Overview of IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) Community Simulations in Support of Upcoming Ozone and Climate Assessments

Veronika Eyring[1], Jean-François Lamarque[2], Peter Hess[3], Florian Arfeuille[4], Kevin Bowman[5], Martyn P. Chipperfiel [6], Bryan Duncan[7], Arlene Fiore[8], Andrew Gettelman[2], Marco A. Giorgetta[9], Claire Granier[10], Michaela Hegglin[11], Doug Kinnison[2], Markus Kunze[12], Ulrike Langematz[12], Beiping Luo[13], Randall Martin[14], Katja Matthes[15], Paul A. Newman[7], Thomas Peter[13], Alan Robock[16], Tom Ryerson[17], Alfonso Saiz-Lopez[18], Ross Salawitch[19], Martin Schultz[20], Theodore G. Shepherd[11], Drew Shindell[21], Johannes Staehelin[13], Susann Tegtmeier[22], Larry Thomason[23], Simone Tilmes[2], Jean-Paul Vernier[23], Darryn W. Waugh[24], Paul J. Young[25]

[1]DLR Institut für Physik der Atmosphäre, Germany, veronika.eyring@dlr.de, [2]National Center for Atmospheric Research, USA, lamar@ucar.edu, andrew@ucar.edu, dkin@ucar.edu, and tilmes@ucar.edu, [3]Cornell University, USA, pgh25@cornell.edu, [4]Bern University, Switzerland, florian.arfeuille@giub.unibe.ch, [5]NASA Jet Propulsion Laboratory, Pasadena, USA, kevin.w.bowman@jpl.nasa.gov, [6]University of Leeds, UK, martyn@env.leeds.ac.uk, [7]NASA Goddard Space Flight Center, USA, Bryan.N.Duncan@nasa.gov, and Paul.A.Newman@nasa.gov, [8]Columbia University, USA, amfiore@ldeo.columbia.edu, [9]Max Planck Institute for Meteorology, Germany, marco.giorgetta@zmaw.de, [10]IPSL, Paris, France, cgranier@latmos.ipsl.fr, [11]University of Reading, UK, m.i.hegglin@reading.ac.uk, and theodore.shepherd@reading.ac.uk, [12]Freie Universität Berlin, Germany, markus.kunze@met.fu-berlin.de, and ulrike.langematz@met.fu-berlin.de, [13]ETH Zürich, Switzerland, beiping.luo@env.ethz.ch, thomas.peter@env.ethz.ch, and johannes.staehelin@env.ethz.ch, [14]Dalhousie University, Canada, randall.vaughn.martin@gmail.com, [15]GEOMAR Kiel, Germany, kmatthes@geomar.de, [16]Rutgers University, USA, robock@envsci.rutgers.edu, [17]NOAA, USA, Thomas.B.Ryerson@noaa.gov, [18]Laboratory for Atmospheric and Climate Science, Spain, a.saiz-lopez@ciac.jccm-csic.es, [19]University of Maryland, USA, rjs@atmos.umd.edu, [20]Forschungszentrum Juelich, Germany, m.schultz@fz-juelich.de, [21]NASA Goddard Institute for Space Studies, USA, dshindell@giss.nasa.gov, [22]Helmholtz Centre for Ocean Research (GEOMAR), Germany, stegtmeier@geomar.de, [23]NASA Langley Research Center, USA, l.w.thomason@nasa.gov, and jeanpaul.vernier@nasa.gov, [24]Johns Hopkins University, USA, waugh@jhu.edu, [25]Lancaster University, UK, paul.j.young@lancaster.ac.uk

1. Introduction

The IGAC and SPARC communities are jointly defining new reference and sensitivity simulations to address emerging science questions, improve process understanding and support upcoming ozone and climate assessments. These simulations were discussed as part of the IGAC/SPARC Global Chemistry-Climate Modelling and Evaluation Workshop (Davos, May 2012) and are described in this document.

1.1 Background

The workshop participants recommended the creation of a joint IGAC/SPARC Chemistry-Climate Model Initiative (CCMI) to coordinate future (and to some extent existing) IGAC and SPARC chemistry-climate model evaluation and associated modelling activities. The CCMI has now been approved by both the IGAC and SPARC scientific steering committees at their respective steering committee meetings. The IGAC/SPARC CCMI is superseding the SPARC Chemistry-Climate Model Validation (CCMVal) activity, expanding the goals and deliverables of CCMVal to include tropospheric chemistry-climate questions. Similarly, the IGAC hindcast activity is now embedded into the CCMI rather than being a separate activity, so as to benefit from overlapping interests and approaches of the tropospheric and stratospheric chemistry modelling communities. Also, new phases of the Atmospheric Chemistry-Climate Model Intercomparison Project (ACCMIP, see **http://www.giss.nasa.gov/projects/accmip/**) may merge with the CCMI activities. A white paper summarizing the goals of the CCMI will be published in the IGAC and SPARC newsletters in 2013. A website for the CCMI has been created at **http://www.pa.op.dlr.de/CCMI/**, where further information can be found and ongoing efforts are reported.

1.2 Purpose and scope of the proposed CCMI community simulations

In this document, the **CCMI reference (REF)** and **sensitivity (SEN)** simulations for Chemistry-Climate Models (CCMs), Earth-System Models (ESMs) with interactive chemistry, and Chemistry-Transport Models (CTMs) are proposed. The over-arching principle behind the choice of the CCMI simulations is to produce the best possible science.

There are two overall goals for the choice of REF simulations:

1. Quantify how well the models can reproduce the past behaviour (climatology, trends and interannual variability) of tropospheric and stratospheric ozone, other oxidants, and more generally chemistry-climate interactions, as well as to understand processes that govern these interactions. This is the rationale behind the "past" transient hindcast reference simulations in either free-running (**REF-C1**) or specified dynamics (**REF-C1SD**) mode. These simulations are forced by boundary conditions specifie from observations or empirical data (*e.g.*, sea surface temperatures (SSTs), sea ice concentrations (SICs), emissions, greenhouse gas (GHG) concentrations) and meteorology in the case of REF-C1SD. One of the goals for the new REF-C1SD simulation is to provide an improved evaluation against observations, in particular new satellite, ground-based, and *in situ* measurements.
2. Analyse projections of the future evolution of tropospheric and stratospheric ozone. This is the rationale behind the "future" transient reference simulation (**REF-C2**), which is forced by trace gas projections and either prescribed modelled SSTs and SICs, or an interactively coupled ocean. Experience gained from the evaluations performed for the SPARC-CCMVal (2010) report shows that it is important to have a continuous time series from the models, covering both past and future, in order to avoid inhomogeneity in the data sets (in terms of both absolute values and variability), and also that the simulations extend to 2100 in order to fully capture the process of ozone recovery from the effects of ozone-depleting substances (ODSs). Accordingly, REF-C2 simulations should cover the period 1960-2100, with a 10-year spin-up starting in 1950.

It is recommended that groups perform a small ensemble of simulations covering the 'past' 1960-2010 (**REF-C1**) and 'future' 1960-2100 (**REF-C2**) periods, so as to establish an uncertainty range in the simulations.

The proposed **SEN** simulations are designed to augment the science that can be obtained from the reference simulations. These simulations include investigating the sensitivity to various GHG scenarios, ODSs, and emissions. Further sensitivity simulations that might be proposed to answer specific science questions will be made available on the CCMI website.

All simulations are open to a broad range of participating CCMs, as well as to ESMs with interactive stratospheric and/or tropospheric chemistry. The specific dynamics simulation **REF-C1SD** is designed for CTMs, CCMs or ESMs with the capability of nudging using meteorological input.

All participating models should use the **standard set of specifie forcings** that is specified in this document. The forcings to drive the models can be downloaded from the CCMI website or through the links given throughout this document.

1.3 Scientific question and timelines

While the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations are now being studied in great detail in support of the IPCC Fifth Assessment Report (AR5), along with analysis of simulations performed under ACCMIP, Geoengineering Model Intercomparison Project (GeoMIP) and Aerosol Comparisons (AeroCom) activities, the next WMO/UNEP Scientific Assessment of Ozone Depletion should be supported by updated simulations of stratospheric ozone. It is envisaged that the new simulations broadly follow the recommendations of the SPARC-CCMVal (2010) report, in particular:

- CCM simulations of ozone depletion/recovery should be performed seamlessly over the entire 1950-2100 period with consistent forcings, and with data produced in a standard format to allow for multi-model intercomparison.
- A range of different scenarios should be simulated, *e.g.*, using fixed GHG and different GHG projections. To be consistent with CMIP5, these scenarios should generally follow the four Representative Concentration Pathways (RCPs; Moss *et al.,* 2010; van Vuuren *et al.*, 2011a), but with ODS values replaced with those from WMO (2011). These simulations will allow correct attribution of the projected changes and an understanding of the sensitivity to the GHG scenario employed.
- Development should continue towards comprehensive troposphere-stratosphere CCMs, which include an interactive ocean, tropospheric chemistry, a naturally occurring QBO, spectrally resolved solar irradiance, and a fully resolved stratosphere.
- The next generation of CCMs should also include a better representation of tropospheric chemical processes (*e.g.*,

non-methane hydrocarbons, lightning NO_x production, detailed inclusion of dry and wet deposition processes). This is certainly important for science studies in the troposphere and Upper Troposphere Lower Stratosphere (UTLS) region, but may also be important for better representation of the overall climate system.

