Report on the IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) 2013 Science Workshop

Veronika Eyring[1], Jean-François Lamarque[2], Irene Cionni[3], Bryan Duncan[4], Arlene Fiore[5], Andrew Gettelman[2], Michaela Hegglin[6], Peter Hess[7], Tatsuya Nagashima[8], Tom Ryerson[9], Ted Shepherd[6], Drew Shindell[10], Darryn Waugh[11], and Paul Young[12]

[1]Deutches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Germany, **veronika.eyring@dlr.de**, [2]National Center for Atmospheric Research, USA, [3]ENEA, Bologna, Italy, [4]NASA Goddard Space Flight Center, USA, [5]Columbia University, USA, amfiore@ldeo.columbia.edu, [6]Department of Meteorology, University of Reading, UK, [7]Cornell University, USA, [8]National Centre for Environmental Studies, Tsukuba, Japan, [9]NOAA, USA, [10]NASA Goddard Institute for Space Studies, USA, [11]Johns Hopkins University, USA, [12]Lancaster University, UK

Approximately 130 participants (see **Figure 1**) attended the IGAC/SPARC Chemistry-Climate Model Initiative (CCMI, **http://www.pa.op.dlr.de/CCMI/**) 2013 Science Workshop, held in Boulder, CO, USA, at the Center Green Campus of the National Center for Atmospheric Research (NCAR) from 14-16 May 2013. The workshop was followed by a Scientific Steering Committee Meeting held on the morning of 17 May 2013. Workshop participants' expertise ranged from global chemistry and climate model developers and users, to in situ and satellite observational experts, with interests in tropospheric and stratospheric chemistry and climate. Science topics discussed included key observations needed for model evaluation to improve constraints on tropospheric and stratospheric chemistry and dynamics, as well as stratosphere-troposphere coupling. Examples of process-oriented evaluation of CCMs were presented and discussed.

There were three days of scientific talks and discussions, focusing on upcoming multi-model simulations and their analysis. The recorded videos and presentations from the workshop are available from the workshop website at **http://ccmi.ucar.edu/**. Three breakout groups were held, targeting specific topics around: (1) the CCMI data request and diagnostic tool, (2) tropospheric chemistry, and (3) CCMI support for the upcoming WMO/UNEP Scientific Assessment of Ozone Depletion (see details below). Throughout the meeting, upcoming CCMI multi-model analyses were discussed extensively. 22 different global chemistry-climate models are currently participating in the first round of CCMI simulations (see **Table 1**) and representatives from each of the modelling groups presented an update on the status and plans of their simulations and analyses. The CCMI Phase 1 (CCMI-1) simulations (Eyring *et al.*, 2013a) are being carried out partly in support of the 2014 WMO/UNEP Scientific Assessment of Ozone Depletion, and will also form an ensemble for a first comprehensive inter-comparison of transient chemistry-climate hindcasts of the late 20th and early 21st century, spanning both the troposphere and stratosphere. Hindcast simulations will be used to constrain the models and facilitate detailed comparisons between models and observations, as well as process-oriented model evaluation. These simulations feed into the evaluation for assessing future chemistry-climate projections.

Figure 1: Participants of the IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) 2013 Science Workshop that was held in in Boulder, CO, USA at the Center Green Campus of the National Center for Atmospheric Research (NCAR) in May 2013..

Hindcast and future scenarios in support of the Ozone Assessment must be completed by end of 2013. Model groups are producing output that will be uploaded to the British Atmospheric Data Centre (BADC), and distributed to the community for analysis.

Breakout Group 1: CCMI data request and diagnostic tool

This group met to discuss model output format, specifications, and timelines for the CCMI-1 data request, as well as possible pathways to make progress with a CCMI diagnostic tool for routine evaluation of the models.

The CCMI data request combines the output specifications from ACCMIP (Atmospheric Chemistry and Climate Model Intercomparison Project) and CCMVal-2 (Chemistry Climate Model Validation Activity), as well as additional requests from the CCMI simulation document (Eyring et al., 2013a). Additional input requests to this table, as discussed at the workshop, and as further collected from the community (see updates on the CCMI website) are also included. Qi Tang and Peter Hess (Cornell University, USA) have taken the lead in compiling this data request. A large emphasis in the first round of CCMI is placed on improving the comparability between models and observations (see also Eyring *et al.* (2013a)), so the data request includes additional output for improved comparison with aircraft and satellite data. Model simulations with specified meteorology (REF-C1SD) also facilitate detailed comparisons with individual campaigns, not just climatologies. A first draft of the CCMI-1 data request was sent to the CCMI model groups and users in early July 2013 to collect comments on the feasibility for the model groups and possible missing output to be used for process-oriented analysis of the model simulations. The comments were then considered in the final data request, which will be available on the CCMI website from around end of July 2013. Climate Model Output Rewriter (CMOR, see **http://www2-pcmdi.llnl.gov/cmor**) tables corresponding to this output are being created under the lead of Philip Cameron-Smith (PCMDI, USA), and will be available on the CCMI website from around mid-August 2013.

