# Chapter 1

# Introduction

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## 1.1 Rationale

The stratospheric ozone layer has been depleted by anthropogenic emissions of halogenated species over the last decades of the 20th century until present. Observations show that tropospheric halogen loading is now decreasing (Montzka *et al*., 2003; WMO, 2007), which reflects the controls on production of ozone-depleting substances (ODSs) by the Montreal Protocol and its Amendments and Adjustments. Ozone is expected to continue to respond to these changes in ODSs but the timing and sensitivity of the response will depend on other changes in the atmosphere. Atmospheric concentrations of greenhouse gases (GHGs) have also increased, and are expected to increase further in the future (IPCC, 2000), with consequences for the ozone layer. As a result of climate change, it is unlikely that the ozone layer will return to precisely its unperturbed state even if the abundance of halogens returns to background levels. Furthermore, climate change complicates the attribution of ozone recovery to the decline of halogenated species.

To predict the future evolution of stratospheric ozone and attribute its behaviour to the different forcings, models are required that can adequately represent both the chemistry of the ozone layer and the dynamics and energetics of the atmosphere, as well as their natural variability. The coupling of stratospheric chemical models with climate models has led to a new generation of models far more complex than those available when the Montreal Protocol was agreed in 1987. Such models, known as coupled Chemistry-Climate Models (CCMs), are three-dimensional atmospheric circulation models with fully coupled chemistry, *i.e.*, where chemical reactions drive changes in at-

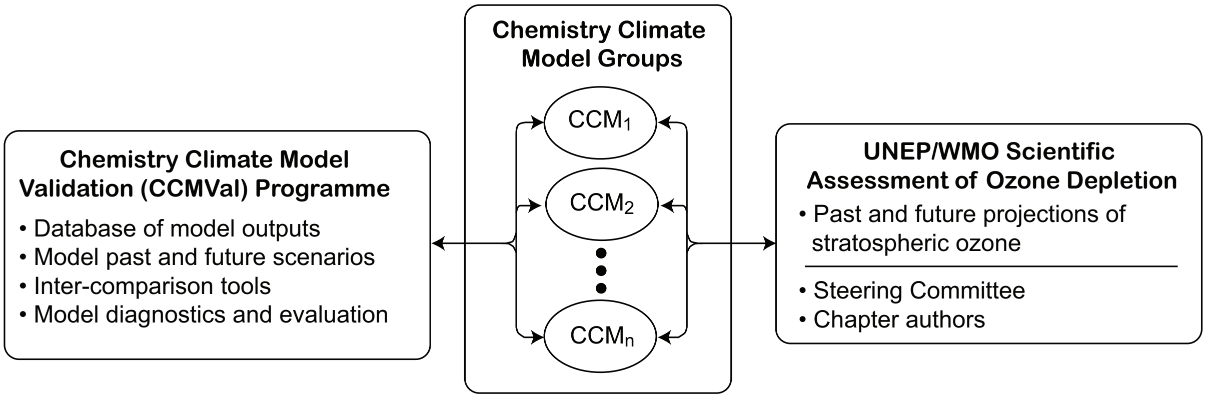

**Figure 1.1:** Model of the relationships between CCMVal, the CCM groups, and the WMO/UNEP Assessment. From Eyring et al. (2008).

mospheric composition which in turn change the atmospheric radiative balance and hence dynamics. Sea surface temperatures (SSTs) and sea ice distributions in CCMs are either prescribed or calculated internally if the model is interactively coupled to an ocean. CCMs are key tools for the attribution and projection of the response of stratospheric ozone to ODSs and other factors, and allow questions about future stratospheric ozone and UV radiation levels to be studied in a more comprehensive manner than could be done when the Montreal Protocol was signed. In particular, by including a representation of tropospheric climate change, they make it possible to address the coupling between climate change and ozone depletion/recovery in a comprehensive manner. However, the workings of these CCMs themselves are also much harder to fully understand, and it is therefore necessary to quantitatively assess the confidence that can be placed in their projections.

