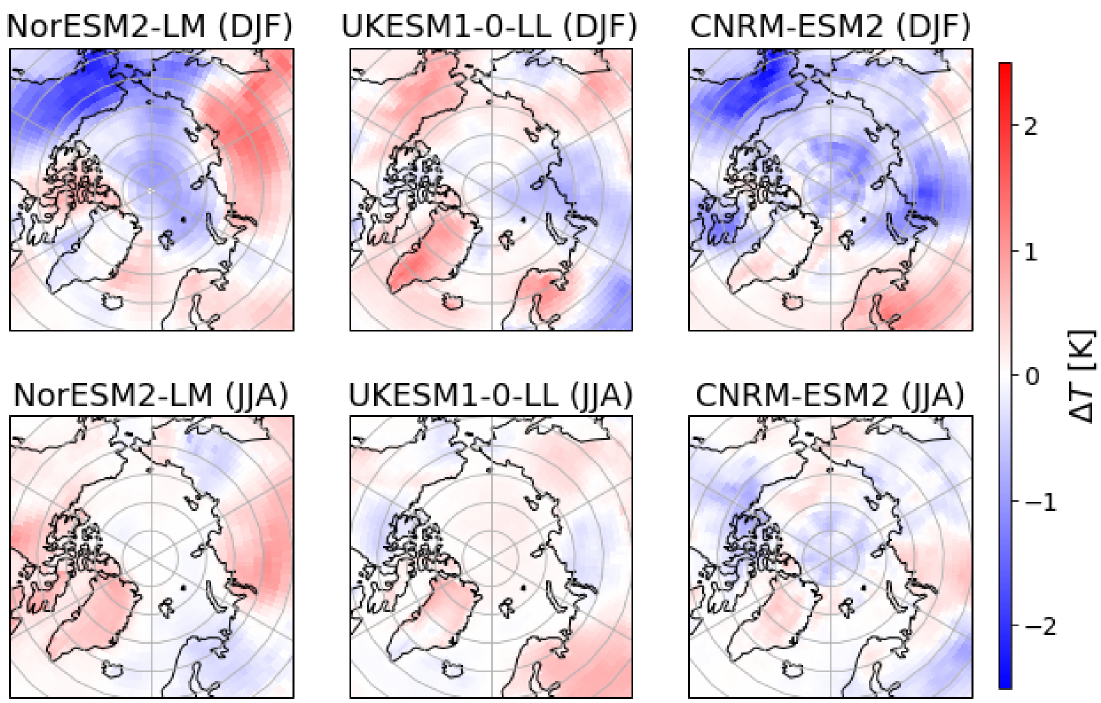

Figure 6: Surface temperature differences between PI-BC and PI control experiments in CMIP6. The winter season is denoted by DJF (December, January, February); the summer season is denoted by JJA (June, July, August).

A positive ΔT indicates that increased BC aerosol emissions are introducing a warming above the control state; a positive ΔAOD difference indicates an increased overall aerosol optical depth above that of the control state. Scales are adjusted to show the variations in the Arctic more clearly; global variations in temperature and AOD are greater than in the Arctic region.

