SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	EC-Earth climate simulation for AerChemMIP
Computer Project Account:	SPNLNOIJ
Start Year - End Year :	2017 – 2019
Principal Investigator(s)	Dr. T.P.C. van Noije
Affiliation/Address:	Royal Netherlands Meteorological Institute (KNMI) P.O. Box 201 3730 AE De Bilt Netherlands
Other Researchers (Name/Affiliation):	Dr. P. Le Sager (KNMI), Dr. T. Bergman (KNMI)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

Within this special project, we have carried out climate simulations with the global climate model EC-Earth within the context of the Coupled Model Intercomparison Project Phase 6 (CMIP6). The simulations have been done with a model configuration with interactive aerosols and atmospheric chemistry (EC-Earth3-AerChem), and are part of the consortium's contribution to the Aerosols and Chemistry Model Intercomparison Project (AerChemMIP). The set of simulations consist of the CMIP coupled DECK simulations (Diagnostic, Evaluation and Characterization of Klima), the CMIP6 historical simulation, and a coupled simulation for AerChemMIP.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

The project has faced some serious delays. These were caused by 1) delays in the development and tuning of the physical model configuration (EC-Earth3), 2) additional efforts needed to tune the model configuration with interactive aerosols and atmospheric chemistry (EC-Earth3-AerChem) used in this project, and 3) a coding error in the implementation of stratospheric aerosols, which specifically affected EC-Earth3-AerChem. As a consequence, part of the resources has been spent on development and tuning of EC-Earth3-AerChem, and the CMIP6 production simulations were only started in the final year of the project.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The application procedure and reporting obligations are reasonable. We appreciate that there is a possibility to request for an amendment of the original plan during the course of the project.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

This project can be divided into three phases:

1. Model development
2. Model tuning
3. CMIP6 production

Below we will report on the development activities and the CMIP6 production simulations. The tuning and CMIP6 production simulations have been shared with the SPSEECCMIP special project (under account SPNLTUNE), and will be described in more detail there.

1. Model development

The development activities focused on the following aspects of the model:

- Improved description of secondary organic aerosols and new particle formation
- Implementation of CMIP6 forcing data sets and options
- Improved computational performance
- Implementation of diagnostics for CMIP6 and CRESCENDO
- Atmosphere-only simulation for CRESCENDO and AeroCom

A short summary for each of these activities is given below.

Improved description of secondary organic aerosols and new particle formation

The representation of secondary organic aerosol (SOA) in TM5 has been improved. The simple representation using surrogate emissions has been replaced by an explicit scheme in which SOA is formed in the atmosphere as presented by Jokinen et al. (Proc. Natl. Acad. Sci., 2015). The new scheme is a two-product model where isoprene and monoterpene are oxidized by ozone and hydroxyl radical to produce semi-volatile organic compounds (SVOC) and extremely volatile compounds (ELVOC). Together with the new scheme we also implemented a new particle formation mechanism as a function of ELVOC and sulfate concentrations (Paasonen et al., Atm. Chem. Phys, 2010; Riccobono et al., Science, 2014) and condensation of ELVOCs and SVOCs. A set of sensitivity simulations has been carried out in off-line mode to test the new SOA formation scheme, and prepare for a model description and evaluation paper. Figure 1 shows the impact of these model improvements on the vertically integrated organic aerosol mass distribution.