In the past there has been insufficient time to evaluate CCM performance thoroughly while preparing international ozone and climate assessments. The Chemistry-Climate Model Validation (CCMVal) Activity for WCRP's SPARC project is producing this Report on the evaluation of CCMs so that it provides useful and timely information for the 2010 WMO/UNEP Scientific Assessment of Ozone Depletion, and the IPCC 5th Assessment Report (AR5). The Report is a response to the need to quantitatively assess the confidence that can be placed in the CCMs by a comprehensive evaluation of the ability of CCMs to represent key processes for stratospheric ozone and its impact on climate. Compared to the WMO/UNEP ozone and IPCC climate assessments, the SPARC CCMVal report allows the inclusion of a lot more detail and provides a coherent, integrated assessment of the CCMs based on the CCMVal concept (Eyring *et al.*, 2005, see also Section 1.2). The two-way communication linking the CCM groups with CCMVal and the WMO/UNEP Ozone Assessment is illustrated in **Figure 1.1**. CCMVal acts as a resource for the modelling groups and for the Ozone Assessment by developing and maintaining evaluation tools for the models, maintaining definitions and boundary condition data for "scenario" experiments, and archiving output data from the models. The CCM groups interact with CCMVal in defining and applying the evaluation tools, using the boundary condition data, and providing model output. It is anticipated that the Ozone Assessment will make use of CCMVal resources by working with the CCM groups to help in defining relevant model scenarios, using the CCMVal data archive at the British Atmospheric Data Centre (BADC) and applying the tools and metrics derived by CCMVal in their evaluation of model results. In addition, the Assessment authors may solicit data from other model groups and, if they wish, may apply CCMVal diagnostic tools to evaluate these model results. The coordination, support, and products that SPARC CCMVal provides for the CCM community represent an important additional resource for the Assessment process.

This Report provides an up-to-date process-oriented evaluation of the ability of CCMs to represent the stratospheric ozone layer, stratospheric climate and climate variability, and the coupled ozone-climate response to natural and anthropogenic forcings. This comprehensive evaluation improves our understanding of the strengths and weaknesses of CCMs and thus increases their integrity and credibility. The evaluation of the CCMs is also used to guide the assessment of the projections of changes in ozone in the 21st century and their impact on tropospheric climate. This Report builds on previous assessments of the family of stratospheric CCMs and their General Circulation Models (GCMs) much of which have been organised under the auspices of the SPARC GCM-Reality Intercomparison Project (GRIPS) and CCMVal activities (Pawson *et al.*, 2000; Eyring *et al.*, 2005) and have contributed directly to the evaluation of CCMs during the preparation of the WMO/UNEP Scientific Assessments of Ozone Depletion (Austin *et al.*, 2003; Eyring *et al.*, 2006, 2007).

The strategy of setting up benchmarks and criteria for a process-oriented model evaluation presented in this Report could also be beneficial for the assessment of other components of the Earth system and the development of Earth System Models that integrate our knowledge regarding the atmosphere, ocean, cryosphere and land surfaces, and account for the coupling between physical and biogeochemical processes. Developing the science of quantitative performance metrics is an emerging focus within the WCRP and will be an emphasis of the IPCC AR5.

## 1.2 CCMVal concept for model evaluation and analysis

The goal of the SPARC CCMVal activity is to improve understanding of CCMs through process-oriented evaluation and to provide reliable projections of stratospheric ozone and its impact on climate. The model evaluation is based on a set of core processes relevant for stratospheric ozone centred around four main categories (radiation, dynamics, transport, and stratospheric chemistry and microphysics), with each process associated with one or more model diagnostics and with relevant data sets that can be used for the evaluation (Eyring *et al*., 2005, see **Figure 1.2**). The four ingredients are fundamentally interdependent and interactive and require as inputs, knowledge of human activities and natural processes. These inputs help quantitatively define processes in the atmosphere and expectations for future changes. Trends in atmospheric constituents and parameters associated with climate forcing are examples of important inputs. The CCM output includes a wide array of parameters and diagnostics associated with the four different aspects. The distribution of stratospheric ozone is highlighted separately here because of the strong contemporary interest in halogen-based ozone depletion and the recovery of the ozone loss that has developed over recent decades. The comparisons of model diagnostics and other outputs with atmospheric observations and meteorological analyses are the key to process-oriented CCM evaluation. Finally, the results of the comparisons can be used to provide feedback to the representation of processes in CCMs in order to improve the models. In this way, the uncertainties in future changes in stratospheric ozone and other key model outputs can be reduced, and errors better quantified.