- The coupling of CCMs to interactive oceans is recommended in the future, in order to make the representation of climate change in the models more physically self-consistent.
- The community should address the issue of how to include very short-lived (VSL) organic bromine species into the boundary conditions and chemical mechanisms of CCMs.
- An accurate knowledge of the atmospheric lifetime of gases is essential for predicting ozone depletion and the climatic effects of emissions. A re-evaluation of the lifetimes of important halogen source gases (*e.g.*, CFC-11, CCl_4, halons, HFCs, HCFCs, and related species) is currently underway as part of the SPARC activity on 'Lifetime of halogen source gases' (see **http://www.sparc-climate.org/activities/lifetime-halogen-gases/**), since evidence has emerged that in many cases the actual lifetimes may be considerably longer than those currently assumed in the 2010 WMO/UNEP Ozone Assessment (WMO, 2011) and in the scenarios used to drive the CCMs. This represents a major uncertainty in reconciling top-down and bottom-up emission estimates, and in model projections.

Some of the above-mentioned points are already considered in existing simulations. For example, a subset of models participating in CMIP5 has interactive chemistry and a coupled ocean. These runs can be included in studies that analyse the ozone evolution under different GHG scenarios. On the other hand, some of the model groups that did not participate in any of the above mentioned model intercomparison projects (MIPs) might want to additionally run simulations that extend the science beyond what was possible for WMO (2011).

In addition, the scientific questions that can be addressed through a new hindcast simulation with models including interactive chemistry are diverse. A non-exhaustive list of questions includes:

i. How well does the current generation of global chemistry models capture the interannual variability in tropospheric and stratospheric constituents?
ii. How well do we understand the tropospheric OH budget? Can we capture the estimated interannual variability and trends?
iii. How have changes in atmospheric forcings impacted chemical composition and chemistry over the last 30 to 50 years? These forcings include: a) changes in climate forcing with resulting impacts on temperature, water vapour and meteorology, possibly extending to stratosphere-troposphere exchange, b) changes in ozone and aerosol precursor emissions, c) changes in land cover, and d) changes in ODSs.
iv. How have changes in aerosol loading impacted oxidative capacity of the troposphere over the last 30 to 50 years?
v. To what extent do the increased satellite retrievals of tropospheric and stratospheric constituents constrain constituent variability over the last 10-15 years?
vi. To what extent can CCMs forced with observed SSTs and solar particles capture the observed interannual variability of the hindcast simulations?
vii. What is the role of very short-lived halogen species (VSLS)?

The proposed hindcast simulations will address these questions through observationally-based simulations and sensitivity tests. Additionally, a re-assessment of temperatures, trace species and ozone in the simulations will allow documenting the progress of individual models and overall progress on the representation of key processes compared to the last CCM assessments. The comparison of CCM results with observations will also allow some groups to identify and correct previously unrecognised model errors and will help to indicate a range of model uncertainties. The hindcast simulations are also incorporated in the work plan of the UNECE/EMEP Task Force Hemispheric Transport (**http://iek8wikis.iek.fz-juelich.de/HTAPWiki/WP3.6**), focusing on aspects specifically relevant for hemispheric transport of air pollution and its contribution to observed pollution trends.

Overall, there are two competing timescales for performing these simulations: the shorter term ozone assessment timescale, including the need to perform new hindcast simulations for improved understanding, and the longer term timescale for integrated climate and chemistry assessment of both the troposphere and stratosphere. These competing timescales have been recognised, and a key aspect of this document is to detail a long-term strategic plan for simulations that can meet the complex needs of simulating chemistry-climate interactions, while also seeking to prioritize simulations for near term (~next 3 years) needs. The result is that these simulations are envisaged to occur in two main phases over the next few years, see further details Section 5 and **Figure 28**.

Table 2: Summary of proposed IGAC/SPARC CCMI reference simulations:

Name of Reference Simulation	**Period**	**Greenhouse Gases**	**ODSs**	**SSTs/SICs**	**Background & Volcanic Aerosol**	**Solar Variability**	**VSLS**	**QBO**	**Ozone and Aerosol Precursors**
REF-C1	**Transient simulation 1960-2010** Appropriate spin up prior to 1960	**OBS** GHG used for CMIP5 simulations, updated until 2010.	**OBS** (WMO, 2011)	**OBS** HadISST1	**OBS** Surface Area Density data (SAD)	**OBS** Spectrally resolved irradiance data, Proton ionization, Ap	**YES**	**OBS or internally generated**	**OBS** Based on Lamarque *et al.* (2010), but annual emissions
REF-C1SD (nudged for CCMs, or CTMs)	**Transient simulation 1980-2010**	**OBS** Same as **REF-C1**	**OBS** Same as **REF-C1**	**OBS** Consistent with met. reanalysis	**OBS** Same as **REF-C1**	**OBS** Same as **REF-C1**	Same as **REF-C1**	Same as **REF-C1**	**OBS** Same as **REF-C1**
REF-C2	**Transient simulation 1960-2100** 10-year spin up prior to 1960	**OBS to 2005 then RCP 6.0 (Masui *et al.*, 2011)**	**OBS + A1 scenario from WMO (2011)**	**Modeled SSTs**	**OBS** Background SAD	**YES** Spectrally resolved irradiance data, Proton ionization, Ap	**YES**	**YES**	**Same as REF-C1 until 2000 + RCP 6.0 scenario in the future**

1.4 Outline

The three, highest priority reference simulations that should be run by the various modelling groups are described in Section 2. It is recommended that, in addition to the reference simulations, the sensitivity simulations described in Section 3 are performed by as many groups as possible. It is important that groups simulate the full time period specified, to allow a reliable comparison between the different models and observations, and to provide projections until the end of the 21st century. Section 4 describes model output, dynamics and composition diagnostics, and comparison to observations. Section 5 outlines a timeline for the CCMI and Section 6 closes with a summary and outlook.

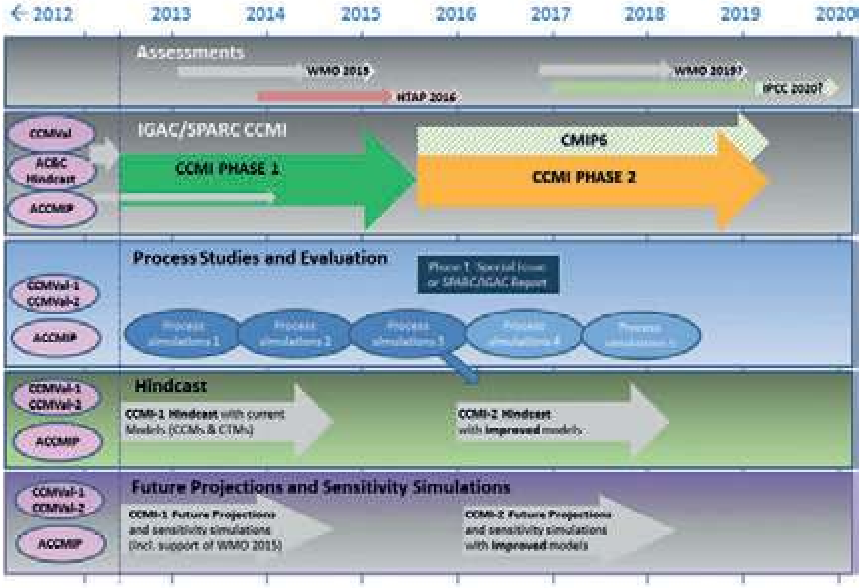


Figure 28: Timeline for the IGAC/SPARC CCMI community simulations.

2. IGAC/SPARC CCMI Reference Simulations

This section gives an overview of the main characteristics of the new IGAC/SPARC CCMI REF simulations. In many instances, the forcings follow the recommendations of CMIP5 (**http://cmip-pcmdi.llnl.gov/cmip5/forcing.html**). The key characteristics are also summarized in **Table 2**.

2.1 HINDCAST: Reference Simulation 1 (REF-C1, 1960-2010; REF-C1SD, 1980-2010)

REF-C1 (1960-2010) covers the time period from 1960 to 2010 (with a 10-year spin-up prior to 1960) to examine model variability and to replicate as closely as possible the atmospheric state in the period during which ozone and other atmospheric constituents were measured. It allows a detailed investigation of the role of natural variability and other atmospheric changes important for ozone balance and trends. All forcings in this simulation are taken from observations or empirical data, including anthropogenic and natural forcings based on changes in trace gases, solar variability (spectral irradiance and particles), volcanic eruptions, quasi-biennial oscillation (QBO), SSTs, and SICs; see details below. In contrast to CCMVal-2 simulations, the forcings are extended to 2010 based on observations as much as possible. Note, that many of these forcings are not necessary for models without explicit representation of stratospheric chemistry or alternatively, without explicit tropospheric chemistry. The primary focus of the proposed hindcast simulation is the evolution and variability of tropospheric and/or stratospheric ozone over the last 40-50 years. The proposed hindcasts will include a number of new aspects not previously examined in multi-model chemical hindcast simulations, including detailed evaluations of tropospheric oxidants and chemistry, in addition to stratospheric chemistry, interactions between stratospheric and tropospheric chemistry, chemistry-aerosol interactions, the inclusion of very short-lived species, and more generally, the impact of using stratospheric-tropospheric CCMs versus primarily tropospheric or stratospheric CCMs.

