Executive Summary

Preface

Three-dimensional climate models with a fully interactive representation of stratospheric ozone chemistry — otherwise known as stratosphere-resolving chemistry-climate models (CCMs) — are key tools for the attribution and prediction of stratospheric ozone changes arising from the combined effects of changes in the amounts of greenhouse gases (GHG) and ozone-depleting substances (ODS). These models can also be used to infer potential effects of stratospheric changes on the climate of the troposphere. In order to know how much confidence can be placed in the results from the CCMs, both individually and collectively, it is necessary to assess their performance by comparison with observations and known physical constraints.

The Stratospheric Processes And their Role in Climate (SPARC) core project of the World Climate Research Programme (WCRP) initiated the CCM Validation (CCMVal) activity in 2003 to coordinate exactly such an evaluation. The CCMVal concept (see Chapter 1) takes as a starting point the premise that model performance is most accurately assessed by examining the representation of key processes, rather than just the model's ability to reproduce long-term ozone trends, as the latter can be more easily tuned and can include compensating errors. Thus a premium is placed on high-quality observations that can be used to assess the representation of key processes in the models. This Report does not provide a detailed assessment of the quality of the observational databases; the compilation and assessment of data sets suitable for model evaluation is the focus of a future SPARC activity, which has been motivated by this Report.

The first round of CCMVal (CCMVal-1) evaluated only a limited set of key processes in the CCMs, focusing mainly on dynamics and transport. This Report, which describes the second round of CCMVal (CCMVal-2), represents a more complete effort by CCMVal to assess CCM performance. As with CCMVal-1, it also includes an assessment of the extent to which CCMs are able to reproduce past observations in the stratosphere, and the future evolution of stratospheric ozone and climate under one particular scenario. 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 and its impact on climate. The Report is targeted at a variety of users, including: (1) international climate science assessments, including the WMO/UNEP Ozone Assessments and the IPCC Assessment Reports; (2) the CCM groups themselves; (3) users of CCM simulations; (4) measurement and process scientists who wish to help improve CCM evaluation; (5) space agencies and other bodies involved in the Global Climate Observing System.

The Report was prepared by dozens of scientists and underwent several revisions and extensive peer review, culminating in a Final Review Meeting in Toledo, Spain on November 9-11, 2009. This Executive Summary outlines the overall key findings, overall recommendations, and detailed key findings and recommendations by chapter.

Overall Key Findings

- Comprehensive process-oriented validation has led to a much better understanding of the strengths and weaknesses of CCMs. As well as identifying unphysical behaviour (*e.g.*, dehydration properties), this has led to a more precise understanding of the processes involved in CCM simulations and the connections between them. This can be used to understand some of the spread in model predictions, and will help focus model improvements.
- CCMVal-2 has provided a much more detailed assessment of model performance than CCMVal-1. For the first time, chemical and radiative processes in the CCMs have been assessed, and the upper troposphere / lower stratosphere (UTLS) has been explicitly examined. Radiation schemes have been found to be sufficient for representing the major causes of observed temperature changes in the stratosphere and the main radiative drivers of surface climate. Chemistry schemes are generally found to agree with benchmark schemes, while exceptions have been identified. Model performance in the UTLS was found to be better than might have been expected based on the spatial resolution of the models.
- The identification of model deficiencies in CCMVal-1 led to quantifiable improvements in particular models (*e.g.*, transport, Cl_y abundance, tropical tropopause temperatures). CCMVal-2 has benefited from the greater number of participating models and the larger number of processes represented in those models. However, this complicates a quantitative assessment of overall model improvement between CCMVal-1 and CCMVal-2 in those diagnostics assessed by CCMVal-1.
- Compared with WRCP Coupled Model Intercomparison Project phase 3 (CMIP3) simulations, CCMVal-2 simulations have a mean stratospheric climate and variability that is much closer to that observed. In the troposphere, mean climate and synoptic variability are similarly close to the observations in both groups of simulations, while interannual variability tends to be better simulated by the CCMVal models.
- Common systematic errors in CCM results include: tropical lower stratospheric temperature, water vapour, and transport; response to volcanic eruptions; details of the Antarctic polar vortex and the ozone hole; lower stratospheric Cl_y; a wide variation in values of surface area density of sulphate aerosols.
- Another systematic error in CCMs concerns the representation of the quasi-biennial oscillation (QBO), which is a dominant mode of natural stratospheric variability. Most of the current models do not simulate a QBO, and the representation of the QBO in models remains a challenge. For comparison with past observations, some modelling groups therefore choose to relax tropical winds towards observed values. This technique is fully successful in reproducing the phase of the observed QBO signal in ozone, but not its amplitude.
- Models that represent solar variability only in terms of total solar irradiance cannot properly simulate the effect of solar variability on radiative heating rates, stratospheric temperature and ozone. A spectrally resolved treatment of solar variability is required.
- Use of simulations extending through the entire period of ozone depletion and recovery (1960-2100) in CCMVal-2 has allowed a more accurate estimate of the projected long-term changes in the stratosphere and the relative contributions of ODSs and GHGs to those changes, compared with CCMVal-1. This, plus the increased number of contributing models, has reduced the statistical uncertainty in the projected future ozone changes under the scenario considered.
- The multi-model trend estimates of past ozone changes are consistent with the observed changes. Compared with CCMVal-1, the availability of model simulations from 1960 onwards together with a more robust statistical analysis has provided a more reliable estimate of the long-term ozone changes in the models.
- Widespread use of simulations beginning in 1960 has revealed that models consistently show substantial ODS-induced ozone depletion prior to 1980, especially in the SH.
- Models consistently predict an increase in tropical tropopause height and a slight warming of the tropical tropopause due to climate change. As a result, the entry value of stratospheric water vapour is predicted to increase in the future, although the magnitude of this increase is uncertain.