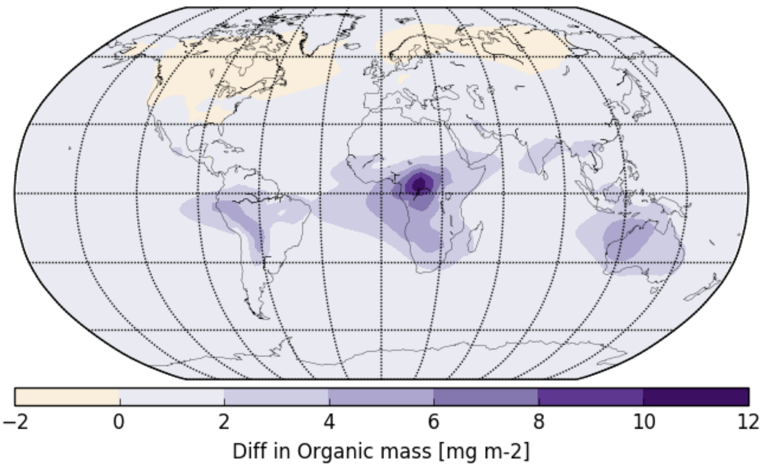

Figure 1. Difference in vertically integrated organic aerosol mass density compared to the earlier model version.

A number of offline TM5 simulations were carried out to evaluate the quality of the new schemes describing the formation of secondary organic aerosols (SOA) and boundary layer nucleation. Results from these simulations will be described and evaluated in a scientific publication (Bergman et al., in preparation). Results have also been evaluated in model intercomparison studies carried out within the AeroCom project (Aerosol Comparisons between Observations and Models; http://aerocom.met.no) and EU project BACCHUS (Fanougakis et al., 2019; Sporre et al., 2020). The new schemes have also been merged into EC-Earth3-AerChem.

Implementation of CMIP6 forcing data sets and options
New CMIP6 forcing data sets for the pre-industrial and historical periods (1850-2014) have been implemented in TM5. These include data sets describing the evolution of the mixing ratios of stratospheric ozone, methane and carbon dioxide since 1850, as well as updated versions for the historical emissions of aerosol and ozone precursors from both anthropogenic and biomass burning sources. In addition, new output routines have been implemented in TM5 to provide the aerosol data required for AerChemMIP.

Because the model does not include a comprehensive stratospheric chemistry scheme, ozone mixing ratios are nudged towards their desired zonal mean values, which can now be chosen to be based on the CMIP6 pre-industrial climatology or historical time series. Methane mixing ratios in the model are constrained both at the surface and in the stratosphere. At the surface, mixing ratios are nudged to concurrent zonal means from the CMIP6 data set, while in the stratosphere the annual global mean mixing ratio from CMIP6 is used with a one-year delay for scaling a present-day climatology from the HALOE (Halogen Occultation Experiment) satellite instrument. Global mean mixing ratio of carbon dioxide is used in TM5 to calculate the acidity of cloud droplets, which is relevant for aqueous phase chemistry.

For anthropogenic emissions, a more detailed sector dependence of the size distribution and solubility of primary emissions of carbonaceous particles has been introduced, e.g. by making explicit use of the supplementary information on solid biofuel combustion emissions, provided as part of the CMIP6 anthropogenic emissions from the Community Emissions Data System (CEDS).

Improved computational performance
Work has been done to improve the model's computational performance. The exchange of non-spectral fields between IFS and TM5 now involves all cores of TM5 instead of one. This has reduced the MPI communication, and has substantially increased the scalability of the model. A number of test simulations have been performed to estimate the effects on model performance. We estimated that the use of multi-core coupling increases the speed of the model in atmosphere-only configuration from about 1.4 to slightly more than 2.0 simulation years per day (see Figure 2).