REF-C1SD (REF-C1 Specifie Dynamics) is a transient simulation from 1980 to 2010 (there is a discontinuity in meteorological reanalysis datasets near 1979 with the incorporation of satellite data into the reanalysis product, making the use of reanalyses prior to 1980 problematic) that is either nudged towards observed meteorology in a CCM or simulated with a CTM, where the meteorology is prescribed. Otherwise, all forcings are the same as in REF-C1. Compared to REF-C1, this simulation can be more directly compared to observations since there is a more direct correspondence between the simulation period and the observations. This is particularly beneficial since some observational data often only cover short time periods.

It should be noted that the proposed REF-C1 setup is similar to the historical simulation of the CMIP5 protocol (Taylor *et al.*, 2009), but covers a different time period (later starting date but extended to 2010 instead of 2005). Therefore, some of the multi-model analysis could include the historical simulations from the CMIP5 archive that were carried out with an ESM with interactive chemistry.

2.1.1 Chemical fields and emissions in the hindcast simulations

- **Greenhouse Gases** (N_2O, CH_4, and CO_2) between 1950 and 2005 are taken from Meinshausen *et al.* (2011) and continued to 2010 from the RCP 8.5 scenario (Riahi *et al.*, 2011). Values are available at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**. Note that these are the same values that were used for CMIP5.
- **Surface mixing ratios of Ozone Depleting Substances** (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, CCl_4, CH_3CCl_3, HCFC-22, HCFC-141b, HCFC-142b, Halon1211, Halon1202, Halon1301, Halon2402, CH_3Cl, and CH_3Br) are taken from Table 5-A3 of WMO (2011). The WMO mixing ratios provided in Table 5A-3 represent January 1 values, and are closely tied to observations in the years that are shaded, and are based on scenario calculations in future years (additional information on the scenarios can be found in WMO, 2011). For models that do not wish to represent all the brominated and chlorinated species, the halogen content of species that are considered should be adjusted such that model inputs for total chlorine and total bromine match the time series of total chlorine and bromine given in this table at about the year 2000. Missing species can be added to existing model tracers with similar lifetimes to preserve total chlorine or bromine. Table 5-A3 of WMO (2011) is available at **http://ozone.unep.org/Assessment_Panels/SAP/Scientific_Assessm nt_2010/index.shtml**. For convenience, the corresponding excel spread sheet with mixing ratios (ppt) of the ODSs given for every year from 1951 to 2100 is provided on the CCMI website, courtesy of Guus Velders.
- **Very short lived species (VSLS)**. In order for the models to have a realistic stratospheric bromine loading, and thereby be able to reproduce past ozone depletion, they will need to account for the transport of bromine to the stratosphere by VSLS. We recommend that models explicitly include the two major VSLS species $CHBr_3$ and CH_2Br_2. The tracers should decompose directly to inorganic Br_y. Based on past experience we expect that imposing a surface volume mixing ratio of 1.2pptv of each (6pptv bromine) should lead to about the required 4.5–5.0pptv Br_y reaching the stratosphere. For models who do not wish to include these VSLS and model tropospheric loss, the model CH_3Br tracer can be increased by a constant 5pptv.
- **Natural biogenic emissions and lightning NO_x emissions.** These emissions are sensitive to meteorological variability and climate change. It is preferable that models diagnose these emissions online through parameterisations sensitive to changes in meteorology and climate. However, we recognise that not all groups may have the capacity to specify internally interactive emissions.

We recommend that those groups obtain biogenic emissions, preferably consistent with their meteorology, from a group with the capability of diagnosing these emissions online (the PEGASOS project will provide biogenic emissions from 1980 to 2010). Climatological emissions may provide an acceptable solution for those models with an upper tropospheric emphasis. Lightning emissions are more difficult to specify in an externally consistent manner, but are important to upper tropospheric variability and the tropospheric oxidant balance.

- **Anthropogenic and biofuel emissions**. The MACCity emission dataset (Granier *et al.*, 2011) is proposed for anthropogenic and biofuel emissions and covers the full period 1960-2010. Since no global database existed which provided emissions of the main tropospheric gases for each year during the 1960–2010 period, a dataset was created, based on the 1960 and 2000 ACCMIP emissions (Lamarque *et al.*, 2010), and the 2005 and 2010 emissions provided by RCP 8.5. This scenario was chosen since it includes some information on recent emissions at the regional scale in Europe and North America. The emissions for each compound were linearly interpolated for each sector and each year between 2000 and 2005, and for each year between 2005 and 2010, using the ACCMIP and RCP 8.5 emissions. For anthropogenic emissions, a seasonal cycle was first applied sector by sector, species were then lumped to MOZART-4 species (21 species), and finally emissions were interpolated on a yearly basis between the base years (every decade 1960-2010 + 2005). Prior to 2005, the emissions are interpolated from decadal time slices. In 2005 and 2010 the emissions are extrapolated using the RCP 8.5 emissions scenario. The MACCity emission inventory translates from the ACCMIP VOC emissions to those appropriate for the MOZART mechanism. Stevenson *et al.* (2006) recommend using the global speciation given in Prather *et al.* (2001), with species not included either lumped into others or ignored. Regionally, there is likely to be more information for lumping VOCs, but to gather and incorporate this information would need additional work. The simulated VOC emissions, speciation and chemistry (Stevenson *et al.*, 2006) likely lead to important differences in the chemistry and need to be clearly documented in the output. In addition, sensitivity studies will also likely be needed to document the impact of different emission inventories. The MACCity emissions can be downloaded from the Emissions of atmospheric Compounds & Compilation of Ancillary Data (ECCAD) database website at **http://pole-ether.fr/eccad**, after registration as a user.
- **Biomass burning emissions.** Biomass burning emissions are provided for the 1960-2010 period from AEROCOM2, which has been extended to most chemical compounds used in models. This dataset is based on the ACCMIP historical emissions dataset (Lamarque *et al.*, 2010), work done as part of the CityZen European project (**www.cityzen-project.eu**), the GFEDv2 inventory (van der Werf *et al.*, 2006) for 1997-2008, and the RETRO inventory (Schultz *et al.*, 2008) for the 1960-1996 period. All emissions are provided on a monthly-basis at a 0.5°x0.5° resolution. Another set of biomass burning emissions for the 1960-2010 period will be made available to the CCMI modellers for sensitivity studies purposes. This dataset, called PEGAERESS, is based on the LPJ-GUESS surface emissions (Knorr *et al.*, 2012), which uses the dynamical vegetation model LPJ (Smith *et al.*, 2001).
- **Stratospheric boundary conditions for models without interactive stratospheric chemistry.** As recommended for CMIP5 simulations without interactive chemistry, ozone can be prescribed from the AC&C/SPARC ozone database (Cionni *et al.*, 2011). Other stratospheric boundary conditions need to be specified. Monthly-mean zonal-mean fields for CH_2O, CH_4, CO, H_2, H_2O, H_2O_2, HNO_3, HNO_4, HO_2, N_2O, N_2O_5, NO, NO_2, NO_y, and O_3 covering 1960 to 2006 (as available at **https://jshare.johnshopkins.edu/dwaugh1/public_html/ccmval/multi-model/**) have been formed by taking a mean over the CCMVal-2 simulations. All are monthly-mean zonal-means. The mean and standard deviation of the ensemble are both stored as functions of time, pressure level and latitude where time is from 1960.01 to 2006.12, the vertical distribution is given on 31 pressure levels, and the latitudinal grid ranges from -90° to 90° by increments of 2.5°.

2.1.2 Meteorological fields in the hindcast simulations

- **Sea surface temperatures (SSTs) and sea ice concentrations (SICs)** are prescribed as monthly mean boundary conditions following the global sea ice concentration and sea surface temperature (HadISST1) data set provided by the UK Met Office Hadley Centre (Rayner *et al.*, 2003). This data set is based on blended satellite and *in situ* observations and can be downloaded from **http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html**. To prepare the data for use in forcing a model, and in particular to correct for the loss of variance due to time-interpolation of monthly mean data, it is recommended that each group follows the procedures described on the C20C project web site (see **http://grads.iges.org/c20c/c20c_forcing/karling_instruct.html**). This describes how to apply the AMIP II variance correction method (see **http://www-pcmdi.llnl.gov/projects/amip/AMIP2EXPDSN/BCS/amip2bcs.php for details**) to the HadISST1 data.
- **Quasi-Biennial Oscillation**. The QBO is generally described by zonal wind profile measured at the equator. The QBO is an internal mode of variability of the atmosphere that dominates the interannual variability of wind in the tropical stratosphere and contributes to variability in the extra-tropical dynamics. It is recognised that the QBO is important for understanding interannual variability in ozone and other constituents of the middle atmosphere, in the tropics and the extra-tropics. Currently, only a few atmospheric General Circulation Models (GCMs) or CCMs simulate a realistic QBO and hence QBO-related influences. Simulated QBOs are generally independent of observed time series because their phase evolutions are not bound by external boundary conditions. A realistic simulation of the QBO, however, would have similar periods, amplitudes and composite structures as the observations. Assimilation of the QBO, for example, by a relaxation of zonal winds in the QBO domain ("nudging"), may hence be useful for two reasons: first to obtain a QBO in GCMs that do not simulate the QBO internally, so that, for example, QBO effects on the general circulation are present, and second to synchronize the QBO simulated in a CCM with a given QBO time series, so that simulated QBO effects, for example, on ozone, can be compared to observed signals. As for CCMVal-2, a dataset is provided for this purpose, which is based on updated radiosonde measurements following the method of Naujokat (1986) and extended to the upper stratosphere as discussed on the CCMI website.
- **Reanalysis**. The meteorological fields for nudged CCMs and CTMs must come from a continuous reanalysis system (e.g., ERA-Interim (Dee *et al.*, 2011), MERRA (Rienecker *et al.*, 2011), or NCEP (Kanamitsu *et al.*, 2002)). ERA-Interim data are available from **http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_12458543158227759**. The complete MERRA dataset, as processed and re-gridded to 1.9°x2.5° for CESM/MOZART are available on the Earth System Grid (**http://www.earthsystemgrid.org/; search for MERRA**). The atmospheric and surface flux fields from the NCEP/NCAR reanalysis are available from **http://rda.ucar.edu/datasets/ds090.0/#description**. The Reanalysis Intercomparison wiki at **http://reanalyses.org/** provides an overview of current reanalyses.