[8]:
```
fu.plot_pibc_aod()
```

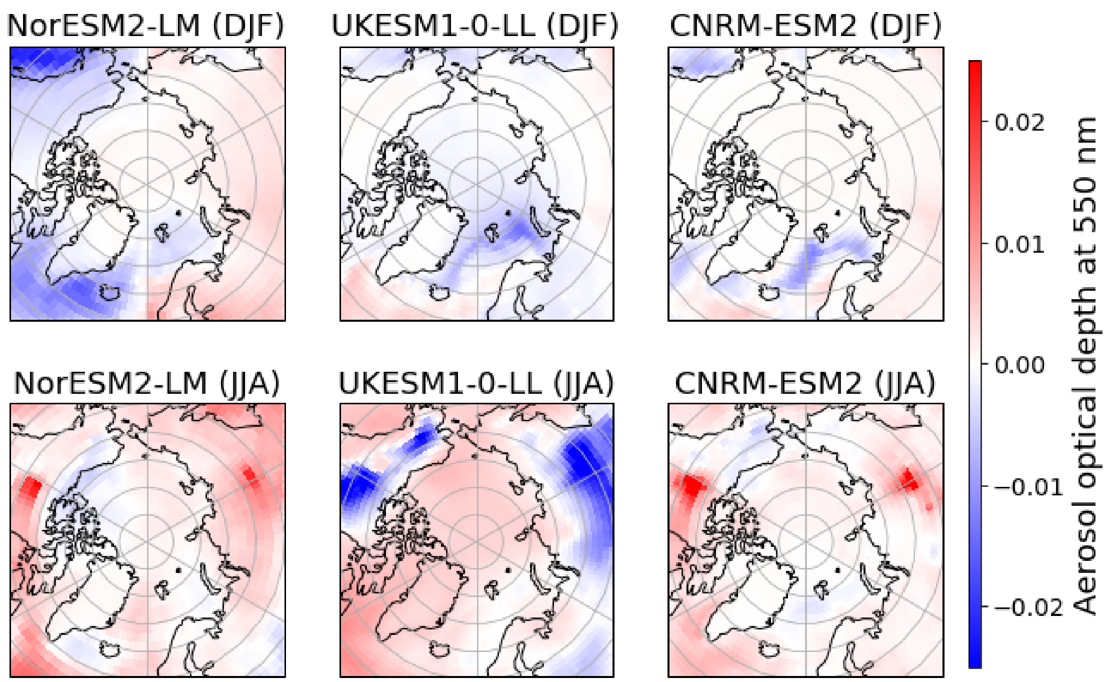

Figure 7: AOD differences between PI-BC and PI control experiments in CMIP6. The winter season is denoted by DJF (December, January, February); the summer season is denoted by JJA (June, July, August).

4 Discussion and outlook

It is quite clear in the observations that models do not accurately represent the optical properties of aerosols in the Arctic. At least some seasonal cycle should be present; observations show that aerosols tend to reach a peak during winter and spring, and then trough in summer, during the months between June and September; only one model comes close (UKESM1-0-LL). Most models show little to no variation throughout the annual cycle (NorESM2-LM, CESM2, CNRM-ESM2). CanESM5 represents the annual cycle with roughly twice the highest AOD measured by both satellite and sun photometer, but the seasonal cycle is represented quite well, with the peak occurring between winter and spring and the minimum during late summer months.

BC cycles in the Arctic vary greatly between models in the CMIP6 ensemble. For in-situ measurements, Alert may provide a better idea of an average BC cycle in the Arctic as the measurements are averaged over a two-year period: a peak during winter and spring, and a minimum during June through September. Most notable is CESM2, which models a double-peak cycle with a secondary increase during summer and a local maximum in August; CESM2-WACCM shows a similar cycle, but with a decreased load, and a less pronounced “false” summer peak. Both CESM2 and CESM2-WACCM have peaks of maximum BC loading during December-January, which is earlier than the observed peak. IPSL-CM6A-LR models the opposite of the natural cycle: a peak during June through September, and decreased BC loading during winter and spring.

Lastly, BC cycles in GFDL-CM4 peak in springtime and reach a minimum between October and January. The in-situ measurements of BC concentrations during the

In the PI-BC experiment in CMIP6, smaller temperature responses to the increased BC emissions are seen during the summer than in the winter. The two models that showed almost no annual cycle (NorESM2-LM and CNRM-ESM2) show a cooling response over open ocean during the winter months. As UKESM1-0-LL shows a slightly different pattern, this is likely due to the presence of an annual cycle of aerosols that are not represented in the other models. Stronger responses during winter are seen south of the polar circle, as is expected from the presence of incoming solar radiation. The only response shared between models is a warming response over Greenland during the summer months; warming during the summer with increased BC aerosol emissions can be easily explained by an increase in radiative absorption in the column, increasing temperature. Across all models and seasons, stronger responses are seen over land than over the Arctic ocean. In AOD, the stronger change in AOD in the PI-BC experiment can however be seen in the summer; stronger point sources in the northern Eurasian and North American continents most likely contribute to increasing AOD in NorESM2-LM and CNRM-ESM2 during the summer. The locations may explain the warming warming over land in these models during the same season. UKESM1-0-LL, however, displays the opposite reduction in the northern continents over land, which indeed shows the opposite pattern as NorESM2-LM and CNRM-ESM2. For the winter months, a reduction in AOD is seen across models over the North Sea, where a slight winter warming response is seen. AOD is on the order of 10^{-1}, and ΔAOD is seen here to be on the order of 10^{-2}. Since data on cloud variables for these experiments were not available, more investigation on changes in cloud behavior due to increased BC emissions are warranted to understand the rest of the story.