To eliminate many of the uncertainties in the conclusions of earlier multi-CCM evaluations (*e.g*., Austin *et al*., 2003) that resulted from differences in anthropogenic and natural forcings as well as from the experimental set-up of individual models, CCMVal has defined reference simulations for the past and for the future. The simulations used

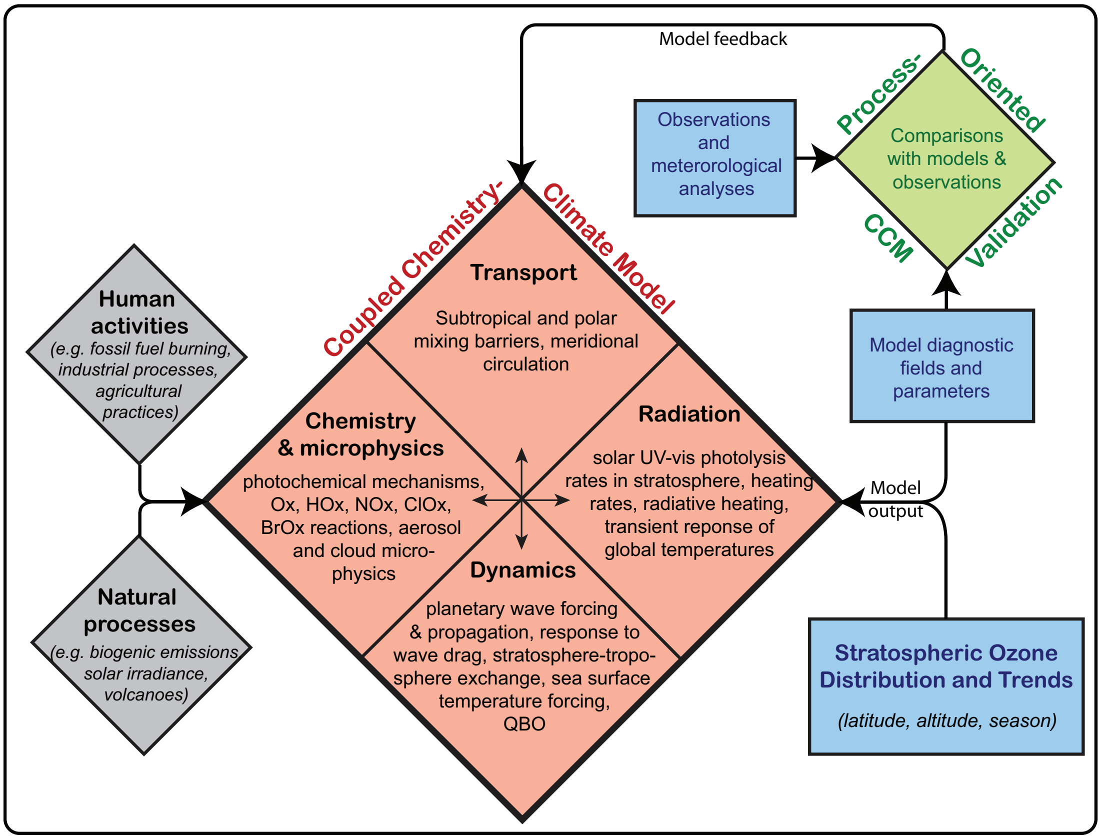

**Figure 1.2:** Schematic diagram of the CCMVal evaluation approach. The centre-piece is a CCM comprised of four basic ingredients: transport, dynamics, radiation, and stratospheric chemistry and microphysics. From Eyring et al. (2005), Figure 2.

**Table 1.1:** CCMs used in the SPARC CCMVal Report. The models are listed alphabetically by name.

| CCM name | Institution(s) | Investigator(s) | References |
|---|---|---|---|
| AMTRAC3 | GFDL, US | John Austin | *Austin and Wilson (2009)* |
| CAM3.5 | NCAR, US | Jean-François Lamarque | *Lamarque et al. (2008)* |
| CCSRNIES | NIES, JP | Hideharu Akiyoshi, Yousuke Yamashita, Tetsu Nakamura | *Akiyoshi et al. (2009)* |
| CMAM | Univ. of Toronto/ CCCma, CA | David Plummer, John Scinocca, Ted Shepherd | *Scinocca et al. (2008); de Grandpré et al. (2000)* |
| CNRM-ACM (ARPEGE-Climat 4.6 Coupled MOCAGE-Climat) | CNRM/GAME, Météo-France/CNRS, FR | Martine Michou, Hubert Teyssèdre, Dirk Olivié | *Déqué (2007); Teyssèdre et al. (2007)* |
| E39CA | DLR, DE | Martin Dameris, Hella Garny | *Stenke et al. (2009); Garny et al. (2009)* |
| EMAC (version 1.6) | MPI-C, DE | Andreas Baumgärtner, Christoph Brühl, Patrick Jöckel | *Jöckel et al. (2006)* |
| GEOSCCM (version 2) | NASA/GSFC, US | Steven Pawson, Rich Stolarski | *Pawson et al. (2008)* |
| LMDZrepro | CNRS, FR | Slimane Bekki, Marion Marchand | *Jourdain et al. (2008)* |
| MRI (v. MJ98) | MRI, JP | Kiyotaka Shibata | *Shibata and Deushi (2008a, b)* |
| NiwaSOCOL | NIWA, NZ | Dan Smale, Olaf Morgenstern | *Schraner et al. (2008); Egorova et al. (2005)* |
| SOCOL (version 2) | PMOD/WRC, CH<br>IAC, ETH Zürich, CH | Eugene Rozanov, Tom Peter | *Schraner et al. (2008)* |
| ULAQ | Univ. L'Aquila, IT | Eva Mancini, Giovanni Pitari | *Pitari et al. (2002); Eyring et al. (2006, 2007)* |
| UMETRAC | NIWA, NZ | Olaf Morgenstern | *Austin and Butchart (2003)* |
| UMSLIMCAT | Univ. Leeds, UK | Martyn Chipperfield, Sandip Dhomse, Wenshou Tian | *Tian and Chipperfield (2005); Tian et al. (2006)* |
| UMUKCA-METO | Met Office, UK | Steven Hardiman, Neal Butchart | *Morgenstern et al. (2008, 2009)* |
| UMUKCA-UCAM | Univ. Cambridge, UK | Peter Braesicke, Olaf Morgenstern, John Pyle | *Morgenstern et al. (2008, 2009)* |
| WACCM (version 3.5.48) | NCAR, US | Doug Kinnison, Andrew Gettelman, Rolando Garcia | *None yet. Based on WACCM 3.1.9 (Garcia et al., 2007)* |