- Models consistently predict a strengthening of the Brewer-Dobson circulation and a decrease in mean age of air as a result of climate change, but they disagree on the relative role of resolved and parameterised wave drag.
- Models consistently predict the following changes in ozone:
  - a partial recovery of tropical ozone followed by a decrease in the second half of the 21st century, such that tropical column ozone is predicted not even to return to 1980s values within this century; the long-term decrease is mainly found in the lower stratosphere
  - a steady increase in NH mid-latitude and polar ozone, such that 1980s values are exceeded well before halogens return to 1980s values
  - a slow recovery of SH mid-latitude and polar ozone, with mid-latitude ozone returning to 1980 values slightly before halogens do, and polar ozone returning roughly in line with halogens
  - major contributors to these changes include the recovery of ozone from ODS, the strengthened Brewer-Dobson circulation, and the cooling of the upper stratosphere.
- Although Antarctic ozone is expected to recover during the 21st century, a residual intermittent ozone hole may still occur at the end of the century.
- Both models and observations indicate that Antarctic stratospheric ozone loss, together with increasing GHG concentrations, has led to a poleward shift and strengthening of the SH westerly tropospheric jet during summer. CCMVal-2 models project that in the 21st century ozone recovery will largely offset the effects of increasing GHG concentrations, so that the position of the tropospheric jet will not change significantly.
- The strengthened Brewer-Dobson circulation leads to an increased stratospheric ozone flux into the NH troposphere of ~20% between 1965 and 2095. In the SH, the change is modulated by ozone depletion and recovery, and is smaller (~10%) due to the smaller predicted change in the Brewer-Dobson circulation in that hemisphere. The model range is smaller than that obtained from tropospheric models used for the IPCC assessment, which may be attributable to a more self-consistent and comprehensive representation of the stratosphere in the CCMs.
- Stratosphere-resolving CCMs continue to evolve towards more comprehensive, self-consistent stratosphere-troposphere CCMs. In this round of CCMVal, one model was coupled to an interactive ocean, while three models included comprehensive tropospheric chemistry. These developments provide a pathway for including a better representation of stratosphere-troposphere and chemistry-climate coupling in Earth System models used for ozone and climate assessments.