The second part of the breakout group was devoted to discussions on the CCMI diagnostic tool. The existing Chemistry-Climate Model Validation Diagnostic tool (CCMVal-Diag, Gettelman *et al.* (2012)) forms the basis of the evaluation tool to be used in CCMI. The CCMVal-Diag tool is currently being further extended into an Earth System Model Evaluation tool (ESMValTool) in various projects, and, compared to the CCMVal-Diag tool, already includes many additional climate diagnostics and several technical improvements. The ESMValTool is a flexible and extensible open source package that facilitates the complex evaluation of global models. It is currently based on Python and the NCAR Command Language (NCL), but discussions in the breakout group called for the need to allow for other open source libraries (*e.g.*, R, CDAT, Fortran) to be called. The tool can be used to evaluate single models (or dif-

Table 1: Chemistry-climate models currently participating in the first round of CCMI simulations:

	Model Name	Modeling Center
1	**ACCESS**	University of Melbourne, CAWCR, AAD, Australia, NIWA, NZ
2	**CCSM4**	NCAR, ESL, USA
3	**CCSRNIES-MIROC3.2**	NIES, Tsukuba, Japan
4	**CESM-Superfast**	LLNL, USA
5	**CICERO-OsloCTM3**	CICERO, Norway
6	**CMAM**	EC (Environment Canada), Canada
7	**CNRM-CCM**	Météo-France; France
8	**EMAC**	Modular Earth Submodel System (MESSy) -Consortium (DLR, KIT, FZJ, FUB, UMZ; MPIC), Germany
9	**GEOS CCM**	NASA/GSFC, USA
10	**GFDL-AM3**	NOAA, GFDL, USA
11	**GISS-E2-R**	NASA-GISS,USA
12	**HadGEM3-ES**	Hadley Centre, Met Office, United Kingdom
13	**LMDZrepro**	IPSL, France
14	**MIROC-ESM-CHEM**	NIES, Nagoya Univ., JAMSTEC, Japan
15	**MOCAGE**	GAME/CNRM, MétéoFrance, France
16	**MRI**	MRI, Japan
17	**NIWA-UKCA**	NIWA, NZ
18	**SOCOL**	PMOD/WRC and IAC ETHZ, Switzerland
19	**ULAQ**	University of L'Aquila, Italy
20	**UMSLIMCAT**	University of Leeds, UK
21	**UMUKCA**	University of Cambridge, UK
22	**WACCM4**	NCAR, USA

ferent versions of a model), as well as multiple models from CCMI, the Coupled Model Intercomparison Project (CMIP), and other Model Intercomparison Projects that use CMOR-formatted output. The tool is built in such a way that the code allows for further extensions to be made by different users for different applications and types of ESMs. Several institutions have already joined the development of the ESMValTool as part of various projects in a version-controlled repository that is hosted at the German Aerospace Center (DLR) using Subversion (see **http://svnbook.red-bean.com/index.en.html**). Subversion is a free and open source version control system, which manages files and directories, and the changes made to them. The CCMI community is encouraged to help developing this evaluation tool by either joining the core development team or by contributing routines. In particular, it is hoped that those people who volunteered to lead a CCMI multi-model analysis (see **http://www.pa.op.dlr.de/CCMI/CCMI_DataRequests.html**) will contribute their codes to the tool to allow for future efforts to repeat these analyses, allowing further model evaluation and benchmarking. Please contact Veronika Eyring for more information.

Breakout Group 2: Tropospheric Chemistry

A clear set of chemistry-climate research themes emerged from the discussions in the tropospheric working group. These can be broadly summarized as: (1) understanding long-term trends and variability in tropospheric ozone, a major greenhouse gas (GHG) and air pollutant; (2) exploring links between chemical constituents and climate variability (*e.g.*, ENSO); and (3) a deep exploration of the drivers of the hydroxyl radical (OH), a gas that influences concentrations of important GHGs, such as methane and ozone. For these themes, observational datasets, both satellite and in situ, have been identified for use to constrain and evaluate CCMI model simulations. The first phase of analysis will focus largely on the hindcast simulations (covering 1960-2010), identifying biases and determining whether constraints derived from observations can help to narrow the range of future projections.

A thorough exploration of 1960-2010 tropospheric ozone trends will provide insights into how changing ozone precursor emissions (natural and anthropogenic), together with changing climatic factors, have shaped our environment over the last five decades. For example, an analysis of long-term ozone trends at European sites with a focus on their seasonal variability was presented at the meeting, and the shortcomings in the current generation of models as well as the emissions used were identified. Can we use the CCMI models to understand and reduce this discrepancy?