2.1.3 Solar forcing in the hindcast simulations

- **Solar variability**. The solar radiative forcing data are provided at **http://sparcsolaris.gfz-potsdam.de/input_data.php**. Daily, spectrally-resolved solar irradiance data from the NRLSSI model (Lean *et al.*, 2005), which have been used in previous CCMVal and CMIP5 experiments, are recommended. In addition, the inclusion of atmospheric ionization by solar protons (and related HO_x and NO_x production) are strongly encouraged by using the GOES-based ionization rate data set and a methodology to derive HO_x and NO_x production rates from Jackman *et al.* (2009). Models capable of considering indirect particle effects by the inclusion of an Ap-parameterised auroral source or upper boundary condition are encouraged to do so.

2.1.4 Aerosols and heating rates in the hindcast simulations

- **Aerosol concentrations**. Models that do not simulate tropospheric aerosols interactively might need to specify a time varying aerosol climatology. In particular, a subset of models for CMIP5 have used decadal averages from Lamarque et al. (2010), which are available at

http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download.

- **Surface Area Densities (SADs)**. Monthly, zonal mean time series for SADs (units: $\mu m^2/cm^3$) and (if required) mean radii (r_{mean}, units: μm^2) in conjunction with the radiative parameters of the stratospheric aerosol (extinction coefficient, asymmetry factor, and single scattering albedo, see next bullet point) have been created, covering the full **REF-C1** period 1960-2010. These data sets are internally consistent with each other (which was not the case for CCMVal-2), based on a single lognormal particle size distribution (Arfeuille *et al.*, 2012). The cornerstone for this approach is the four-wavelength SAGE II extinction data, retrieval version V6, which span the period 1985-2005. The 525nm and 1024nm data from SAGE II V6 already featured in the SPARC Assessment of Stratospheric Aerosol Properties (ASAP) report (SPARC, 2006). Uncertainties of the SAGE II dataset are described in detail by Thomason *et al.* (2008). From 1979 to 1985 the data were retrieved from single wavelength extinctions measured by the SAM II and SAGE I satellite instruments (SPARC, 2006), relying on correlations between aerosol properties (SAD, r_{mean}) and the extinctions derived from the SAGE II period. The 1960-1979 pre-satellite period has been constructed from SAGE-II background measurements in the late 1990s, superimposing the volcanic eruptions of Agung and Fuego. These eruptions were calculated by means of the AER 2-D aerosol model (Weisenstein *et al.*, 1997), and the results were scaled by means of stellar and solar extinction data (Stothers, 2001). The 2006-2011 period is derived from CALIPSO 532nm backscatter data, again using correlations between aerosol properties (SAD, r_{mean}) and the CALIPSO backscatter, which were obtained during the SAGE II period. The altitude and latitude range of all derived data (SAD, r_{mean} and radiative parameters) for the entire 1960-2010 period is 5.0–39.5km and 80°S–80°N, respectively. It should be noted that the SAGE II data and hence the ASAP SAD (SPARC, 2006) have data gaps, in particular when the atmosphere became opaque directly after volcanic eruptions, which occurred mainly in lower tropical altitudes (below 16km). Above 26km there are also large data gaps in the mid-to-high latitude regions. Furthermore, there are missing data at all altitudes in the high latitude polar regions. After the eruptions of El Chichón and Pinatubo, the resulting data gaps were filled by means of lidar ground station data and interpolation, as described in SPARC (2006). As for CCMVal-2, for CCMI the remaining data gaps were filled using a linear interpolation approach in altitude and latitude. Large gaps of data above 26km were filled with background values obtained from SAGE II during years without gaps. See next bullet point for a recommendation on how to pass from tropospheric to stratospheric aerosols. SADs and mean radii can be found through a link on the CCMI website.
- **Stratospheric heating rates, aerosol albedo and tropospheric-surface cooling due to volcanic eruptions**. Data sets for the radiative parameters of the stratospheric aerosol (extinction coefficient (km^{-1}), asymmetry factors (–) and single scattering albedos (–) have been created based on a single lognormal particle size distribution in a similar way to the SAD data (Arfeuille *et al.*, 2012). These data cover the full **REF-C1** period 1960-2010. By means of a simple lookup procedure the radiative parameters can be derived for any wavelength band in each of the models participating in CCMI, whose radiation transport modules subsequently calculate stratospheric heating rates and tropospheric cooling. The progress with respect to CCMVal-2 is the internal consistency between the SAD and radiative datasets, and the use of the new SAGE II V6 retrieval. The V6 data are superior to the V5 data used in CCMVal-2, which should no longer be used. The V5 series had major difficulties handling dense volcanic aerosol layers and tended to spread the enhanced extinction several kilometres away from the layer, forcing low values to occur at other altitudes in compensation. During the densest parts of the Pinatubo period, it could significantly affect data as high as 30km. Also, the extrapolation down to the tropopause was done by filling the missing data simply by extending the last reported measurement down to the tropopause, leading regularly to too-high extinctions at the tropopause. The V6 filling is far more robust than that used in the earlier dataset. According to the standard SAGE grid, zonally averaged data will be provided on a grid with 5° latitude (averaged 0-5°, 5-10°, etc.). Altitude resolution will be 0.5km between 5.0-39.5km altitude. Every modeller needs to provide their

own tropospheric aerosols (see aerosol concentrations above). In order to avoid misrepresentations of tropopause altitude, which might lead to too strong heating at the tropopause, models should use their own tropospheric aerosol data set all the way up to (and including) the model's local tropopause, and use the stratospheric SAD and optical parameters only in the first grid cell above the model's local tropopause and higher up. At this altitude models should switch from the tropospheric data set to the stratospheric data set (*i.e.* not as addition). For those models that do not calculate this effect online, pre-calculated zonal mean aerosol heating rates (K/day) and net surface radiative forcing (W/m^2) monthly means from January 1960 to December 2010 for all-sky condition will be made available. The data can be found through a link on the CCMI website.

2.2 Future projections: Reference simulation 2 (REF-C2, 1960 to 2100)

REF-C2 is an internally consistent simulation from the past into the future between 1960 and 2100. This simulation is designed for CCMs. The objective of REF-C2 is to produce best estimates of the future ozone and climate changes up to 2100, under specific assumptions about GHG as well as tropospheric ozone and aerosol precursors that follow RCP 6.0 and a specifie ODS scenario that follows the halogen scenario A1 from WMO (2011). REF-C2 includes solar variability, but possible volcanic eruptions in the future are not considered, as they cannot be known in advance. In contrast to the **REF-C1** simulation, where forcings are as much as possible based on observations until 2010, the emissions in REF-C2 follow those used in CMIP5, *i.e.* Lamarque *et al.* (2010) until 2000 and RCPs from there on (this has to be done in 2000 because that was the reference period for the harmonization of the RCPs with the historical emissions).

2.2.1 Chemical fields and emissions in the future projections

- **Greenhouse gas concentrations** (N_2O, CH_4, and CO_2) are taken from Meinshausen *et al.* (2011), but extended so that they cover annual concentrations and the period from 1950 to 2100 from the RCP 6.0 scenario. Values are available at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**. Note that these are the same values that were used for CMIP5.
- **Surface mixing ratios of Ozone Depleting Substances** are based on the halogen scenario A1 from WMO (2011). The new lifetimes from the SPARC Lifetime Assessment will be released in early 2013. The report will include new lifetime estimates along with uncertainties for those lifetimes. After the release of these new lifetimes, the production of a new scenario A1 will start. In addition to a new A1, a "high" ODS scenario and a "low" ODS scenario based upon the uncertainties of the lifetimes will be produced. Additional sensitivity simulations with the new ODS scenarios might be defined on the CCMI website
- **Very short lived species (VSLS)**. The same methodology as for **REF-C1** is recommended, namely that models that explicitly include the two major VSLS species $CHBr_3$ and CH_2Br_2 should impose a surface volume mixing ratio of 1.2pptv for each, through to 2100. For models who do not wish to include these VSLS and model tropospheric loss, the model CH_3Br tracer can be increased by a constant 5pptv through to 2100.
- **Anthropogenic and biofuel emissions** in **REF-C2** are the same as in **REF-C1** until 2000. After 2000 they follow RCP 6.0, as was done for the CMIP5 and ACCMIP simulations. These emissions can be found at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**.
- **Biomass burning emissions** in **REF-C2** are as in CMIP5, *i.e.* using Lamarque *et al.* (2010) for the 1960-2000 period and RCP 6.0 for 2000-2100. These emissions can be found at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**. Note that the **REF-C1** biomass burning emissions cannot be used because of the potential discontinuity between the AEROCOM2 emissions and RCP 6.0.
- **Stratospheric boundary conditions for models without interactive stratospheric chemistry.** As recommended for CMIP5 simulations without interactive chemistry, ozone can be prescribed from the AC&C/SPARC ozone database (Cionni *et al.*, 2011). Monthly-mean zonal-mean fields for CH_2O, CH_4, CO, H_2, H_2O, H_2O_2, HNO_3, HNO_4, HO_2, N_2O, N_2O_5, NO, NO_2, NO_y, and O_3 for the period 2006-2100 have been formed by taking a mean over the CCMVal-2 simulations (see **https://jshare.johnshopkins.edu/dwaugh1/public_html/**

ccmval/multi-model/ for details and data).