Overall Recommendations

- CCM simulations of ozone depletion/recovery should be performed seamlessly over the entire 1960-2100 period, with consistent forcings, and with data produced in a standard format to allow for multi-model inter-comparison.
- A range of different scenarios should be simulated (*e.g.*, fixed GHG, fixed ODS, different GHG projections) to allow correct attribution of the predicted changes and an understanding of the sensitivity to the scenario employed.
- Models should routinely undergo tests concerning their implementation of physical processes where benchmark comparisons are available. This is especially the case for chemistry and radiation (*e.g.*, line-by-line comparisons, PhotoComp). In the case of radiation, such comparison is facilitated if the CCM radiation codes can be run in a stand-alone offline form.
- Metrics of model performance on a wide suite of diagnostics need to be made as standard practice and calculated routinely by individual model groups and through multi-model comparisons. More analysis is needed of the robustness of the application and interpretation of metrics, and their possible use to assign relative weights to ozone projections.
- More attention needs to be paid to model development to address major persistent deficiencies, *e.g.*, the

late-spring breakdown of the Antarctic vortex, and simulations of the Antarctic ozone hole.

- Long-term vertically resolved data sets of constituent observations in the stratosphere are required to assess model behaviour and test model predictions. This includes ozone, but also other species that can be used to diagnose transport and chemistry. The current set of GCOS Essential Climate Variables is not sufficient for process-oriented validation of CCMs.
- More global vertically resolved observations are required, particularly in the UTLS. As CCMs evolve towards including tropospheric chemistry, lack of observations in this region will become a major limitation on model validation.
- A systematic comparison of existing observations is required in order to underpin future model evaluation efforts, by providing a more accurate assessment of measurement uncertainties.
- CCMs should use self-consistent formulations with the appropriate conservation properties (*e.g.*, primitive-equations dynamics, self-consistent treatment of chemistry, a unified treatment of photolysis and short-wave heating, a prognostic water vapour field, momentum-conserving gravity-wave drag).
- 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 CCMVal assessment and projection process should be synchronized with that of CMIP to make the maximum use of human and computer resources, and to allow time for model improvements.

Key Findings by Chapter

CHAPTER 2

- CCMs have undergone considerable development since the CCMVal-1 inter-comparison. For CCMVal-2 there were
  - 18 models participating, with 13 models producing a total of 22 REF-B2 simulations covering the requested 1960-2100 time period. In contrast, 11 models participated in CCMVal-1, with 1 model producing 3 REF2 simulations covering the entire 1960-2100 time period.
  - 5 models using online photolysis (*vs*. 3 for CCMVal-1);
  - 3 models using comprehensive tropospheric chemistry (*vs*. 1 for CCMVal-1);
  - 3 models having implemented improved transport schemes since CCMVal-1;
  - 1 model using an interactive ocean (*vs*. 0 for CCMVal-1);
- 4 new models contributed to the CCMVal-2 activity. While it should be noted that model improvements do not necessarily translate into improvements in model performance, the developments listed above, along with numerous smaller changes across the models, demonstrate progress made in the state-of-the-art of CCM modelling over the period since CCMVal-1.
- An unprecedented level of documentation concerning the models has been achieved. This has been invaluable in understanding model behaviour.

CHAPTER 3

- CCM global mean temperatures and their change can give an indication of errors in radiative transfer codes and/or atmospheric composition. Biases in the global mean temperature climatology are generally small, although 5 out of 18 CCMs show biases that likely indicate problems with their radiative transfer codes. Temperature trends also generally agree well with observations, although one model shows significant discrepancies that appear to be due to radiation errors.
- Heating rates and estimated temperature changes from CO_2, ozone and water vapour changes are generally well modelled. Other gases (N_2O, CH_4, CFCs) have only played a minor role in stratospheric temperature

change but their heating rates are estimated with large fractional errors in many models.

- Models that do not account for variations in the spectrum of solar irradiance but only consider changes in total (spectrally-integrated) solar irradiance cannot properly simulate solar-induced variations in stratospheric temperature.
- The combined long-lived greenhouse gas global annual mean instantaneous net radiative forcing at the tropopause is within 30% of that from line-by-line models for all CCM radiation codes tested. Problems remain simulating radiative forcing for stratospheric water vapour and ozone changes, with a range of errors between 3% and 200% compared to line-by-line models.