in the first round of CCMVal (CCMVal-1) were used in the 2006 WMO/UNEP Scientific Assessment of Ozone Depletion (Chapter 6 of WMO, 2007). This Report, which describes the second round of CCMVal (CCMVal-2), defines new reference simulations (see Chapter 2) in support of the 2010 Assessment and evaluates the performance of the eighteen participating CCMs (see **Table 1.1**).

The role of observations in model evaluation is crucial since both the opportunities and the limitations in the available data need to be well known. A large number of observations from a variety of different platforms and instruments are used in this Report to assess the CCMs. These are summarized in **Table 1.2**, with further details given within individual chapters.

## 1.3 Quantitative performance metrics

A key aspect of the model evaluation within this Report is the application of observationally-based performance metrics to quantify the ability of models to reproduce key processes for stratospheric ozone. Quantitative performance metrics have been applied to evaluate the CCMVal-1 models (Waugh and Eyring, 2008), and have also been used for the evaluation of three-dimensional chemical transport models (*e.g.*, Douglass *et al.*, 1999; Brunner *et al.*, 2003; Strahan and Douglass, 2004) and coupled atmosphere-ocean models (*e.g.*, Schmittner *et al.*, 2005; Connolley and Bracegirdle, 2007; Reichler and Kim, 2008; Gleckler *et al.*, 2008; Santer *et al.*, 2009). In contrast to most of the previous studies, the focus in this Report is, as in Waugh and Eyring (2008), on evaluating the key processes rather than the quantity of interest itself, which in this Report is stratospheric ozone. This follows the CCMVal philosophy described in Eyring *et al.* (2005), and is done partly to more accurately identify the sources of model errors, and partly to circumvent the case where an ozone metric may look good because of compensating errors in the underlying processes.

Applying quantitative performance metrics to a range of observationally-based diagnostics provides several benefits for model evaluation, including

- Easy recognition of the models' performance for multiple aspects of the simulations;
- Identification of missing or incompletely modelled processes (in the case of systematic biases in the models); and
- Quantitative assessment of model improvements, both for different versions of individual CCMs and for different generations of community-wide collections of models (*e.g.*, CCMVal-1 and CCMVal-2).

However, the application of performance metrics is still an active research topic and involves many subjective decisions, which means that caution is required with the interpretation of metrics. Important issues include the choice of diagnostics, the relative importance of different processes/diagnostics, the choice of the metric, uncertainties in observations, and the statistical limitations of the metrics.

Several different metrics have been used in previous evaluations of atmospheric models. Waugh and Eyring (2008) used the simple metric

$$g = 1 - \frac{1}{n_g} \frac{|\mu_{\text{mod}} - \mu_{\text{obs}}|}{\sigma} \qquad (1.1)$$

where $\mu_{mod}$ is the model climatological mean, $\mu_{obs}$ is the observed climatological mean, $\sigma$ is a measure of the uncertainty (see discussion below), and $n_g$ is a scaling factor (typically 3). Other previously applied climatological mean state metrics include the squared difference between model and observed climatological mean values divided by the observed variance (Reichler and Kim, 2008) and the root mean squared difference between the model and observed climatological mean values (Gleckler *et al.*, 2008). Santer *et al.* (2009) applied metrics for the seasonal cycle, the variability amplitude and the variability pattern to climate models in addition to the climatological mean and combined them into three overall ranking metrics.