2.2.2 Meteorological fields in th future projections

- **Sea surface temperatures and sea ice concentrations**. Because of potential discontinuities between the observed and modelled data record, the **REF-C2** simulations use simulated SSTs and SICs for the entire period. There are three alternate approaches, depending on the resources of each modelling group.

1. First, groups that have fully coupled atmosphere-ocean models with coupled chemistry and a middle atmosphere should perform a fully coupled run that calculates the SSTs/SICs internally. Due to the inertia of the coupled atmosphere ocean system, such integrations should be started from equilibrated control simulations for preindustrial conditions, as is standard for the 20th century integrations in CMIP5 (*i.e.*, from 1850-2100). Solar forcing according to the CCMI recommendation (see 2.2.3) should be used.
2. Second, groups that have a coupled atmosphere-ocean model that does not include chemistry should use their own modelled SSTs/SICs to prescribe those in the CCM integration for the period 1960-2100. Solar forcing according to the CCMI recommendation (see 2.2.3) should be used.
3. Third, groups that do not have their own coupled ocean-atmosphere model should use SSTs/SICs from an RCP 6.0 CMIP5 simulation. Please make sure that you use the same solar forcing that was used for the CMIP5 simulations so that the SSTs/SICs and the atmosphere use the same solar forcing.

- **Quasi-Biennial Oscillation.** To take the QBO variability into account in future simulations, the data set provided for the **REF-C1** simulation has been extended to 2100. The **REF-C2** QBO data set includes observations from 1953 to 2011 and repeats past cycles in the future. Alternative time series for extensions of the observational dataset after 2011 can be composed individually following the procedure on the CCMI webpage.

2.2.3 Solar forcing in the future projections

- **Solar variability**. For the future solar forcing data, we recommend, as for CCMVal-2, to repeat the last four solar cycles (20-23) **http://sparcsolaris.gfz-potsdam.de/input_data.php**. Since data from 1960-2010 will be used for the **REF-C1** simulations and this passes the last solar cycle minimum in 2008 we will provide a point where the future solar cycles should be used. Note that the repetition of the last four solar cycles is not compliant with the recommendation for CMIP5, where a repetition of solar cycle 23 was recommended but was used only by a small number of modelling groups. Proton forcing and Ap data as described for REF-C1 should be repeated over the last solar cycles in consonance with the solar irradiance data.

2.2.4 Aerosols and heating rates in the future projections

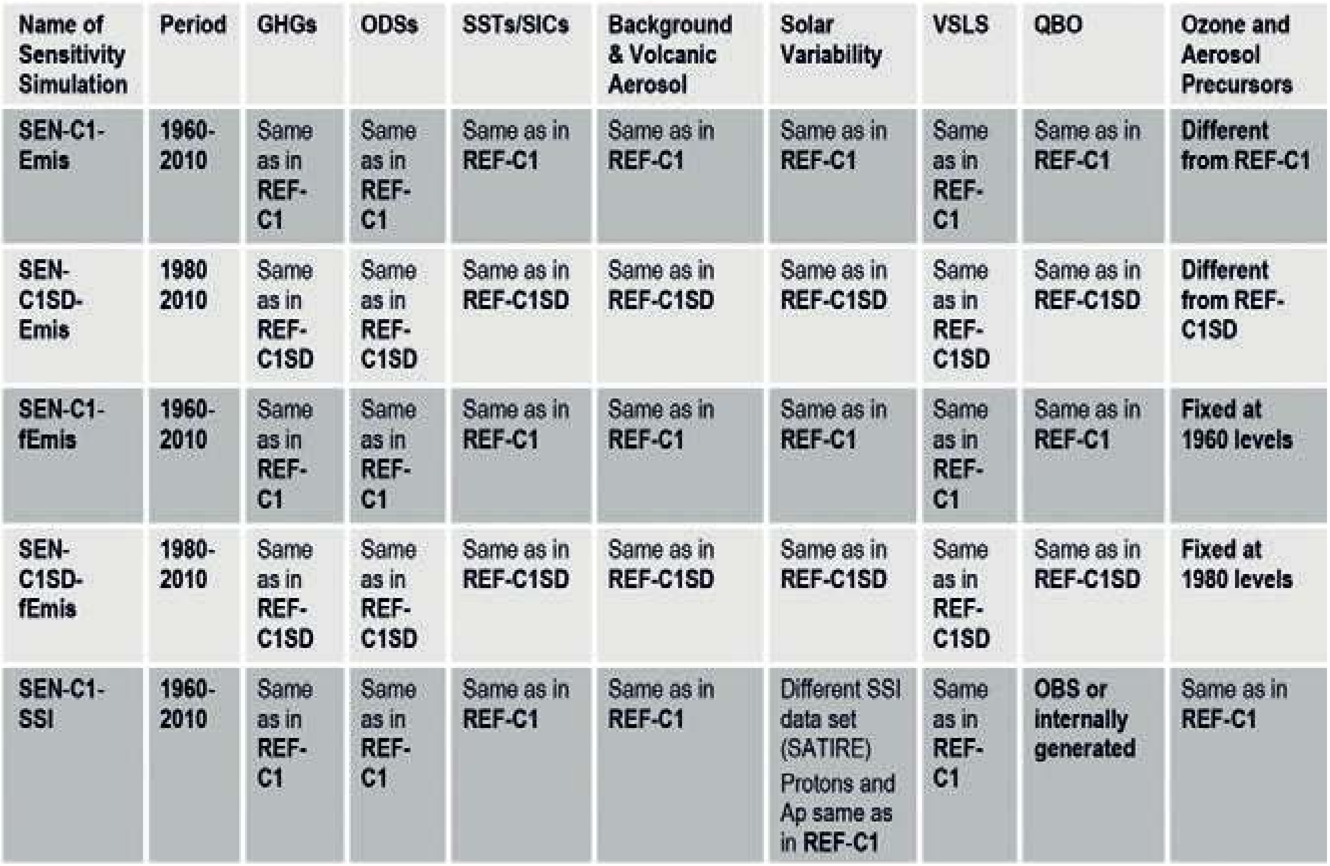
- **Aerosol concentrations**. Models that do not simulate tropospheric aerosols interactively might need to specify a time varying aerosol climatology. In particular, a subset of models for CMIP5 used decadal averages from Lamarque *et al.* (2011) which are available at **http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=download**.
- **Background aerosol**. Surface area densities (and, if required, mean radii) and radiative parameters (extinction coefficients, single scattering albedos and asymmetry factors for each wavelength band of each model participating in CCMI) will be prescribed by a perpetual average of the years 1998-1999 from the **REF-C1** data set, which is characteristic for a volcanically quiescent period. Data will be offered through a link on the CCMI website.
- **Stratospheric warming and tropospheric-surface cooling due to volcanic eruptions** are not specified for the future **REF-C2** simulation.

3. IGAC/SPARC CCMI Sensitivity Simulations

The following IGAC/SPARC CCMI sensitivity simulations are currently proposed and their specification summarized in **Table 3** (past) and **Table 4** (future). Additional sensitivity simulations that might be suggested to answer specific scientifi questions will be defined and documented on the CCMI website. No priority ranking is implied by the following list.

SEN-C1-Emis / SEN-C1SD-Emis is a sensitivity study that involves individual groups specifying their own emission inventory, different to that in **REF-C1** and **REF-C1SD**. Otherwise the specification of forcing is as in REF-C1 or REF-C1SD.

Table 3: Summary of proposed IGAC/SPARC CCMI past sensitivity simulations:



Name of Sensitivity Simulation	Period	GHGs	ODSs	SSTs/SICs	Background & Volcanic Aerosol	Solar Variability	VSLS	QBO	Ozone and Aerosol Precursors
SEN-C1-Emis	1960-2010	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Different from REF-C1
SEN-C1SD-Emis	1980 2010	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Different from REF-C1SD
SEN-C1-fEmis	1960-2010	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Fixed at 1960 levels
SEN-C1SD-fEmis	1980-2010	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Same as in REF-C1SD	Fixed at 1980 levels
SEN-C1-SSI	1960-2010	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Same as in REF-C1	Different SSI data set (SATIRE) Protons and Ap same as in REF-C1	Same as in REF-C1	OBS or internally generated	Same as in REF-C1

This simulation will assess the importance of using different emission inventories in tropospheric chemical variability.

SEN-C1-fEmis / SEN-C1SD-fEmis is a sensitivity study that involves using constant anthropogenic, biofuel, biogenic and biomass burning emissions. Otherwise the specification of forcings is as in **REF-C1** or **REF-C1SD**. This simulation will assess the importance of meteorology in tropospheric chemical variability.

