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Research article

Model evaluation of short-lived climate forcers for the Arctic Monitoring and Assessment Programme: a multi-species, multi-model study

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Abstract. While carbon dioxide is the main cause for global warming, modeling short-lived climate forcers (SLCFs) such as methane, ozone, and particles in the Arctic allows us to simulate near-term climate and health impacts for a sensitive, pristine region that is warming at 3 times the global rate. Atmospheric modeling is critical for understanding the long-range transport of pollutants to the Arctic, as well as the abundance and distribution of SLCFs throughout the Arctic atmosphere. Modeling is also used as a tool to determine SLCF impacts on climate and health in the present and in future emissions scenarios.

In this study, we evaluate 18 state-of-the-art atmospheric and Earth system models by assessing their representation of Arctic and Northern Hemisphere atmospheric SLCF distributions, considering a wide range of different chemical species (methane, tropospheric ozone and its precursors, black carbon, sulfate, organic aerosol, and particulate matter) and multiple observational datasets. Model simulations over 4 years (2008–2009 and 2014–2015) conducted for the 2022 Arctic Monitoring and Assessment Programme (AMAP) SLCF assessment report are thoroughly evaluated against satellite, ground, ship, and aircraft-based observations. The annual means, seasonal cycles, and 3-D distributions of SLCFs were evaluated using several metrics, such as absolute and percent model biases and correlation coefficients. The results show a large range in model performance, with no one particular model or model type performing well for all regions and all SLCF species. The multi-model mean (mmm) was able to represent the general features of SLCFs in the Arctic and had the best overall performance. For the SLCFs with the greatest radiative impact (CH_4, O_3, BC, and SO_4^{2-}), the mmm was within ±25 % of the measurements across the Northern Hemisphere. Therefore, we recommend a multi-model ensemble be used for simulating climate and health impacts of SLCFs.

Of the SLCFs in our study, model biases were smallest for CH_4 and greatest for OA. For most SLCFs, model biases skewed from positive to negative with increasing latitude. Our analysis suggests that vertical mixing, long-range transport, deposition, and wildfires remain highly uncertain processes. These processes need better representation within atmospheric models to improve their simulation of SLCFs in the Arctic environment. As model development proceeds in these areas, we highly recommend that the vertical and 3-D distribution of SLCFs be evaluated, as that information is critical to improving the uncertain processes in models.

1 Introduction

The Arctic atmosphere is warming 3 times more quickly than the global average (Bush and Lemmen, 2019; NOAA, 2020; AMAP, 2021; IPCC, 2021). Arctic warming is a manifestation of global warming, and the main driver for this is the increasing carbon dioxide (CO_2) radiative forcing (IPCC, 2021). Arctic warming is amplified by sea ice and snow feedbacks and affected by local radiative forcings in the Arctic, including radiative forcings by short-lived climate forcers (SLCFs), such as methane, black carbon, and tropospheric ozone (AMAP, 2015a, b, 2022). The remote pristine Arctic environment is sensitive to the long-range transport of atmospheric pollutants and deposition (Schmale et al., 2021). At the same time, it is difficult to carry out in situ measurements (Nguyen et al., 2016; Freud et al., 2017) and satellite observations over the Arctic. The majority of the Arctic surface is ocean covered with sea ice that is usually adrift for most of the year. The Arctic environment is also harsh. These aspects have historically kept surface-based measurements sparse. The overwhelming majority of the satellite observations either depend on the visible spectrum, are limited by the presence of clouds, or have very low sensitivity in the lower troposphere where the atmospheric processes mainly determine the fate of the pollutants. Many satellite measurements also do not have good coverage in the Arctic, given their orbital parameters or problems measuring areas with high albedo (Beer, 2006).