This Report makes use of a variety of metrics: The metric *g* used by Waugh and Eyring (2008) is applied in Chapters 4, 5, 6, and 7. In Chapter 7 similar metrics to the mean metric *g* are additionally applied to gauge the performance of the models to simulated correlated variability and variance. Chapter 6 also applies a slightly modified version of *g* which considers the models' interannual variability in addition to the uncertainty in the observations in $\sigma$ of Equation 1.1. In the extra-tropics, evaluation of Chapter 7 as well as in Chapters 8 and 10 the statistical summary of how well two patterns from a test field (*f*) and a reference field (*r*) match each other in terms of their correlation (*R*), their root-mean-square difference (*E'*), and the ratio of their variances ($\sigma_f$ / $\sigma_r$) are visualised with the help of "Taylor diagrams" (Taylor, 2001) and the correctness of phase and amplitude of the seasonal cycles quantified with the help of skill factors.

A major issue with the application and interpretation of metrics is the robustness of the scores obtained from the metrics. Grewe and Sausen (2009) have recently highlighted the statistical limitations in the metric *g* used by Waugh and Eyring (2008), and these limitations need to be considered when interpreting quantitative measures of performance ("grades") derived from this and other metrics. Observational uncertainties (*e.g.,* $\sigma$ in Equation 1.1) can influence the outcome of model-data consistency tests (see, *e.g.*, Santer *et al.*, 2003), especially if there are biases in observational data sets. Wherever possible, the possibility of biases in this Report is assessed by using observations from several sources, *e.g.*, from different satellite instruments and platforms.

A possible application of metrics is to form a single model score that can be used to assign relative weights to the ozone projections from each CCM. This was explored by Waugh and Eyring (2008) for different combinations of weights for the diagnostics and metrics applied to the CCMVal-1 simulations. For the limited set of diagnostics that was used in this study there were generally only small differences between weighted and unweighted multi-model mean and variances of total ozone projections, suggesting that the multi-model mean was a robust quantity in CCMVal-1 simulations. However, there are many issues with weighting projections, including the choice and relative importance of diagnostics when forming a single score (Gleckler *et al.,* 2008). Because of this, aggregated model scores are not produced in this Report nor are the performance metrics used to weight ozone projections. However, the metrics are used to provide overall qualitative assessments of model performance and to help interpret model results that are outliers in the ozone projections. Furthermore, the robustness of the multi-model mean ozone projections and uncertainty is tested by taking out these outliers in the projections (see Chapter 9).

**Table 1.2:** Overview of observations used in this report for the evaluation of CCMs.

| Species | Diagnostic (Chapter) | Instrument | Time Period | Reference |
|---|---|---|---|---|
| ***Satellite Data*** | | | | |
| $O_3$ columns | Mean, variability and trends (8,9), Multiple linear regression analyses (MLR) analysis (8) | Merged satellite data | 1970-2007 | *Stolarski and Frith (2006)* |
| | | NIWA | 1978-2007 | *Hassler et al. (2008)* |
| | | SAGE | 1978-2007 | *updated from Miller et al. (2002); Randel and Wu (2007)* |
| | | TOMS | 1980-2008 | *Stolarski and Frith (2006)* |
| $O_3$ profiles and 3D fields | Mean, annual cycle,and trends (7,8), Meridional tracer gradients @200 hPa (7), PDFs of $O_3$ variability (7), seasonal cycles (7,8), ExTL depth and width (7), MLR analysis (8), stratospheric ozone fluxes (10) | UARS HALOE | 1991-2002 | *Russell et al. (1993); Grooß and Russell (2005)* |
| | | MLS | 2004-2008 | *Livesey et al. (2008)* |
| | | NIWA-3D | 1980-1999 | *Hassler et al. (2008)* |
| | | SAGE | 1979-2005 | *Randel and Wu (2007)* |
| | | MIPAS | 2004-2008 | *von Clarmann et al. (2009)* |
| | | Ozone climatology | 1991-2002 | *McPeters et al. (2007)* |
| $H_4$, $H_2O$, CO, $O_3$, HCl, $ClONO_2$, $HNO_3$, $N_2O_5$, $NO_2$, BrO | Mean evolution (6) | ENVISAT-MIPAS, Oxford L2 | 2002-2009 | *Fischer et al. (2008)* |
| | | ENVISAT-SCIAMACHY | 2002-2009 | *Rozanov et al. (2005)* |
| | | ACE-FTS | 2003-2009 | *Bernath et al. (2005)* |
| | | ODIN | 2001-2009 | *Murtagh et al. (2002)* |
| $H_2O$ | Dehydration in SH Polar region (6) | Aura-MLS v2.2 | 2004-2009 | *Lambert et al. (2007)* |
| | Seasonal cycles@ 80, 100, 200 hPa (7), Vertical profiles in TP coordinates (7), ExTL depth and width (7), H2O tape recorder (5) | UARS HALOE | 1991-2002 | *Russell et al. (1993); Grooß and Russell (2005)* |
| | | MIPAS | 2004-2008 | *von Clarmann et al. (2009)* |
| | | ACE-FTS | 2004-2007 | *Hegglin et al. (2008)* |
| $CH_4$ | Tropical gradient (5) | UARS HALOE | 1991-2002 | *Russell et al. (1993); Grooß and Russell (2005)* |
| $N_2O$ | Tropical gradient (5), annual cycle (5) | ENVISAT-MIPAS | 2002-2004 | *Glatthor et al. (2005)* |
| | | Aura MLS | 2004-2008 | *Lambert et al. (2007)* |
| HCl | Mean evolution in SH Polar region – surrogate for chlorine activation (6) | Aura-MLS v2.2 | 2004-2009 | *Froidevaux et al. (2008)* |
| CO | Vertical profiles in TP coordinates (7) | ACE-FTS | 2007 | *Hegglin et al. (2008)* |
| $Cl_y$ | Time series (5) | Multiple Instruments (*e.g.*, HALOE HCl, Aura MLS) | 1991-2006 | *Lary et al. (2007) and references therein* |
| $HNO_3$ | De-nitrification in SH Polar region (6) | Aura-MLS, v2.2 | 2004-2009 | *Santee et al. (2007)* |