SEN-C1-SSI (1960-2010, REF-C1 with a different SSI forcing data set, *i.e.* SATIRE (Krivova *et al.*, 2006) is designed to address the sensitivity of the atmospheric response to a higher UV forcing than in the standard NRLSSI data set (Lean *et al.*, 2005) used so far for all model experiments within CCMVal and CMIP5. The larger UV forcing has consequences not only for atmospheric heating but also for ozone chemistry. It is therefore important to understand the atmospheric impacts of using different SSI datasets in a consistent and coordinated way in a number of CCMs, as recently highlighted by Ermolli *et al.* (2012).

SEN-C2-RCP (2000-2100, REF-C2 with GHG scenario other than RCP 6.0) is a transient simulation similar to **REF-C2**, but with the GHG and ozone precursor scenario changed from RCP 6.0 to RCP 2.6 (van Vuuren *et al.*, 2011b), RCP 4.5 (Thomson *et al.*, 2011), and/or RCP 8.5 (Riahi *et al.*, 2011). Accordingly, if the model does not include an interactive ocean, SSTs and SICs are prescribed from an AOGCM simulation that is consistent with the GHG scenario. The ODS scenario in all these simulations remains as in REF-C2. The sensitivity of stratospheric ozone has been studied in Eyring *et al.* (2010b), but with a limited number of scenarios performed by only a small number of models. These sensitivity simulations will allow the assessment of the future evolution of ozone and climate change under GHG scenarios other than the RCP 6.0 scenario used in REF-C2.

SEN-C2-fODS (1960-2100, REF-C2 with halogens fixed at 1960 levels) is a transient simulation similar to **REF-C2**, but with halogens fixe at 1960 levels throughout the simulation, whereas GHGs and SSTs/SICs are the same as in REF-C2. It is designed to address the science question of what are the effects of halogens on stratospheric ozone and climate, in the presence of climate change (Eyring *et al.*, 2010a). By comparing **SEN-C2-fODS** with **REF-C2**, the impact of halogens can be identified and it can be assessed at what point in the future the halogen impact is undetectable, *i.e.*, within climate variability. This was the definition of full recovery of stratospher-

Table 4: Summary of proposed IGAC/SPARC CCMI future sensitivity simulations:

Name of Sensitivity Simulation	Period	GHGs	ODSs	SSTs/SICs	Background & Volcanic Aerosol	Solar Variability	VSLS	QBO	Ozone and Aerosol Precursors
SEN-C2-RCP2.6	2000-2100	OBS + RCP 2.6	Same as in REF-C2	SSTs/SICs consistent with RCP 2.6 GHG scenario	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as REF-C1 until 2000 + RCP 2.6 beyond
SEN-C2-RCP4.5	2000-2100	OBS + RCP 4.5	Same as in REF-C2	SSTs/SICs consistent with RCP 4.5 GHG scenario	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as REF-C1 until 2000 + RCP 4.5 beyond
SEN-C2-RCP8.5	2000-2100	OBS + RCP 8.5	Same as in REF-C2	SSTs/SICs consistent with RCP 8.5 GHG scenario	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as REF-C1 until 2000 + RCP 8.5 beyond
SEN-C2-fODS	1960-2100	Same as in REF-C2	Fixed halogens at 1960 level	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-fODS2000	2000-2100	Same as in REF-C2	Fixed halogens at 2000 level	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-fGHG	1960-2100	Fixed GHG at 1960 levels	Same as in REF-C2	1955-1964 average of values used in REF-C2, repeating each year	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-fEmis	1960-2100	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Fixed at 1960 levels
SEN-C2-GeoMIP	2020-various	4xCO_2, 1%/year CO_2 or RCP 4.5	Same as in REF-C2	Modeled or specified SSTs	Specified by GeoMIP experiment	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2
SEN-C2-SolarTrend	1960-2010	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Trend in SSI and Ap, Protons same as in REF-C2	Same as in REF-C2	Same as in REF-C2	Same as in REF-C2

ic ozone from the effects of ODSs that was applied in WMO (2011).

SEN-C2-fODS2000 (2000-2100, REF-C2 with halogens fixed at 2000 levels) is a transient simulation similar to **REF-C2**, but with halogens fixed at 2000 levels throughout the simulation, whereas GHGs and SSTs/SICs are the same as in REF-C2. This simulation is designed to address the climate and composition change due to the implementation of the Montreal Protocol, which caused chlorine and bromine to go into reverse at around the year 2000. This simulation covers 2000 to 2100, and is initialized from REF-C2.

SEN-C2-fGHG (1960-2100, REF-C2 with GHGs fixed at 1960 levels) is a transient simulation similar to **REF-C2**, but with GHGs fixed at 1960 levels throughout the simulation and the adjusted scenario A1 halogens the same as in REF-C2. It is designed to address the science question of how non-linear are the atmospheric responses to ozone depletion/recovery and climate change (Eyring *et al.*, 2010a). To that end, GHGs are fixed at 1960 levels throughout the simulation. SSTs/SICs will be a 1955-1964 average of the values used in REF-C2. By comparing the sum of **SEN-C2-fODS** and **SEN-C2-fGHG** (each relative to the 1960 baseline) with REF-C2, the non-linearity of the responses can be assessed. SEN-C2-fGHG also addresses the policy-relevant (if academic) question of what the impact of halogens on the atmosphere would be in the absence of climate change.

SEN-C2-fEmis (1960-2100, REF-C2 with emissions fixed at 1960 levels) is designed to address the impact of climate change (Stevenson *et al.*, 2006).

SEN-C2-GeoMIP is a set of transient simulations to test the climate system response to solar radiation management with stratospheric aerosols, as part of GeoMIP. Kravitz *et al.* (2011) describe four sets of standardized experiments using solar constant reduction or stratospheric aerosol clouds to either balance anthropogenic radiative forcing or reduce it quickly. Many of these runs have been completed and are now being analysed, but there are still many interesting questions that can be addressed by CCMs. The G1 and G2 experiments involve reducing the total solar irradiance to balance either an instantaneous quadrupling of CO_2 or a 1%/year increase of CO_2, and would be most appropriate for models with interactive oceans. G3 and G4 involve balancing an RCP 4.5 forcing with sulphate aerosols in the stratosphere or a continuous 5Tg/year stratospheric sulphate injection, and all CCMs could simulate the stratospheric chemical and dynamical responses, in addition to other climate changes. Models without oceans will need to have SSTs provided from other GCM runs. SADs and net radiative flux changes will be needed for models that do not create their own stratospheric aerosols and the radiative response from SO_2 or sulphate injections. See **http://climate.envsci.rutgers.edu/GeoMIP/** for more details on GeoMIP.

SEN-C2-SolarTrend (1960-2100, REF-C2 but with a trend in future solar cycle) aims at looking at the effects of a possible new grand minimum in solar activity. Predictions of the solar cycle are extremely difficult and uncertain, but it is known that the sun will move out of its grand maximum, which peaked in the mid-20th century. There is a lot of ongoing research looking into whether or not the sun will move into a new Maunder Minimum-like period, and whether and how this might counteract the recent global warming. To avoid speculation and put research on firm ground, a simulation with a future trend in the solar cycle amplitude will be prescribed and the atmospheric response will be investigated. This future trend will be based on past cycles that will be repeated in reversed order (cycles 20, 18, 17, 16, 15, 14, 13, 12). A detailed description and the data set will be provided on the SOLARIS website at **http://sparcsolaris.gfz-potsdam.de/input_data.php**.

4 Model output, online diagnostics, and comparison with observations

4.1 Requested output and format

Output from this new set of CCMI simulations will be collected in Climate and Forecast (CF) standard compliant netCDF format from all models, and held in the central CCMI database at the British Atmospheric Data Centre (BADC). The use of CMOR is strongly encouraged. We will provide CMOR tables for all requested output and will make them available on the CCMI website. CMOR-compliant data will be published through the Earth System Grid Federation (ESGF) system.

Output requests will broadly follow the requests made by the ACCMIP and CCMVal activities, with some additional output for new suggestions for process-oriented model evaluation and improved comparison with observations. These additional specific diagnostics are discussed in Section 4.2. It is recommended that model groups provide these data to the extent possible. CMOR tables for these additional diagnostics will also be provided on the CCMI website.

4.2 Additional transport and composition diagnostics

Diagnostics not yet available from the previous ACCMIP and CCMVal activities include synthetic tracers (Section 4.2.1), diagnostics for tropospheric ozone and HO_x budgets (Section 4.2.2 and 4.2.3, respectively), and output of some high-frequency model data for tropospheric OH (Section 4.2.4).

4.2.1 Synthetic tracers

Following discussions at the Davos workshop, modellers are encouraged to include the following synthetic tracers:

1. NH_5: Fixed surface layer mixing ratio over 30°-50°N (100ppbv), uniform fixed 5-day exponential decay (e-folding time $\tau=4.32x10^5$s).
2. NH_50: Fixed surface layer mixing ratio over 30°-50°N

(100ppbv), uniform fixed 50-day exponential decay.