Modeling the Arctic atmosphere comes with its own challenges due to extreme meteorological conditions, its great distance from major global pollution sources, poorly known local emissions, high gradients in physical and chemical fields, and a singularity in some model grids at the pole. Models have been improving in the last 2 decades, but many models still have inaccurate results in the Arctic (Shindell et al., 2008; Eckhardt et al., 2015; Emmons et al., 2015; Sand et al., 2017; Marelle et al., 2018). That said, there has recently been a number of improvements in numerous models that have allowed for better representation of certain processes (Morgenstern et al., 2017; Emmons et al., 2020a; Swart et al., 2019; Holopainen et al., 2020; Im et al., 2021). In this study, model simulations for the 2021 Arctic Monitoring and Assessment Programme (AMAP) SLCF assessment report (AMAP, 2022) have been thoroughly evaluated by comparison to several freely available observational datasets in the Northern Hemisphere and assessed in more detail in the Arctic. In order to support the integrated assessment of climate and human health for AMAP, 6 SLCF species (methane – CH_4, ozone – O_3, black carbon – BC, sulfate – SO_4^{2-}, organic aerosol – OA, and fine particulate matter – $PM_{2.5}$) and 2 O_3 precursors (carbon monoxide – CO; nitrogen dioxide – NO_2) from 18 atmospheric or Earth system models are compared to numerous observational datasets (from three satellite instruments, seven monitoring networks, and nine measurement campaigns) for 4 years (2008–2009 and 2014–2015), with the goal of answering the following questions.

1. How well do the AMAP SLCF models perform in the context of measurements and their associated uncertainty?
   - What do the best-performing models have in common?
   - Are there regional patterns in the model biases?
   - Are there patterns in the model biases between SLCF species?
2. How does the model performance impact model applications, such as simulated climate and health impacts?
3. What processes should be improved or studied further for better model performance?

Out of scope of this study are any sensitivity tests by the models to assess different components of model errors. Also out of scope are the models' simulations of aerosol optical properties and cloud properties (e.g., cloud fraction, cloud droplet number concentration, cloud scavenging), though those parameters do have a large impact on climate and a tight relationship with some SLCFs. Their initial evaluation can be found in AMAP (2022) (chap. 7). Estimates of effective radiative forcings of SLCFs in the Arctic by the AMAP participating models are also provided elsewhere (Oshima et al., 2020).

The next section summarizes the models used in this study, with more information in the Appendix. Section 3 summarizes the measurements used for model evaluation. Section 4 presents our model evaluation for each SLCF species, followed by a summary of all SLCFs. Finally, Sect. 5 is the conclusion where the questions posed above are answered.

2 Models

In this section we briefly describe the models used for the AMAP SLCF study and refer the reader to Appendix A for individual model descriptions and further information. All models were run globally with the same anthropogenic emissions dataset (see Sect. 2.1), and most were run for the years 2008–2009 (as was done for the 2015 AMAP assessment report) and 2014–2015 (to evaluate more recent model results) inclusive for this evaluation, as these were years with numerous Arctic measurements. Unless otherwise indicated, all model output was monthly-averaged.

The models used for this study are summarized in Table 1. As is shown in the table, not all models provided all SLCF species, and not all models provided all 4 years. There were eight chemical transport models (CTMs), two chemistry–climate models (CCMs), three global climate models (GCMs), and five Earth system models (ESMs). Many models used specified or nudged meteorology, which allows the day-to-day variability of the model meteorology to be more closely aligned with the historical evolution of the atmosphere than occurs in a free-running model. The ERA-Interim reanalysis was the most commonly used meteorology (in 7 out of 18 models), but some were free-running (simulating their own meteorology) and some used other reanalysis products (Table 1).

2.1 Emissions

All models used the same anthropogenic emissions dataset, which is called ECLIPSE (Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants) v6B. These emissions were created using the IIASA-GAINS (International Institute for Applied Systems Analysis – Greenhouse gas – Air pollution Interactions and Synergies) model (Amann et al., 2011; Klimont et al., 2017; Höglund-Isaksson et al., 2020), which provides emissions of long-lived greenhouse gases and shorter-lived species in a consistent framework. These historical emissions were provided for the years 1990

Table 1. Summary of models used in this study. GCM: global climate model, CCM: chemistry–climate model, ESM: Earth system model, CTM: chemical transport model.