CHAPTER 4

- Climatological mean polar temperature biases are generally small (< 5 K) across the model ensemble except in the southern hemisphere (SH) lower stratosphere during spring. On average models produce the correct accumulated-area of Antarctic temperatures low enough for ice PSC formation, but too small accumulated-area for NAT PSC formation. In the Arctic, there is a large model spread in PSC area, and in general the PSC areas are smaller than reanalysis estimates.
- The model ensemble reproduces the structure of the polar night jet well, apart from the equator-ward tilt in the SH upper stratosphere. There are significant late biases in the spring-time breakup of the SH vortex. Polar night jet variability is not well reproduced by the models and has a large variation amongst the models.
- The orientation and shape of the polar vortex is well captured by the majority of models, but there are some significant outliers in the SH which are biased towards large amplitudes of zonal wavenumber 2.
- Tropical upwelling velocity is well simulated in the lower stratosphere compared to analyses, but is slightly too strong in the middle stratosphere. There is large disagreement between models on the relative contribution of resolved and parameterised (sub-grid-scale) waves to driving the Brewer-Dobson circulation.
- A common weakness of all models in the tropical upper stratosphere is a weak annual cycle in zonal-mean zonal winds, which is independent of the treatment of the QBO in models. Only a few of the CCMVal-2 models simulated a QBO-like oscillation in tropical winds. In the majority of models the QBO was absent or artificially forced.
- There is a wide spread in both the mean frequency of major stratospheric sudden warmings (SSWs) and their seasonal distribution in the models. No major SSWs were found in the SH of any of the simulations.
- Many of the persistent biases present in CCMVal-1, particularly temperature bias in the SH lower stratosphere spring and the late breakup of the Antarctic vortex, have not significantly improved in the CCMVal-2 models.
- Models simulate robust and consistent trends in southern hemisphere polar temperatures, PSC areas and final warming dates, with opposite trends during the periods of strong ozone depletion and recovery.
- In the Northern Hemisphere (NH) lower and middle polar stratosphere models on average show no significant long-term changes in winter-time temperature.
- There is a strong consensus between models that the strength of the Brewer-Dobson circulation will increase, with about a 2% per decade increase in the tropical upwelling mass flux over the 21st century. There is, however, little agreement between models on the relative contributions of resolved and parameterised waves to this trend.
- Models do not predict large changes in mid- and high-latitude 100 hPa meridional heat-flux or stratospheric stationary-wave amplitude over the 21st century.

CHAPTER 5

- Model tracer-derived vertical velocities tend to be faster than the observed tracer-derived vertical velocities in the tropical lower stratosphere. This appears not to be related to errors in zonal-mean upwelling. In the tropical middle stratosphere, both the modelled residual vertical velocity and the tracer-derived velocities show better agreement with observations.

- Errors in vertical transport in models complicate the interpretation of tropical-extra-tropical mixing diagnostics that depend on the attenuation of tracer signals since the attenuation cannot be assumed to result primarily from dilution by tropical-extra-tropical mixing.
- The average of all mean age diagnostic grades provides a very useful integrated transport assessment. Comparing modelled and observed mean ages over a wide range of latitudes and altitudes is a more reliable indication of transport credibility than individual mean age diagnostics because it is difficult to match the mean age everywhere through compensating errors. Seven of 15 models performed well on average mean age grade.
- There is a positive correlation between the average mean age grade and these key diagnostics: tropical ascent, tropical-mid-latitude mixing, and Antarctic descent. Tropical ascent and polar descent are physically linked through the diabatic circulation, and the average mean age grade depends on both the diabatic circulation and quasi-horizontal mixing, particularly between the tropics and mid-latitudes. Because of the physical basis for these correlations, good performance on all of these fundamental diagnostics is essential for building model credibility.
- Lower stratospheric Antarctic vortex isolation is not correlated with the average mean age grade, suggesting that the transport barrier at the vortex edge is, to first order, independent of the overall transport circulation. Because vortex isolation is a requirement for confining perturbed chemistry and producing a realistic ozone hole, it is essential to include this transport diagnostic in evaluations of simulations predicting future ozone. Eight of 13 models evaluated for vortex isolation had adequate Antarctic vortex isolation in the lower stratosphere. Of these, only four also performed well on the average mean age grade.
- Despite the spread in model performance revealed by the transport diagnostics, all 10 CCMs running the REF-B2 future scenario predict a faster circulation (based on mean age gradients) and younger mean age at the end of the 21st century, indicating that this is a robust result.