Model responses to a parameterized aerosol interaction are a way to understand the possible responses of the climate system to a perturbation in aerosols. While not in agreement across models, it is interesting to understand why individual models may behave the way they do; the first remarkable result is that there is a cooling response in surface temperatures over the Arctic Ocean during winter in NorESM2-LM and CNRM-ESM2. In the absence of sunlight during the winter, it is difficult to explain how increased BC aerosol loading would lead to cooling. On the contrary, increased BC in the atmospheric column should lead to greater absorption and reemission of outgoing long wave radiation, inducing a warming response. Since models typically implicate an ageing process so that sulfate may interact with BC in order to produce new cloud condensation nuclei (CCN), the increased CCN concentration in the PI-BC experiment may lead to more cloud cover. How these clouds may interact with radiation (particularly in the season with reduced incoming solar radiation) requires characterization of the clouds; how increased BC aerosols could induce cooling over the Arctic Ocean during the polar night in the absence of radiation remains to be explained. However, as is apparent in Table 1, both global and Arctic mean temperature responses in the models are small and with wide spread, making it difficult to draw conclusions without further investigating each model's employment of aerosol interactions.

With UKESM1-0-LL being the only model that reasonably approximates the annual cycle in AOD, what can be said about its distinctive wintertime response to increased BC emissions compared to the NorESM2-LM and CNRM-ESM2? The strength of the response (south of the polar circle) in the latter, which includes cooling over Alaska and northwestern North America, are greater in magnitude. Both of these models have a reduced AOD during winter months in the Arctic, where there should be a peak; the reproduction of a seasonal cycle with higher AOD during the winter months in UKESM1-0-LL may be suppressing the winter temperature response to increased BC emissions. If only BC loading is increasing in the PI-BC experiment, then the overall AOD may be increasing greatly over the whole annual cycle, depending on how AOD is determined in the models; this must be determined by a comparison of these variables during the PI-BC and the PI experiments.

5 Conclusions

The combination of the impossibility of obtaining AOD measurements from satellite during the polar night and the few AeroNet locations in the Arctic region leads to a difficulty in confirming AOD cycles in models, but with the data available, models within the CMIP6 multi-model ensemble do not reproduce AOD in the Arctic. The inability of a model to represent the annual cycle and magnitude of AOD leads to a misrepresentation of radiative effects. It is clear from the model results in CMIP6 that aerosol-radiation interactions in the Arctic are difficult to represent, and have no clear bias; this presents problems in our ability to determine uncertainties associated with the radiative effects of aerosols on climate. Due to the fact that Arctic amplification of warming temperatures is accelerating beyond previous predictions by climate models, representing radiative interactions in models is key, as each puzzle piece within the climate system (particularly ones that can be regulated, such as BC aerosol emissions) is key to understanding the evolution of both Arctic and global climate.

The elusiveness of direct BC measurements (and of aerosols in general) in the Arctic is problematic; there is no way to understand the variability of the BC cycle in the Arctic without multi-year observational data. This cannot be solved without expensive campaigns for measurements in remote locations, and the outlook for an improvement on data availability for BC aerosols in this region are bleek; therefore, the interannual variability within models have yet to be compared against observations. For this reason, it is important in future work to focus efforts on ensuring that BC processes and transport in Earth system models at least accurately represent a seasonal cycle of concentration in order to study what role that BC has in the global climate system through models.

References

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Supplementary material

`NeGIcourse_2019_aiden_supp_cdocommands.ipynb` contains the CDO operations used to calculate means and standard deviations for the AOD observation section as well as seasonal means for the CMIP6 PI-BC and PI-control simulations. `functions.ipynb` and `functions.py` contain the functions used in this report to work with and plot data. `imports.py` contains a list of the packages needed to replicate this project.

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The EBAS database has largely been funded by the UN-ECE CLRTAP (EMEP), AMAP and through NILU internal resources. Specific developments have been possible due to projects like EUSAAR (EU-FP5) (EBAS web interface), EBAS-Online (Norwegian Research Council INFRA) (upgrading of database platform) and HTAP (European Commission DG-ENV) (import and export routines to build a secondary repository in support of www.htap.org). A large number of specific projects have supported development of data and metadata reporting schemes in dialog with data providers (EU) (CREATE, ACTRIS and others). For a complete list of programmes and projects for which EBAS serves as a database, please consult the information box in the Framework filter of the web interface. These are all highly acknowledged for their support.