Name	Type	Meteorology	Simulation period	SLCF output	Primary reference(s)
CanAM5-PAM	GCM	nudged to ERA-Interim reanalysis	1990–2015	BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	von Salzen et al. (2000); von Salzen (2006); von Salzen et al. (2013) Ma et al. (2008); Peng et al. (2012); Mahmood et al. (2016, 2019)
CESM2.0	ESM	free-running	2008–2009, 2014–2015	O_3, CO, NO_2, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Danabasoglu et al. (2020) Liu et al. (2016)
CIESM-MAM7	GCM	nudged to ERA-Interim reanalysis	1990–2015	BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD	Lin et al. (2020); Liu et al. (2012)
CMAM	CCM	nudged to ERA-Interim reanalysis	1990–2015	O_3, CO, NO_2, CH_4	Jonsson et al. (2004) Scinocca et al. (2008)
DEHM	CTM	nudged to ERA-Interim reanalysis	1990–2015	O_3, CO, NO_2, CH_4, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Christensen (1997); Brandt et al. (2012); Massling et al. (2015)
ECHAM6-SALSA	GCM	nudged to ERA-Interim reanalysis	2008–2009, 2014–2015	BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Tegen et al. (2019); Schultz et al. (2018); Kokkola et al. (2018)
EMEP MSC-W	CTM	driven by 3-hourly ECMWF met	1990–2015	O_3, CO, NO_2, CH_4, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD	Simpson et al. (2012, 2019)
FLEXPART	Lagrangian CTM	driven by 3-hourly ECMWF met	2014–2015	BC, SO_4^{2-}	Pisso et al. (2019)
GEM-MACH	online CTM	driven by GEM numerical forecast	2015	O_3, CO, NO_2, BC, SO_4^{2-}, OA, $PM_{2.5}$	Moran et al. (2018) Makar et al. (2015b, a); Gong et al. (2015)
GEOS-Chem	CTM	Driven by GEOS meteorology	2008–2009, 2014–2015	O_3, CO, NO_2, CH_4, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Bey et al. (2001)
GISS-E2.1	ESM	nudged to NCEP reanalysis	1990–2015	O_3, CO, NO_2, CH_4, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Kelley et al. (2020); Miller et al. (2021); Bauer et al. (2020)
MATCH	CTM	ERA-Interim reanalysis	2008–2009, 2014–2015	O_3, CO, NO_2, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Robertson et al. (1999)
MATCH-SALSA-RCA4	CCM	RCA4	2008–2009, 2014–2015	O_3, CO, NO_2, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Robertson et al. (1999); Andersson et al. (2007); Kokkola et al. (2008)
MRI-ESM2	ESM	nudged to JRA55 reanalysis	1990–2015	O_3, CO, NO_2, CH_4, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD	Yukimoto et al. (2019); Kawai et al. (2019); Oshima et al. (2020)
NorESM1-happi	ESM	free-running	2008–2009, 2014–2015	BC, SO_4^{2-}, OA, AOD, AAOD, AE	Bentsen et al. (2013); Iversen et al. (2013); Gent et al. (2011) Graff et al. (2019)
Oslo-CTM	CTM	driven by 3-hourly ECMWF meteorology	2008–2009, 2014–2015	O_3, CO, NO_2, CH_4, BC, SO_4^{2-}, OA, $PM_{2.5}$	Søvde et al. (2012); Lund et al. (2018a)
UKESM1	CCM & ESM	nudged to ERA-Interim reanalysis	1990–2015	O_3, CO, NO_2, CH_4, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Sellar et al. (2019); Kuhlbrodt et al. (2018); Williams et al. (2018)
WRF-Chem	CCM & CTM	nudged to NCEP FNL reanalysis	2014–2015	O_3, CO, NO_2, BC, SO_4^{2-}, OA, $PM_{2.5}$, AOD, AAOD, AE	Marelle et al. (2017, 2018)