3. NH_50W: Fixed surface layer mixing ratio over 30°-50°N (100ppbv), uniform fixed 50-day exponential decay, wet removal as HNO_3.
4. AOA_NH: Fixed surface layer mixing ratio over 30°-50°N (0ppbv), uniform fixed source (at all levels) everywhere else (source is unspecified but must be constant in space and time and documented). Note that the source could be 1yr/yr, so the tracer concentration provides mean age in years.
5. ST80_25: Fixed mixing ratio above 80hPa (200ppbv), uniform fixed 25-day exponential decay in the troposphere only.
6. CO_25: emitted as anthropogenic CO (emission file available from HTAP, **ftp://ftp.retro.enes.org/pub/emissions/aggregated/anthro/0.5x0.5/2000/RETRO_ANTHRO_V2_2000_CO_aggregated.nc** but only use annual mean), uniform fixed 25-day exponential decay.
7. CO_50: emitted as anthropogenic CO (emission files available from HTAP), 50-day exponential decay.
8. SO2t: emitted as anthropogenic year 2000 SO_2 (as specified in **REF-C1**), wet removal as SO_2.
9. O3S: stratospheric ozone tracer set to ozone in the stratosphere, then destroyed in the troposphere using the ozone chemical loss rate.
10. SF6: specified using emissions from **http://edgar.jrc.ec.europa.eu/datasets_grid_list.php#d**. Note that these emissions are available only as annual averages (1970-2008; emissions before 1970 should be set to 0 while emissions after 2008 should be kept at their 2008 level). Monthly emissions should be built using the available annual file and assigning the value as representative of July 15. Special care should be made that the annual global integral at the model resolution matches the EDGAR generated total (available as argument from the netCDF v42 files)
11. AOA: Stratospheric mean age-of-air. Use existing implementation or implement the same as AOA_NH (item #4) except fixed surface layer mixing ratio is set to 0ppbv over the surface of the whole globe.

The "NH" tracers (NH_5, NH_50, NH_50W, and AOA_NH) are used for defining the transport times and time since air has encountered the surface layer over the latitude band 30°-50°N. From AOA_NH, NH_5 and NH_50 we will be able to estimate the transit time distribution. The NH_50W tracer will, in comparison to NH_50, provide information on the relative role of wet deposition in transport from the northern mid-latitudes. By referencing the age at the tropical tropopause, AOA_NH can also be used for stratospheric age-of-air diagnostics. The tracer ST80_25 is used for diagnosing stratosphere-troposphere exchange. The tracers CO_25, CO_50, and SO2t can be used as surrogates for surface pollution and $PM_{2.5}$, therefore allowing for the diagnosis of the importance of changes in circulation on surface pollutant concentration. In addition, the inclusion of the stratospheric ozone tracer (O3S), SF6 (specifie from observations as a concentration in the surface layer) and mean age-of-air (AOA) tracers are recommended. The SF6 and AOA tracers can be compared with observations. For the analysis, only monthly output for each tracer is requested. Specific models with the capacity for daily output for surface layer mixing ratio CO_25, CO_50, and SO2t are encouraged to generate them to the extent possible.

4.2.2 Tropospheric ozone budget

In order to accurately document the tropospheric ozone budget, we recommend saving the monthly average output of the following fiv fields (see CMOR Tables for additional information):

1. Net chemical tendency dO_3/dt (production *minus* loss, excluding deposition)
2. Production: **only** provide the sum of all the HO_2/RO_2 + NO reactions (as $k*[HO_2]*[NO]$)
3. Loss: **only** provide the sum of the following reactions
   (i) O(1D) + H_2O
   (ii) $O_3 + HO_2$
   (iii) O_3 + OH
   (iv) O_3 + alkenes (isoprene, ethene,…)
4. Dry deposition flux: **only** of O_3
5. Tropopause pressure

At the minimum the net chemical tendency, tropopause pressure and deposition fields should be provided.

4.2.3 Tropospheric HO_x budget

Similarly, specific output for the study of tropospheric OH is recommended as monthly averaged file for the following fields

1. $J(NO_2)$
2. $J(O^1D)$
3. 3D lightning NO production
4. Rate of $(O^1D)+H_2O$ (three-dimensional distribution of $k*[O^1D]*[H_2O]$)
5. Total loss of OH (rate of OH loss from all reactions)
6. Rate of CO+OH and CH_4+OH
7. Production rate of H_2O_2
8. Production rate of HNO_3

9. Production rate of all hydrogen peroxides (*e.g.*, CH_3OOH)
10. Aerosol reactions rates as separate diagnostics (as an example, the MOZART reactions are listed)
    - N_2O_5 -> 2 * HNO_3
    - NO_3 -> HNO_3
    - NO_2 -> 0.5*OH + 0.5*NO + 0.5*HNO_3
    - HO_2 -> 0.5*H_2O_2
11. Reaction rate of SO_2 + OH

In addition, it would be very useful if modellers could provide the additional rates (to further diagnose the fate of hydrogen peroxides) as monthly averages:

1. RO_2+NO
2. RO_2+NO_3
3. RO_2+HO_2
4. RO_2+RO_2
5. RC(O)O_2+NO_2

where R refers to the organic peroxy radical pool.

4.2.4 High-frequency output for tropospheric OH

The following targeted, high-frequency output for evaluating tropospheric OH and related species should be generated if possible:

REF-C1SD: hourly (instantaneous) output for July 1st 2004 (to "coincide" with INTEX-A)
REF-C2: hourly (instantaneous) output for July 1st every decade (1960-2100)

These are therefore 24 time samples of 3D instantaneous fields for one model day for **REF-C1SD** and for every 10 years **for REF-C2**.

- Requested fields: Temperature and either pressure or density
- Chemical species (if applicable):
  – OH, HO_2, NO, NO_2, HNO_3, PAN, H_2O, CH_4, CO, O_3, $O(^3P)$, $O(^1D)$, CH_3, CH_3O_2, CH_3OOH, CH_3O, CH_2O, CHO, H, $(CH_3)_2CO$, CH_3OOH, H_2O_2 & full suite of biogenic & anthropogenic VOCs
  – or- all chemical species (if more convenient)
- Photolysis rates:
  – $J(O_3)$ >> $O(^1D)$, $J(O_3)$ >> $O(^3P)$, $J(NO_2)$, cloud and aerosol optical depth, surface albedo
  – or- all J values (if more convenient).

4.3 Model output for comparison with satellite observations

There is now a wealth of satellite data with which to evaluate processes and trace gas distributions within models. Each of these datasets has its own strengths and limitations, and often provides complementary information to other datasets.

A proper comparison between satellite observations and models requires sampling the model output at the times and locations of the measurements and interpolating the model data to the observed vertical levels. Comparisons to satellite data should, in addition, consider *a priori* profiles and averaging kernels from the retrievals when sampling model output, for example, to calculate tropospheric columns for trace gas species. During the last few years, several satellite simulators have been developed, which either involve online calculations or post-processing to provide model output more directly comparable to remote sensing observations from satellites. Some models now have the capability to sample model output along sun-synchronous satellite orbits (see for example the SORBIT routine in Jöckel *et al.*, 2010). To facilitate and encourage a proper comparison with satellite data, we therefore provide local times and measured species for some remote sensing products that could potentially be used for evaluating trace gases, see **Tables S1**, **S2**, and **S3**[2].

Evaluation of the CCMI simulations will benefit from the Obs4MIPs effort (**http://obs4mips.llnl.gov:8080/wiki**), a pilot activity to make observational products more accessible for climate model intercomparisons, such as CMIP5. Obs4MIPs was initiated by NASA and the Program for Climate Model Diagnosis and Intercomparison (PCMDI; **http://www-pcmdi.llnl.gov/**). Participants of the IGAC/SPARC CCMI are encouraged to use and contribute satellite datasets to the Obs4MIPs database, adhering to the prescribed requirements (**http://obs4mips.llnl.gov:8080/wiki/requirements**). Interested parties should contact the Obs4MIPs team at **obs4mips@lists.llnl.gov**.

The focus of the initial data sets listed in Table S1 is to constrain the magnitude and distribution of those species that are radiatively important in the troposphere or important for controlling tropospheric ozone and OH. Table S1 lists some potential data sets. Methane, ozone, aerosols and water vapour are directly radiatively important. The other factors in Table S1 control the distributions of ozone and OH, such as meteorological variables (*e.g.*, cloud albedo), solar irradiance variables (*e.g.*, ozone column) and chemical variables (*e.g.*, CO, methane, NO*x*, ozone, water vapour). For example, ESMs typically have high biases for water vapour in the mid- and upper troposphere as compared to AIRS data, which can translate into high

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[2] Find Tables S1, S2 and S3 in the Supplementary Material uploaded to **http://www.sparc-climate.org/publications/newsletter/**.

biases of model OH. In addition to evaluating the distributions of trace gases, these data sets can be used to assess the response of model processes to perturbations (*e.g.*, the response of ozone to ENSO).

In addition, we ask for output of cloud properties (cloud fraction and cloud liquid water content), temperature, H_2O, NO_2, CH_2O, SO_2, CO, NH_3 and O_3 at **two local times** (10:00am and 2:00pm). From these local time values, a monthly-average composite can be generated to limit output requirements while still being useful (Aghedo *et al.*, 2011). In the case of **REF-C1SD**, daily output for 2006 is, however, requested to fully document the importance of sub-sampling.