CHAPTER 6

- An accurate representation of photolysis rates is an essential component of any CCM chemical scheme. This chapter defined a photolysis benchmark (PhotoComp-2008) for assessing photolysis rates based on a robust mean and standard deviation for the ensemble of contributing models. PhotoComp was completed by 9 of the 18 CCMVal models of which the majority showed good agreement with the benchmark. However, there are several models that should consider improving their photolysis approach or verify photochemical data for certain species.
- Comparison of the fast (radical) photochemistry results from the CCMs with a benchmark photochemical steady state (PSS) model constrained by the abundance of long-lived species and sulfate surface area density (SAD) from each CCM generally shows very good agreement. This indicates that, for a given chemical background, most CCMs calculate the abundance of radicals that regulate ozone in a realistic manner, while exceptions were easily identified.
- Despite the stratospheric sulfate surface area density (SAD) being one of the specified forcings in the CCMVal runs, there is a wide variation in the values of SAD used inside the chemistry calculations.
- Some CCMs show a lack of conservation of tracer mixing ratios. This results in the total abundance of, for example, chlorine or bromine being larger than that specified as the time-dependent surface boundary condition and is likely due to non-conservation in the models' tracer advection. In addition, not all models followed the specified CCMVal-2 halocarbon scenarios, which complicates interpretation of long-term ozone changes. For bromine some models also included a source due to very short-lived bromocarbons, resulting in a larger inter-model variability in total inorganic bromine (Br_y).
- For the distribution of source gases the most significant potential source of error in the chemistry is in the photolysis (see first bullet). Model long-lived tracer-tracer correlations, which are not necessarily sensitive to this, agree well with observations.

- For H_2O there is a large spread in CCM stratospheric values. A lot of this spread is related to a spread in stratospheric entry values, but there also appear to be models with an incorrect stratospheric source from CH_4 oxidation. These errors in stratospheric H_2O will impact on chemistry *via* HO_x and heterogeneous chemistry.
- For the reservoir species CCMs generally capture the expected spatial and seasonal variations. However, there are significant discrepancies for some models and certain species. These discrepancies, for example in N_2O_5, $ClONO_2$ and HNO_3, are larger than the expected model chemical variability. Moreover, in some cases the abundance of HCl, the main Cl_y reservoir, exceeds the limit of chlorine imposed by the halocarbon scenarios. This can be due to non-conservation (see above) or differences in stratospheric entry values of inorganic chlorine due to inadequate treatment of tropospheric removal.
- Most models overestimate the abundance of gas-phase HNO_3 in the Antarctic winter/spring relative to observations. A few models get the minimum abundance of HNO_3 correct with season, but do not represent the vertical extent correctly. These discrepancies point to either biases in the model temperature or shortcomings in the denitrification scheme. CCMs tend to do a better job representing the evolution of gas-phase H_2O in the same region and period. In addition, the model surface area densities for HNO_3 (*e.g.*, NAT) and H_2O containing aerosols vary by a factor of ~10 within each PSC type. More work is needed to compare model PSCs parameters with available observations.
- The conversion of HCl to more reactive species is generally well represented in the Antarctic winter/spring. Most CCMs show near complete conversion of HCl to reactive species in the 500-600 K region between June and September. Below 500 K many models have too high abundance of HCl suggesting the process of activation is not well represented in this region. All but a few models have HCl recovering to an abundance consistent with observations by October.
- Most CCMs accurately represent chemical ozone loss in the Antarctic spring. There are clearly exceptions. Some models agree well with the loss inferred from observations, but not under the correct dynamical conditions. Some CCMs under-estimate chemical ozone loss even though the dynamics are well represented. Only a few models correctly represent the observed chemical ozone loss in the Arctic. CCMs are typically biased warm or do not have the correct variability in this region. These errors are reflected in the multi-model mean for this process, where the Antarctic is consistent with observations and the Arctic under-estimates chemical ozone loss.