Several participants proposed leading studies focused on the links between tropospheric composition and transport and climate dynamics. A natural first step is the relationship between tropical tropospheric ozone and ENSO, which has been explored in both satellite and in situ observations, and which is also a robust feature of tropospheric chemistry-climate models. The role of stratosphere-troposphere exchange on tropospheric ozone distributions and variability also received much attention. This process could become an increasingly important source of tropospheric ozone if precursor emission decreases are combined with stratospheric ozone recovery and an intensification of the stratospheric circulation. The CCMI effort will also enable study of the links between air quality and large-scale atmospheric flow.

The challenge to understand OH rests on the shoulders of more than three decades of effort to understand its distribution and trends. This area will encompass a broad spectrum of proposed studies involving reconciling modelled and observed lifetimes and distributions of reactive constituent, clouds, and detailed analyses of high time-resolution model output. ACCMIP analyses revealed that models disagree on the sign of the OH trend since the pre-industrial period, or for the projected future, and determining the drivers of the trend was sometimes hampered by the available model diagnostics. A significant effort of the CCMI analysis will involve understanding the origin of this model diversity through targeted requests for detailed and relevant diagnostics.

A unifying thread for these research themes is to make a more thorough use of the wealth of observations available for model comparisons, including ground-, aircraft-, and satellite-based platforms. The CCMI community welcomes observational scientists and there has been a great effort to compile measurement data from many sources, making it available in a format that can be readily used for model evaluation (see the CCMI website).

For the proposed analyses to be successful we emphasize the need for the modelling teams to provide as much of the requested output as possible. In particular, several topics would benefit from high frequency output (daily or more frequent) of a few diagnostics, namely surface ozone and surface temperature. Detailed analysis of even more highly resolved model output (at every model time-step) has been proposed to explore OH, and will be requested for 4 consecutive days (July 1-4) for the years 1960, 1980, 2000 (most important), 2030, 2050, and 2100. This high-frequency output is included in the CCMI-1 data request (see Breakout Group 1, above).

The three themes mentioned here are not intended to be exhaustive, and it is clear that the CCMI dataset will represent an invaluable opportunity to explore many other climate-chemistry questions, be they related to the troposphere, stratosphere, or both. However, these topics provide an initial framework around which many members of the community can coalesce their efforts. Indeed, there are clear ideas for publications in place, and several opportunities for collaborations. An update on the analyses planned can be found on the CCMI website.

Breakout Group 3: CCMI support for 21015 WMO/UNEP Ozone Assessment

This group discussed the CCMI contribution to the upcoming WMO/UNEP Ozone Assessment, so as to ensure the most useful contribution possible within the constraints of the scientific community's ability to produce and analyse new simulations in the short timeframe available.

A major effort has been expended by the modelling community to produce simulations for both CCMVal-2 and CMIP5. These simulations have not yet been fully exploited and can be analysed in ways relevant to the new Ozone Assessment without having to wait for new model data. In particular, new research to connect model evaluation with uncertainties in model projections using CCMVal-2 data could be very useful, as this connection was not made in WMO (2011).

At least a dozen modelling groups expect to complete the reference simulations for both the past (REF-C1, REF-C1SD) and future (REF-C2) by the end of 2013. Based on past experience, this should provide sufficient time for results to be incorporated in the upcoming Ozone Assessment, as well as in papers being prepared for the assessment. Given that the number of simulations to be available by the end of 2013 is likely to be smaller than that provided by CCMVal-2 (especially with regards to fixed-GHG and fixed-ODS sensitivity simulations, which most groups will not likely be able to complete on this timescale), it seems that the best way forward is to use the existing simulations wherever possible, and use new simulations to update or extend results to fill specific gaps in knowledge or address particular uncertainties.

Differences between CCMVal-2, CMIP5, and CCMI REF-C2 simulations will need to be accounted for in the comparison of the different data sets. For GHGs, the reference simulations in CCMVal-2 used the SRES A1B GHG scenario, whereas CMIP5 and CCMI-1 use the Representative Concentration Pathways (RCP). For ODSs, CMIP5 used the WMO (2007) A1 halogen scenario, whereas CCMVal-2 and CCMI-1 use the WMO (2011) scenario. Only a small subset of the CMIP5 models had interactive ozone (Eyring *et al.*, 2013b). For changes tied to surface warming (e.g., strengthened Brewer-Dobson Circulation (Butchart *et al.*, 2011; SPARC-CCMVal, 2010)), it should be relatively straightforward to relate the SRES A1B to RCP 6.0, which is the GHG scenario used in the CCMI REF-C2 simulation. For changes tied to chemistry, the models with interactive chemistry in CMIP5 should be sufficient to address (or at least bound) these effects, given that CMIP5 included a range of RCPs (Eyring *et al.*, 2013b).