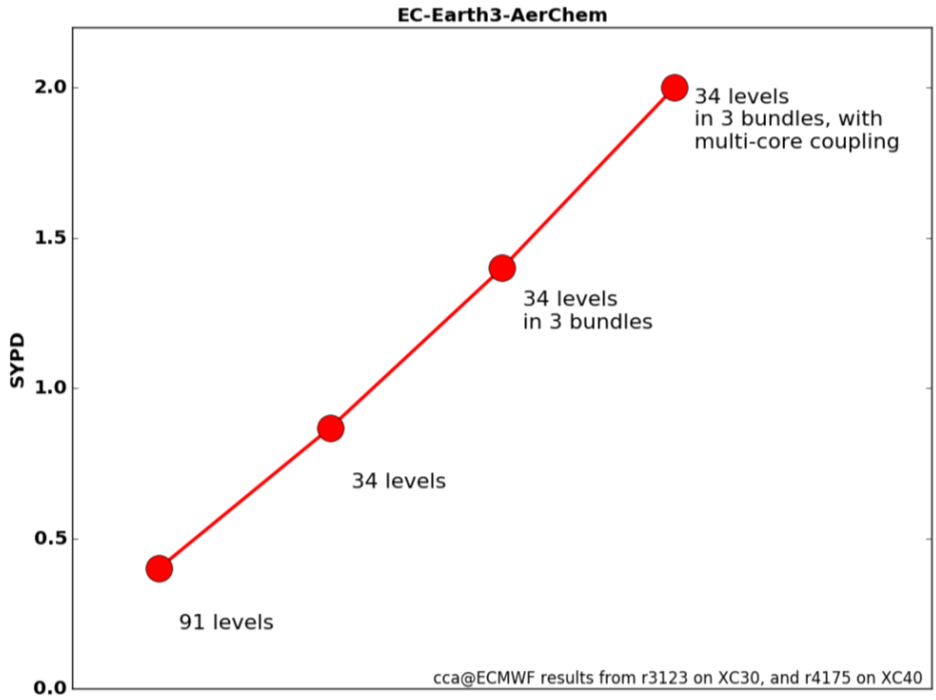

Figure 2. Model speed in simulation years per day (SYPD) obtained in various development stages of EC-Earth3-AerChem in atmosphere-only configuration.

Further efficiency improvements, including a reduction in the number of vertical levels on which aerosol fields are transferred from TM5 to IFS, have increased the performance to about 3.0 SYPD.

Implementation of diagnostics for AerChemMIP and CRESCENDO
We have included all available output diagnostics requested for AerChemMIP into TM5. Additional diagnostics requested for the EU Horizon-2020 project CRESCENDO have also been included. We also added additional AerChemMIP diagnostics to the IFS output, including radiative fluxes from a second call to the radiation scheme in which aerosols are removed.

Atmosphere-only simulations for CRESCENDO and AeroCom
For CRESCENDO we have completed a 15-year (2000-2014) atmosphere-only simulation with EC-Earth3-AerChem. The setup of this simulation is essentially the same as for the CMIP6 AMIP simulation, but then with an earlier model version. Moreover, we have carried out a number of sensitivity simulations with this model version, in which the emission amounts of various sources of natural aerosols or aerosol precursors were varied. The requested output diagnostics from these simulations have been submitted to the project's server at JASMIN.

In addition, we completed a number of simulations for the AeroCom project (Aerosol Comparisons between Observations and Models), viz. the AeroCom Phase-III control experiment AP3-CTRL2019 and the associated experiment using pre-industrial (1850) emissions. These simulations were carried out both with EC-Earth3-AerChem in atmosphere-only mode with wind fields and surface pressure nudged to the ERA-Interim reanalysis, and with the corresponding TM5 model in standalone mode, driven by surface and meteorological fields from ERA-Interim. An evaluation of the aerosol optical properties in the simulations using present-day emissions is presented by Gliß et al. (2020).

2. Model tuning

During the final year of the project, we have started spinning up a near-final version of EC-Earth3-AerChem in ocean-atmosphere coupled mode using pre-industrial emissions and other forcing data sets. Initially we used the same settings of tuning parameters as used in the standard version of EC-Earth3, i.e. the version with aerosols and greenhouse gases, including ozone and methane, prescribed. Starting from an initial state from the EC-Earth3 pre-industrial control simulation, the model configuration with interactive aerosols, ozone and methane, started to warm, especially in the Northern Hemisphere. To reduce the NH warm bias obtained with these parameter settings, we started two additional spinup simulations with slightly changed values of three atmospheric tuning parameters (part of IFS). The behaviour of these two configurations was as expected, resulting in a global cooling of a few tenths of degrees compared to the original run (see Figure 1).