CHAPTER 7

- Several of the CCMs analysed reproduce key observed features in the UTLS (including tracer gradients across the extra-tropical tropopause) even with a fairly coarse vertical (1 km) and horizontal (200-400 km) resolution. CCMVal-2 models with semi-Lagrangian transport schemes show too much mixing across the extra-tropical tropopause.
- The tropical tropopause pressure and cold-point temperature (CPT) exhibit significant biases compared to observations and between models, although the seasonal cycles are reasonable. These biases result in a wide range of tropical lower stratospheric H_2O values. Comparison of the CPT with H_2O reveals in some cases unphysical simulated transport behaviour.
- Lowermost stratosphere (LMS) mass (which is an indicator of tropopause pressure) shows a wide range of skill, with a large number of models performing well, but many performing very poorly. The performance is generally better in the NH than in the SH. The difference can be explained by smaller variations in the LMS mass in the SH, which are more difficult to be captured by the models.
- The seasonal cycle of O_3 in the extra-tropical UTLS is for most models quite good, however the amplitude is generally too high at 100 hPa and too low at 200 hPa. The models have difficulties representing both the amplitude and phase of the seasonal cycle in H_2O.
- CCMVal simulations into the future exhibit a clear signature of stratospheric O_3 depletion and recovery in their extra-tropical tropopause pressure trends. The signature is much stronger in the SH than in the NH,

where ozone depletion is weaker.
- Simulations show good historical fidelity with observed tropical tropopause pressure trends, and project decreases in tropical tropopause pressure in the 21st century. The rising tropopause is associated with increasing tropical tropopause temperatures and water vapour in the tropical lower stratosphere.

CHAPTER 8

- The annual cycles in column ozone and profile ozone are quite well represented in the majority of the models. In the SH polar lower stratosphere, a few models do not reproduce the anthropogenic induced annual cycle (polar ozone depletion) that dominates the column ozone evolution in later winter and spring.
- All models show the expected minimum in polar variability in the respective summer seasons. However, in the NH active period most of the models tend to under-estimate the interannual polar ozone variability. In the SH, the models both over- and under-estimate interannual polar ozone variability.
- Most models capture the connections between the dynamical processes responsible for the interannual polar ozone variations and the ozone response. Moreover, models with poor performance in interannual polar variability also tend to perform poorly in the diagnosed dynamics-ozone connections.
- The annual mean of the solar cycle in column ozone is well represented by most models, although with some amplitude spread. The latitudinal representation of the solar response in column ozone shows improvements from earlier studies, but a large spread remains especially at mid- to high latitudes due to large interannual variability.
- The direct solar response in temperature and ozone in the upper stratosphere is well represented by most models. Large differences in the vertical structure of the solar signal occur in the tropics below 10 hPa between the models but also between different observational data sets. Uncertainties in the lower stratosphere might be related to non-linear interactions or aliasing with other signals such as the QBO, ENSO, and volcanoes.
- The technique of assimilating the QBO winds or vorticity improves the modelled variability in ozone. However, biases in the amplitude of the QBO ozone signal in the models with the assimilated QBO are comparable to those from models with an internally generated QBO.
- The observed tropical ENSO signal in temperature and ozone is evident in the models, especially in the lower stratosphere where most of the models show a cooling and an ozone reduction. Because of the large role of interannual variability, it is not possible to assess model representation of the extra-tropical ENSO signal in ozone.
- The volcanic signal in ozone differs considerably between models and depends on the method by which the direct effect of volcanic aerosols on the radiative transfer of the stratosphere is represented. This limits the ability to evaluate model performance in simulating the volcanic signal. None of the models reproduce the observed hemispheric asymmetry in post-Pinatubo ozone loss, for either full hemispheric means or for mid-latitudes.

CHAPTER 9

- The multi-model trend estimates of past ozone changes are consistent with the observed changes. Compared with CCMVal-1, the availability of model simulations from 1960 onwards, together with a more robust statistical analysis, has provided a more reliable estimate of model behaviour.
- Models consistently show substantial ODS-induced ozone depletion prior to 1980, especially in the SH.
- Nearly all models completed simulations covering the 1960-2100 period. This provides a stronger basis from which to form an assessment of ozone projections than was previously available under CCMVal-1. This, plus the increased number of contributing models, has decreased the statistical uncertainty in the projected future ozone changes.
- Models generally predict only a small amount of chemical ozone depletion in tropical latitudes. The effect

of the expected strengthened tropical upwelling from climate change is to lower ozone column amounts, such that tropical column ozone may not return even to the values of the 1980s.