Table 1.2 continued.

| Species | Diagnostic (Chapter) | Instrument | Time Period | Reference |
|---|---|---|---|---|
| | Seasonal cycles@ 80, 100, and 200 hPa (7) | MIPAS | 2004-2008 | *von Clarmann et al. (2009)* |
| Temperature | TP inversion layer (7), global mean climatology and trends (3) | COSMIC GPS | 2006-2008 | *Anthes et al. (2008)* |
| | | MSU/SSU | 1980-1999 | *Randel et al. (2009)* |
| Sulfate Aerosol Surface Area | Sulfate SAD (6) | Based on SAGE and SAGE II | 1979-2004 | *Thomason et al. (1997)* |
| $O_3$, HCl | Chemical ozone loss (6) | Based on HALOE | 1991-2004 | *Russell et al. (1993); Tilmes et al. (2006)* |
| ***Meteorological Reanalyses*** | | | | |
| Temperature | Mean and trends (3, 4, 7, 10), MLR analysis (8), PSC threshold temperatures (4) | ERA-40 | 1979-1999 | *Uppala et al. (2005)* |
| | | NCEP | 1980-1999 | *Kalnay et al. (1996)* |
| | | ERA-Interim | 1989-1999 | *Uppala et al. (2008)* |
| | | UKMO | 1992-2002 | *Swinbank and O'Neill (1994)* |
| | | NCEP2 | 1980-1999 | *Kanamitsu et al. (2002)* |
| | | JRA25 | 1980-1999 | *Onogi et al. (2007)* |
| Zonal wind | Mean, variability and long-term trends, zonal mean (4, 7,10), vertical profile of the amplitude of the QBO (4), stratospheric sudden warmings (4) | ERA-40 | 1979-1999 | *SPARC (2003)* |
| | | NCEP | 1980-1999 | *SPARC (2003)* |
| *T, u, v* | Potential for Activation of Chlorine (PACl). Also for the Derivation of Eqlat-$\Theta$ (6) | UKMO | 1991-2005 | *Swinbank and O'Neill (1994)* |
| | | ERA-40 | 1958-1999 | *Uppala et al. (2005)* |
| Geopotential height | Annular Modes (10), Annular Mode relationship to column ozone (8) | ERA-40 | 1980-1999 | *Uppala et al. (2005)* |
| | | NCEP | 1980-1999 | *Kalnay et al. (1996)* |
| Heat flux | Heat flux relationship with temperature (4) and ozone (8) | ERA-40 | 1980-1999 | *Uppala et al. (2005)* |
| | | NCEP | 1980-1999 | *Kalnay et al. (1996)* |
| | | ERA-Interim | 1991-2002 | *Uppala et al. (2008)* |
| Residual vertical velocity | Brewer-Dobson circulation and tropical upwelling (4) | UKMO | 1992-2001 | *Swinbank and O'Neill (1994)* |
| | Stratospheric ozone fluxes (10) | ERA-Interim | 1991-2002 | *Uppala et al. (2008), Wohltmann and Rex (2008)* |
| ***Ground-based Data*** | | | | |
| $O_3$ columns | Averaged over a latitude band, annual and monthly means (6) | Ground-based measurements | 1964-2007 | *updated from Fioletov et al. (2002)* |
| | Total Ozone at Halley (10) | Dobson spectrometer | 1969-1998 | *Jones and Shanklin (1995)* |
| $NO_2$, $ClONO_2$, HCl | Mean evolution and variability (6) | NDACC | 1990-2008 | *Rinsland et al. (2003)* |