The SPARC Data Initiative offers an archive (soon accessible via the SPARC Data Center website) with vertically-resolved, monthly, zonal mean time series of stratospheric trace gas climatologies obtained from current and past limb-viewing satellite instruments (Table S3). The climatologies are provided on a latitude-pressure grid using the CCMVal pressure levels (300, 250, 200, 170, 150, 130, 115, 100, 90, 80, 70, 50, 30, 20, 15, 10, 7, 5, 3, 2, 1.5, 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1hPa) and a horizontal binning of 5°, with latitude bins centred at -87.5°, -82.5°, -77.5°,…,87.5°. For longer-lived species (*e.g.*, O_3, N_2O, H_2O, CH_4, CFCs, CO, HF, SF_6), the climatologies can be directly compared to zonal mean model output. For the shorter-lived species, however, model output should be sampled in the same way as the satellite data (*e.g.*, with the help of a satellite simulator) in order to avoid zonal mean differences due to inhomogeneous sampling or diurnal variations. Alternatively, if sampling the model output along the exact sampling pattern cannot be carried out, the zonal mean model output should be based on data sampled at the specific local solar time (LST) of the satellite measurement of each latitude bin. In addition, model profiles output at the observational tangent points (see Table S2) are very important, in particular for the profile-by-profil evaluation of species with large diurnal variation. Detailed sampling patterns and simplified sampling instructions based on LST-latitude relations will be provided by the SPARC Data Center. We specifically ask for the following targeted output from the **REF-C1SD** simulations using the detailed or simplified sampling patterns in order to evaluate the representation of the diurnal cycles of different species and polar stratospheric chemistry (see *e.g.,* Santee *et al.*, 2008):

- O_3, NO_2, NO_x, HNO_3, N_2O_5, $ClONO_2$, and HCl according to the ACE-FTS sampling pattern between 1 July 2004 and 31 June 2006.
- O_3, HNO_3, ClO, HOCl, $ClONO_2$, NO_2, N_2O_5 according to the MIPAS sampling pattern between 1 February 2005 and 31 June 2006.
- O_3, N_2O, HNO_3, HCl, ClO, HOCl according to the Aura-MLS sampling pattern between 1 July 2004 and 31 June 2006.
- O_3, HNO_3, HCl, ClO, HOCl, BrO according to the SMILES sampling pattern between 1 October 2009 and 31 March 2010.
- BrO, NO_2 according to the OSIRIS sampling pattern between 1 July 2004 and 31 June 2006.

4.4 Model output for comparison with aircraft observations

In addition to observations that monitor climate on a global scale, process study observations are made, which are usually more localised and cover limited time periods. Regional field experiments provide the basis for much understanding about key processes in the atmosphere. Examples include field projects such as the SCOUT-O3 Darwin Aircraft Campaign; the African Monsoon Multidisciplinary Analyses (AMMA) experiment; the Tropical Convection, Cirrus and Nitrogen Oxides Experiment (TROCCINOX) aircraft campaign; the HIAPER Pole-to-Pole Observations (HIPPO) of the carbon cycle and greenhouse gases; and the Transport and composition in the UTLS (TACTS) / Earth System Model Validation (ESMVal) campaign carried out with the High Altitude and Long-Range Research Aircraft (HALO).

Comparisons to more local measurements made, for example, during *in situ* aircraft campaigns exhibit the problem of a mismatch of spatial and temporal scales between observations and models. CCMs and ESMs usually run at horizontal resolutions of a few hundred kilometres, whereas field experiments sample local air masses. Similar to sampling model output along sun-synchronous satellite orbits, some models now have the capability to interpolate the model data to the flight path during the model simulation (see for example the S4D routine in Jöckel *et al.,* (2010)). This comparison is very useful, in particular for the **REF-C1SD** simulation, which has specified dynamics matching the meteorological situation of particular years and thus allows a more direct comparison. To facilitate this comparison, we provide the flight paths of several aircraft campaigns on the CCMI website in NASA AMES or ICARTT format. We refer to the CCMI website for updates on this list (follow the link 'Observations for model evaluation').

For the free-running **REF-C1** simulations where the meteorological situation and atmospheric dynamics do not match those observed in a particular year, a comparison to observations is thus only meaningful if longer time records are considered. A possibility to compare with *in situ* data is to combine different campaigns into one database with a horizontal grid comparable to that used in ESMs (Emmons *et al.*, 2000). However, it has to be kept in mind that since aircraft campaigns are often targeted at specific events they do not necessarily provide a good representation of the mean climate or composition.

A CCMI expert team, which was established as part of the Davos workshop, will further work on this topic and will particularly address the following tasks:

- Identify a methodology to meaningfully evaluate CCM simulations against *in situ* observations via analyses that bridge the disparate temporal and spatial scales.
- Following the successful CCMVal exercise, carry out observation-model comparisons by improving access to vetted *in situ* data sets to facilitate the evaluation of models.
- Identify diagnostics suitable for a climatology and provide this climatology (update of Emmons *et al.*, 2000).

Updates from the expert group will be reported on the CCMI Website.

4.5 Model output for comparison with ground measurements

A document describing the availability of ground-based measurements and suggestions for comparisons to ground-based data is available from the CCMI website (follow the link 'Observations for model evaluation'). These comparisons are, in general, possible with the standard monthly output generated using CMOR tables (see Section 4.1).

5. Timeline IGAC / SPARC Chemistry-Climate Model Initiative

A key aspect of this document is to detail a long-term strategic plan for simulations that can meet the complex needs of simulating chemistry-climate interactions, while also seeking to prioritize simulations for near-term (next 3 year) needs. The result is that the CCMI simulations are envisaged to occur in two main phases over the next few years. The timeline is summarized in **Figure 28**.

Near-term efforts in **CCMI Phase 1 (CCMI-1)** focus on hindcast simulations and on simulations in support of the 2014 WMO/UNEP Scientifi Assessment of Ozone Depletion with currently existing models. A comprehensive set of hindcasts and future projections will be repeated in **CCMI Phase 2 (CCMI-2)**, with improved models that are also likely to be more complex and run at higher resolutions than at present. The long-term target of the IGAC/SPARC CCMI initiative is 2017/2018, when chemistry-climate could be addressed in a much more comprehensive way than now, *e.g.* with interactive stratospheric chemistry, aerosols, tropospheric chemistry, biosphere and an ocean. It could be envisaged that the simulations of Phase 2 be part of the sixth phase of CMIP (CMIP6), thus bridging the gap with the climate community at that stage. CCMI Phase 2 simulations are to be delivered only in several years time and are therefore not defined in this document

CCMI PHASE 1 (CCMI-1, near-term, ~next 3 years):
The focus of CCMI PHASE 1 is on hindcast simulations and simulations in support of the 2014 WMO/UNEP Scientific Assessment of Ozone Depletion. The new community-wide hindcast simulations are **REF-C1** and **REF-C1SD**, which are also used in several projects currently underway and thus fulfil multiple purposes. It also includes **REF-C2**, which will be run in support of the 2014 WMO/UNEP Scientific Assessment of Ozone Depletion, and possibly additional sensitivity simulations, with results that can also be taken from existing similar simulations performed for CMIP5 and the SPARC lifetimes assessment.

The timeline for the 2014 Ozone Assessment is predicated on several specific milestones: The co-chairs will start working on a draft outline in fall 2012, and an author team will be assembled in spring 2013. The 1st draft will have to be complete around November 2013, the 2nd draft around February 2014, and the 3rd draft in May 2014. The chapters would be finalized by July-August 2014. Therefore, results from the simulations would be required by around mid- or early autumn 2013.

CCMI PHASE 2 (CCMI-2, long-term, until ~2017/2018):
One of the overall recommendations of the SPARC-CCMVal (2010) report was that the CCMVal assessment and projection process should be synchronized with that of CMIP to make the most of human and computer resources, and to allow time for model improvements. Assuming that there will be another IPCC and WMO/UNEP assessment, they would be much better in phase than today and would present an opportunity to define chemistry-climate simulations as part of the CMIP6 protocol. Hence, as a community, 2017/2018 could be considered as a major target where things could come together in a much more comprehensive way: strato-

spheric change, aerosols, tropospheric chemistry, biosphere, and ocean. There is thus a long-term vision for the IGAC/SPARC CCMI that will need to be more thoroughly define in future.

6. Summary and Outlook

CCM groups are encouraged to run the proposed CCMI-1 reference simulations with the specified forcings. In order to facilitate the set-up of the reference simulations, the forcings and other data sets have been made available on the CCMI website (**http://www.pa.op.dlr.de/CCMI/**) and through the specific links given in this document. The CCMI website has been created to report on ongoing CCMI activities and to serve the needs of the CCM and CTM community. The forcings are made available to encourage consistency of anthropogenic and natural forcings in future model/model and model/observation intercomparisons. Any updates as well as detailed explanation and further discussion will be placed on the CCMI website. In addition to the reference runs, the groups are encouraged to run as many CCMI-1 sensitivity simulations as possible. The hope is that these additional runs will be available in time to provide useful input for the anticipated 2014 WMO/UNEP Ozone Assessment, so that the ozone projections from the CCMs can be assessed for different GHG scenarios and the fixe ODS simulation. A community-wide workshop will be held from 13-17 May 2013 in Boulder (USA), where initial results from the CCMI-1 simulations will be discussed.

The data will be collected in CF compliant netCDF format at BADC. For the collection of the data, a data policy similar to those used in previous CCMVal and ACCMIP intercomparisons will apply. It is expected that the groups submitting model output to BADC, as well as the wider community who will be working with these data, will disseminate the results of this effort through a series of publications.

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