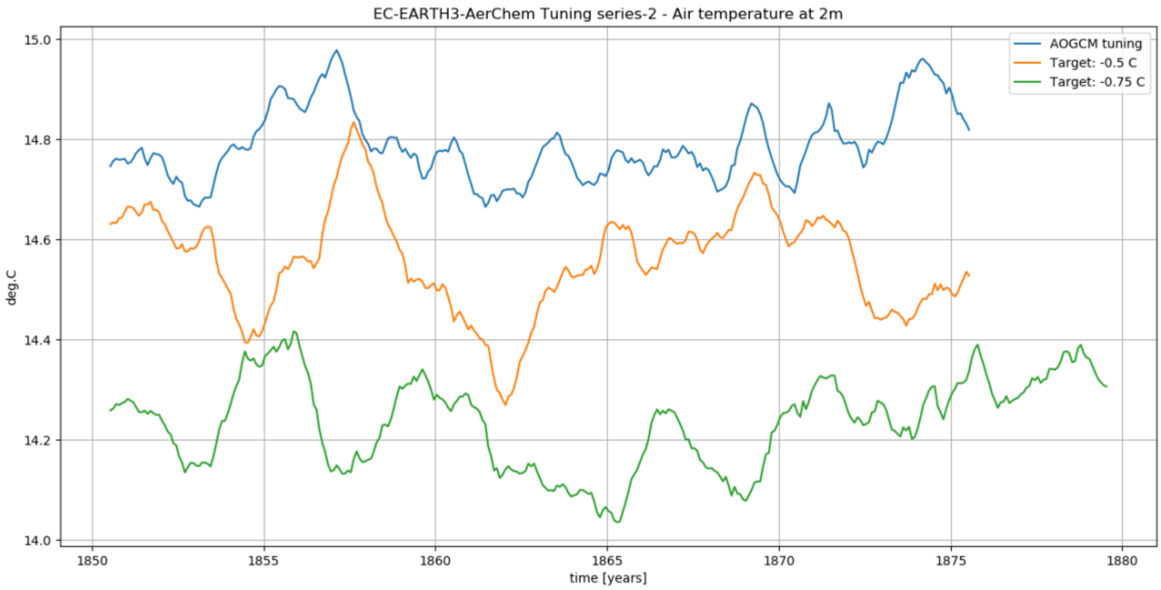

Figure 1. Global mean surface air temperature in the three EC-Earth3-AerChem pre-industrial spinup runs, completed in the final year of the project. The three model configurations differ only in the values of three atmospheric tuning parameters: the blue curve is produced using the standard settings from EC-Earth3, while the orange and green curves are obtained after re-tuning the model, where the target was to cool the model by about 0.5 K and 0.75 K, respectively, compared to the configuration with standard settings. Note that all simulations were started from the same initial state obtained with EC-Earth3; the first 120 years of the simulations are not shown.

The largest impact is realized in the NH. The top panel in Figure 2 shows the multi-annual zonal mean surface temperatures from the three EC-Earth3-AerChem spinup simulations, the EC-Earth3 pre-industrial control simulation (blue line), and from the ERA5 reanalysis for the 1980s (purple line); the bottom panel shows the differences between the simulated zonal means and the reanalysis data set. These differences give an idea of the temperature biases in the simulations, but for a quantitative comparison one would need to account for the warming already realized in the 1980s. It can be seen that the different pre-industrial simulations all have similar warm biases over the Southern Ocean. Moreover, whereas EC-Earth3 is generally too cold in the NH, using the same set of tuning parameters EC-Earth3-AerChem tends to be too warm. Finally, by changing only two or three of the standard tuning parameters used in the tuning of EC-Earth3, more realistic NH temperatures can be obtained.