Table 1.2 continued.

| Species | Diagnostic (Chapter) | Instrument | Time Period | Reference |
|---|---|---|---|---|
| ***Balloon Flights*** | | | | |
| $CO_2$ and $SF_6$ | Mean Age (5) | Various balloon missions | 1986-2005 | *Andrews et al. (2001); Engel et al. (2009)* |
| $N_2O$, $H_2O$, $CH_4$, $NO_y$, and pressure | $N_2O$ profile and tracer-tracer correlations (6) | Mk IV FTIR | Sept. 1993 | *Sen et al. (1998); Osterman et al. (1997)* |
| $O_3$, $N_2O$ | Chemical ozone loss (6) | FOZAN-II, HAGAR | 2005 | *von Hobe et. al. (2006)* |
| $HO_x$, $NO_x$, ClO, and BrO | Fast chemistry (6) | MkIV, SLS, FIRS-2, and SAOZ | Sept 1993; April and May 1997; Nov 1997 | *Osterman et al. (1997); Jucks et al. (1998); Pundt et al. (2002); Salawitch et al. (2002, 2005)* |
| Geopotential height, *T* | Antarctic trends (10) | Radiosondes | 1969-1998 | *Thompson and Solomon (2002)* |
| ***Aircraft Data*** | | | | |
| CO | Vertical profiles in TP coordinates (7) | SPURT | 2001-2003 | *Hoor et al. (2004)* |
| $H_2O$ | Vertical profiles in TP coordinates (7) | Climatology | 1995-2005 | *Tilmes et al. (2010)* |
| $O_3$ | Vertical profiles in TP coordinates (7), ExTL depth and width (7) | Climatology | 1995-2005 | *Tilmes et al. (2010)* |
| | | POLARIS | 1997 | *Pan et al. (2007)* |
| CFC-11, CFC-12, $CO_2$, and $SF_6$ | Fractional Release of $Cl_y$ (5) | NASA ER-2 aircraft missions | 2000 | *Schauffler et al. (2003); Douglass et al. (2008)* |
| FCs and related species, Halons, $CH_3Br$, and $N_2O$ | $Cl_y$ vs $N_2O$ and $Br_y$ vs $N_2O$ (6) | WAS, ACATS, and ATLAS | Repeated sampling from 1992 to 2008 | *Woodbridge et al. (1995); Wamsley et al. (1998)* |
| $HO_x$, $NO_x$, ClO, and BrO | Fast chemistry (6) | Harvard $HO_x$ and ClO/BrO instruments; NOAA $NO_x$ instrument | May 1993; Nov 1995; Feb 1996 | *Wennberg et al. (1994, 1999); Salawitch et al. (1994, 2005); Wamsley et al. (1998)* |
| $N_2O$, $O_3$, $H_2O$, $CH_4$, pressure | $N_2O$ profile and tracer-tracer correlations (6) | ATLAS, NOAA $O_3$, NOAA Lyman-Alpha Hygrometer, ACATS | Feb 1996 | *Lanzendorf et al. (2001); Weinstock et al. (2001); Dessler (2002)* |

## 1.4 Progress beyond the state-of-the-art

This Report describes the second round of CCMVal (CCMVal-2), which presents several advances beyond CCMVal-1. First, the number of participating CCMs has increased from thirteen to eighteen (see Table 1.1). Second, whereas the evaluation in CCMVal-1 focused mainly on diagnostics to evaluate transport and dynamics in the CCMs, a much broader and detailed evaluation, including an assessment of chemical and radiative processes and the UTLS, has been performed in CCMVal-2. Finally, new reference simulations for the future have been performed that cover the entire period from 1960 to 2010.