It was recognized that RCP 8.5 is considered "unrealistic" in terms of its methane scenario, but the group concluded that it would be unwise to try to define an alternative scenario. More generally, it was noted that the RCPs do not span parameter space for stratospheric applications, especially the chemical roles of N_2O and CH_4. However, trying to address this with additional CCMI sensitivity simulations was felt to be a "bridge too far" at this stage. Several single-model studies are addressing this issue.

Three particular topics might arise for the upcoming Ozone Assessment that will not be addressed by a large suite of chemistry-climate models (CCMs) participating in CCMI-1. The first topic is the sensitivity of ozone recovery to different GHG scenarios. Not many groups are committed to performing new GHG sensitivity simulations, so these sensitivities will likely be explored through studies by individual groups, and using the available CCMVal-2 and CMIP5 simulations (see above). Second, the SPARC Lifetimes Report includes revised halogen lifetimes and reaction rates. As a result, new ODS scenarios are being developed. At least three groups — WACCM, GEOSCCM, and SLIMCAT — are planning to explore the sensitivities to lifetimes and kinetics. More would certainly be welcome. The third topic is geoengineering. The consensus was that simulations to address geoengineering should be part of GeoMIP, and that sufficient published model studies exist for this topic to be assessed without an additional CCMI contribution.

Interactive chemistry is not necessarily critical for all topics, for example Arctic vortex variability, to be considered in Chapter 4 (the "climate" chapter of the upcoming Ozone Assessment). This chapter will likely draw heavily on CMIP5 results because of the use of coupled atmosphere-ocean models and the large number of simulations and ensembles available.

It was decided that the CCMVal-2 diagnostics were adequate for the purpose of the ozone assessment and that there was no need to add any more to the data request table. It was also agreed that it is too early to produce a coordinated CCMI report similar to SPARC-CCMVal (2010). Instead, several individuals volunteered to lead a particular CCMI multi-model analysis (see CCMI website for updates) that could be solicited by the chapters.

CCMI Scientific Steering Committee (SSC) Meeting

A CCMI SSC meeting was held following the main workshop. The SSC revisited the timeline and action items that were discussed throughout the meeting and identified individuals to move things forward (see above). It was decided to hold the next CCMI workshop, with a focus on the analysis of hindcast simulations, in Lancaster, UK, from 20-22 May 2014. It was also agreed to push for diagnostics to be collected from the various people who analyse CCMI simulations within the ESMValTool. In addition, SPARC offered resources to be assigned to the development of the tool to ensure some of the key diagnostics for chemistry-climate analysis are integrated into the tool for improved model evaluation and benchmarking.

To help the overall coordination of CCMI, it was agreed that the CCMI SSC would elect a new co-chair through a formal process. The SSC meeting was followed by a nomination and voting period open to all CCMI SSC members. Michaela Hegglin (University of Reading, UK) was elected as new co-chair of CCMI, starting immediately, with Veronika Eyring (DLR, Germany) stepping down as CCMI co-chair at the end of 2013 when she starts as chair of the CMIP Panel.

Acknowledgements

The workshop was held under the auspices of the International Global Atmospheric Chemistry (IGAC) Project, the WCRP's (World Climate Research Programme) SPARC (Stratospheric Processes and their Role in Climate) project, and NCAR. We would like to thank NCAR and the University Corporation for Atmospheric Research (UCAR) as well as the local organising committee (Andrew Gettelman and Christy Edwards) for hosting the workshop.

References

Butchart, N., *et al.*, 2011: Multimodel climate and variability of the stratosphere. *J. Geophys. Res.*, DOI: 10.1029/2010JD014995.

Eyring, *et al.*, 2013a: Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments. *SPARC Newsletter*, **40**, 48-66.

Eyring, V., *et al.*, 2013b: Long-term ozone changes and associated climate impacts in CMIP5 simulations. *J. Geophys. Res.*, DOI: 10.1002/jgrd.50316 .

Gettelman, A., *et al.*, 2012: A community diagnostic tool for chemistry climate model validation. *Geosci. Model Dev.*, **5**, 1061-1073.

SPARC-CCMVal, 2010. SPARC Report on the Evaluation of Chemistry-Climate Models. In: V. Eyring, T.G. Shepherd and D.W. Waugh (Eds.). SPARC Report, WCRP-132, WMO/TD-No. 1526.

WMO, 2007: World Meteorological Organization, Scientific Assessment of Ozone Depletion: 2006, Geneva, Switzerland.

WMO, 2011: World Meteorological Organization, Scientific Assessment of Ozone Depletion: 2010, Geneva, Switzerland.