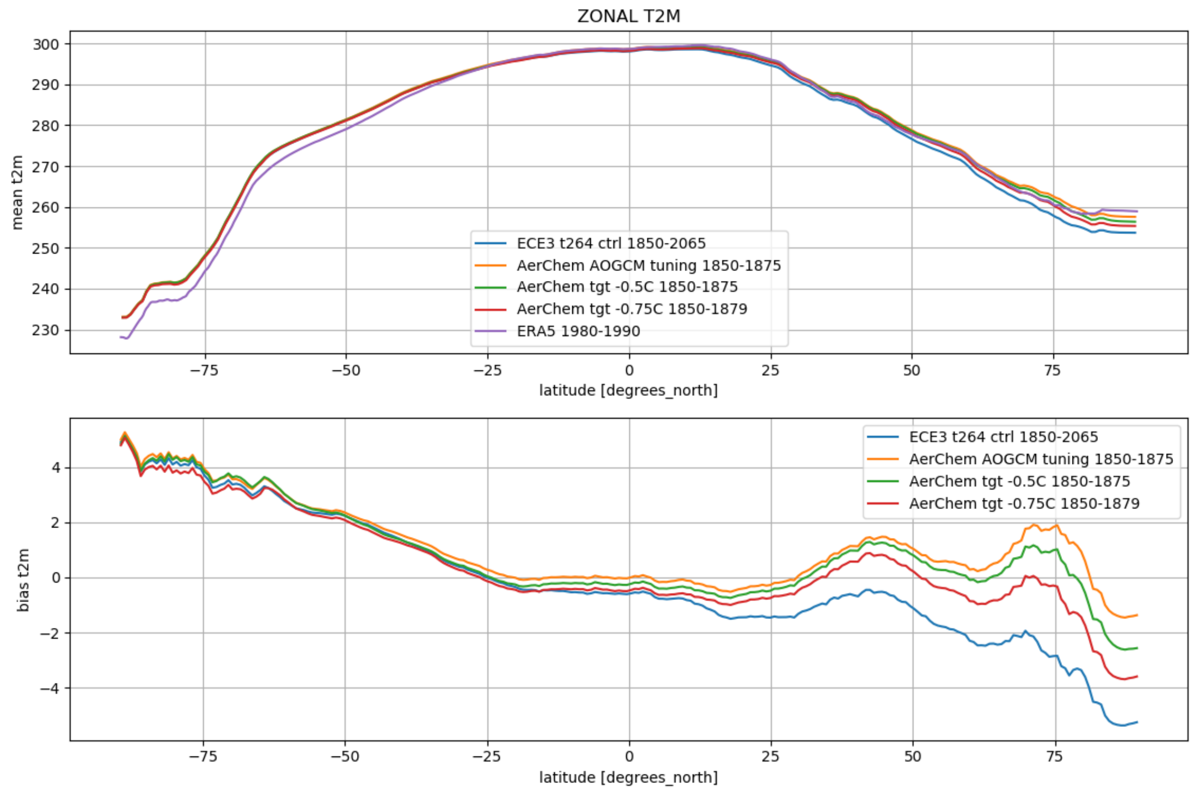

Figure 2. The top panel shows the multi-annual zonal mean surface temperatures from the three EC-Earth3-AerChem spinup simulations (orange, green and red curves) for the periods presented in Figure 1, from the EC-Earth3 pre-industrial control simulations (averaged over more than 200 years), and from the ERA5 reanalysis for the 1980s. The differences between the simulations and the reanalysis are shown in the bottom panel.

Whereas EC-Earth3 produces a pre-industrial climate with large long-term variations in, e.g., NH temperatures and sea ice, and Atlantic Meridional Overturning Circulation (AMOC), likely triggered by a cold bias in the Northern Atlantic, our spinup simulations with interactive aerosols and atmospheric chemistry do not show this behaviour to the same extent. This suggests that the variability in the EC-Earth3-AerChem pre-industrial and historical runs will be more realistic in this respect. Note that the resources for running these spinup simulations have been shared with SPSEECCMIP. Further details about these runs are given in the accompanying annual report.