The CCMVal-2 simulations are used here to answer key scientific issues, including some arising from the 2006 WMO/UNEP Ozone Assessment (Shepherd and Randel, 2007). In particular, the material in this Report aims to provide:

- ***Improved understanding of process-oriented diagnostics and model evaluation.*** A wider suite of process-oriented diagnostics is developed compared to that in CCMVal-1, and attempts are made to assess model skill through quantitative performance metrics. This contributes to the growing field of research in this area. The strengths and weaknesses, as well as benefits, of different approaches are analysed.
- ***A better understanding of the causes of changes in observed past ozone and related variables.*** CCMVal-2 contains improved versions of some of the models that participated in CCMVal-1, and also new CCMs. Together with a more detailed analysis of simulations of past changes in ozone and related variables, and an earlier starting point as compared with CCMVal-1, this allows a more thorough attribution of observed changes and a better understanding of the role of natural variability.
- ***A reassessment of the projections of ozone and UV radiation though the 21st century.*** In CCMVal-1 most projections only started in 1980 or later (several began only in 1995), and only three CCMs ran beyond 2050. In contrast, in CCMVal-2 the simulations begin in 1960, and most future simulations continue to 2100. The earlier starting date allows a more accurate determination of the milestone when total ozone returns to pre-1980 levels, while the extended simulations allow multi-model ozone projections and an analysis of the causes of ozone changes throughout the 21st century. In addition, improved statistical analysis allows a quantification of uncertainties in the projections.
- ***A more detailed understanding of the impact of stratospheric changes on climate.*** The Report contains a chapter that focuses on the effects of the stratosphere on climate. This includes the radiative forcing and UV changes from ozone changes, tropospheric effects of polar ozone depletion, and changes in the flux of ozone to the troposphere over long time scales (past and future).

## 1.5 Report Structure

This SPARC CCMVal report consists of three main parts.

**Part A** (Chapter 2) describes the CCMs and simulations to be examined in the Report. It discusses the basic ingredients in the CCMs, in terms of theoretical fundamentals, and their key approximations and uncertainties, as well as providing detailed documentation of the participating CCMs. Chapter 2 also describes the forcing scenarios (*e.g.*, ODSs, GHGs, SSTs, volcanic aerosols, and solar) used for the CCMVal-2 runs that are analysed, and any deviations thereof for particular models assessed in this report. Since the report shows CCMVal-1 model projections in addition to the new CCMVal-2 simulations in Chapter 9, model improvements for individual CCMs that participated in both rounds are also documented here.

**Part B** (Chapters 3 to 7) evaluates the CCMs' ability to simulate core processes structured around the four categories that are displayed in Figure 1.1 plus the UTLS which is discussed separately here. All key processes in these five categories are evaluated with diagnostics and with relevant data sets, and a quantitative model assessment is made based on performance metrics that confront models with observations. Each chapter discusses the processes that contribute most to uncertainty in current coupled chemistry-climate modelling, future challenges for model developments, and measurement requirements needed to better constrain the models. The key findings per model are also summarized in each chapter, providing a qualitative synthesis of the quantitative assessment. The chapters in Part B also include analysis of long-term changes in the key processes over the past and future (*e.g.*, changes in the Brewer-Dobson circulation, PSC frequency, stratospheric sudden warmings, water vapour budget in the UTLS). This approach provides a coherent framework for the evaluation of CCMs and is used as a basis for the assessment in Part C.

**Part C** (Chapters 8 to 10) examines the coupled ozone-climate response to natural and anthropogenic forcing. Chapter 8 examines the natural variability in the CCMs, and evaluates how well CCMs represent the effects of various sources of coherent forced and unforced natural variability (seasonal cycle, quasi-biennial oscillation (QBO), volcanic, solar, El Niño Southern Oscillation (ENSO)) on stratospheric ozone. Chapter 9 examines long-term projections of stratospheric ozone from the CCMs, focusing on the simulated long-term changes in ozone and the causes of these changes (*i.e.*, their relation to changes in chemistry, dynamics, radiation, transport and UTLS discussed in Part B). Chapter 10 examines the effect of stratospheric changes on the troposphere, and includes analysis of the radiative forcing from ozone changes, tropospheric effects of polar ozone depletion, and changes in the flux of ozone to the troposphere over long time scales.

The key conclusions of the report are summarized in the Executive Summary. It is divided into overall key findings, overall recommendations, and key findings per chapter. The **overall key findings** include a synthesis of the results presented in the individual chapters to provide a coherent assessment of the current generation of CCMs based on the CCMVal concept, including a summary of the results presented in Part C. The **overall recommendations** identify the processes that contribute most to uncertainty in current coupled chemistry-climate modelling, summarize future challenges for model development, and advocate best practices in CCM modelling and model evaluation. Key observations and key gaps needed for model evaluation are also identified.

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