3. CMIP6 production

After the completion of this project, a bug was discovered related to the implementation of stratospheric aerosols, which affected only the EC-Earth3-AerChem configuration. We have been able to correct the code, re-tune the model and complete a first set of production runs for CMIP6. These consists of the coupled DECK simulation (piControl, abrupt-4xCO2, and 1pctCO2), the CMIP6 historical simulation, and an AerChemMIP simulation with near-term climate forcers (NTCFs) fixed to their 1850 values (hist-piNTCF). The completed historical and hist-piNTCF simulations are the first members of what is planned to become a four-member ensemble. Although technically these simulations were done under SPSEECCMIP, the work done under SPNLNOIJ has been critical to get to this stage. As an example, Figure 2 shows the evolution of the global mean surface air temperature and surface solar radiation.

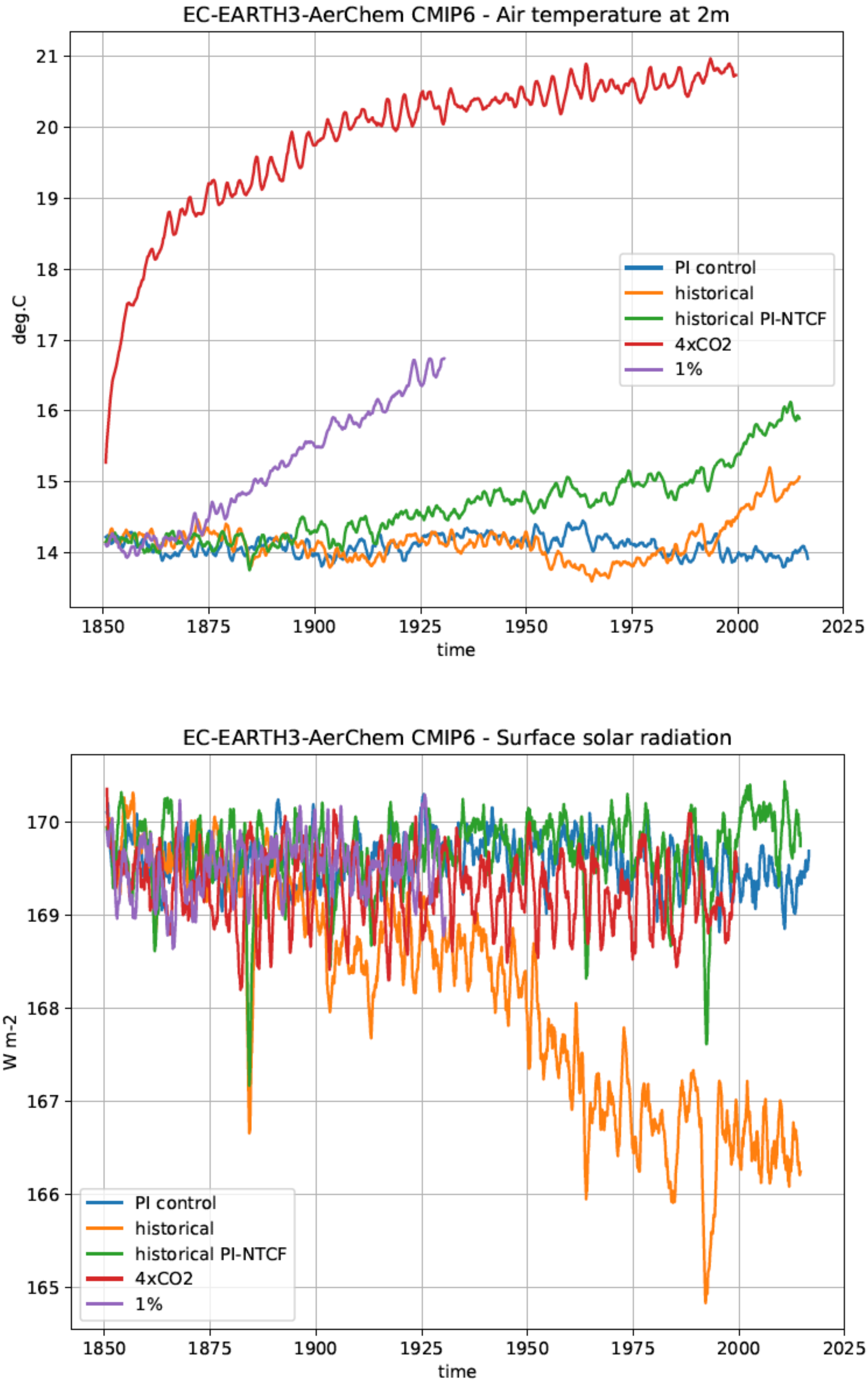

Figure 2. Global mean surface air temperature (top panel) and surface solar radiation (bottom panel) from the first set of EC-Earth3-AerChem CMIP6 DECK and AerChemMIP simulations.

List of publications/reports from the project with complete references

Bergman, T., Makkonen, R., Schrödner, R., Swietlicki, E., Phillips, V., Le Sager, P., and van Noije, T., Evaluation of a secondary organic aerosol and new particle formation scheme within TM5-MP v1.1, in preparation, 2020.

Van Noije, T., Bergman, T., Le Sager, P., et al., EC-Earth3-AerChem, a global climate model with interactive aerosols and atmospheric chemistry participating in CMIP6, Geosci. Model Dev., in preparation, 2020.

Fanourgakis, G. S., Kanakidou, M., Nenes, A., Bauer, S. E., Bergman, T., Carslaw, K. S., Grini, A., Hamilton, D. S., Johnson, J. S., Karydis, V. A., Kirkevåg, A., Kodros, J. K., Lohmann, U., Luo, G., Makkonen, R., Matsui, H., Neubauer, D., Pierce, J. R., Schmale, J., Stier, P., Tsigaridis, K., van Noije, T., Wang, H., Watson-Parris, D., Westervelt, D. M., Yang, Y., Yoshioka, M., Daskalakis, N., Decesari, S., Gysel-Beer, M., Kalivitis, N., Liu, X., Mahowald, N. M., Myriokefalitakis, S., Schrödner, R., Sfakianaki, M., Tsimpidi, A. P., Wu, M., and Yu, F.: Evaluation of global simulations of aerosol particle and cloud condensation nuclei number, with implications for cloud droplet formation, Atmos. Chem. Phys., 19, 8591–8617, https://doi.org/10.5194/acp-19-8591-2019, 2019.

Gliß, J., Mortier, A., Schulz, M., Andrews, E., Balkanski, Y., Bauer, S. E., Benedictow, A. M. K., Bian, H., Checa-Garcia, R., Chin, M., Ginoux, P., Griesfeller, J. J., Heckel, A., Kipling, Z., Kirkevåg, A., Kokkola, H., Laj, P., Le Sager, P., Lund, M. T., Lund Myhre, C., Matsui, H., Myhre, G., Neubauer, D., van Noije, T., North, P., Olivié, D. J. L., Sogacheva, L., Takemura, T., Tsigaridis, K., and Tsyro, S. G.: Multi-model evaluation of aerosol optical properties in the AeroCom phase III Control experiment, using ground and space based columnar observations from AERONET, MODIS, AATSR and a merged satellite product as well as surface in-situ observations from GAW sites, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-1214, in review, 2020.

Sporre, M. K., Blichner, S. M., Schrödner, R., Karset, I. H. H., Berntsen, T. K., van Noije, T., Bergman, T., O'Donnell, D., and Makkonen, R.: Large difference in aerosol radiative effects from BVOC-SOA treatment in three ESMs, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-1166, accepted, 2020.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

We intend to complete the set of planned AerChemMIP simulations under SPSEECCMIP.