- In mid-latitudes, the future column ozone is predicted to recover faster in the NH than in the SH, due to a combination of a stronger Brewer-Dobson circulation in the NH and transport of low ozone from the Antarctic ozone hole in the SH. The projected increase in N_2O appears to play a minor role in ozone depletion for the scenario considered, in part because the impact of stratospheric climate change is to reduce the trend in reactive nitrogen amounts.
- Models consistently predict an increase in Arctic ozone from climate change, such that ozone will return to 1980 values before halogens will. This finding has resulted from the more robust statistical approach together with the longer time series, compared with those used in CCMVal-1. However, the large range in model projections, and natural variability, limit the confidence that can be placed in this conclusion.
- While many models simulate reasonably well the Antarctic ozone hole area and depth, based on the standard 220 DU threshold, most do not. This is due to a number of factors, including a large ozone bias in some models and a polar vortex that is typically too small in extent.
- In the models that simulate the current ozone hole well, a residual, *albeit* intermittent ozone hole remains at the end of the 21st century.

CHAPTER 10

- Compared with CMIP3 simulations, CCMVal-2 simulations have a mean stratospheric climate and variability that is much closer to the observations, based on pointwise comparisons of zonal-mean winds and temperature. In the troposphere, mean climate and synoptic variability are similarly close to the observations in both groups of simulations, while interannual variability tends to be better simulated by the CCMVal models.
- CCMVal-2 models simulate a downward propagation of annular mode anomalies in both hemispheres similar to that observed, with realistic ensemble-mean annular mode variances through the troposphere and stratosphere. However, the peak in variability associated with the break-down of the vortex consistently occurs too late in the year in both hemispheres in the CCMVal-2 models. The simulated SAM tends to be too persistent through the troposphere and stratosphere in summer.
- Over the period 1960-2000 the CCMVal-2 models simulate a spring cooling of the Antarctic polar vortex, and a decrease in Antarctic geopotential height which descends to the troposphere in December-February, and is associated with an intensification and southward shift of the mid-latitude jet.
- The amount of Antarctic ozone depletion in each model is closely correlated with its shift in jet location, amount of broadening of the Hadley Cell, and its increase in SH tropopause height.
- The models indicate that in the 21st century, the effects of ozone recovery and greenhouse gas increases largely cancel leading to little change in jet location, tropopause height, or Hadley Cell width in the SH during summer. The models do not project significant trends in 21st century NH high latitude winter zonal wind.
- Erythemal ultraviolet irradiance, calculated based on CCMVal-2 ozone changes, exhibits an increase throughout the globe in the last decades of the twentieth century. In the 21st century, decreasing chemical depletion is likely to contribute to a decrease in erythemal irradiance globally, while changes in the Brewer-Dobson circulation will tend to enhance the decrease in the Arctic and slow or reverse the decrease in the tropics and Antarctic.
- In the CCMVal-2 simulations ozone depletion causes a small global decrease in the stratosphere-troposphere ozone flux in the 20th century, and its recovery contributes to the 21st century increase. However, a strengthening of the Brewer-Dobson circulation is projected to be the dominant driver of an increase in stratosphere-to-troposphere ozone fluxes in the 21st century.

Recommendations by Chapter

CHAPTER 2

- For future model inter-comparison an online repository for model information should be made available and kept up-to-date by model developers so that users of the model simulations are aware of the specific features of each model.

CHAPTER 3

- CCM radiation schemes should be capable of being run independently of their host models and should regularly be involved in comparison exercises based on detailed sets of reference calculations from line-by-line models. Solar and longwave schemes should be evaluated for a range of realistic circumstances.
- Future radiation scheme comparisons should ideally evaluate the radiative effects of aerosol and cloud as well as trace gases. They should also evaluate the effect of approximations made in CCMs such as the frequency of radiative transfer calculations and the effects of plane-parallel/sphericity approximations.
- Photolysis and solar heating calculations should be merged for consistency.
- Non-local thermodynamic equilibrium effects should be accounted for above 70 km to correctly simulate heating and cooling rates in this region.
- CCMs should include spectral variations in solar irradiance when modelling solar variability in order to induce the correct stratospheric temperature change. Further work is needed to assess the level of spectral detail required.

CHAPTER 4

- Reproducing variability on sub-seasonal time scales (*e.g.*, SSWs and final warming dates) should be regarded as an essential part of a model's ability to simulate stratospheric dynamics, since this variability can play a key role in determining the mean stratospheric climate. This assessment has shown that many models have significant over- or under-estimates in this variability.
- A key outstanding issue is understanding the cause of the robust multi-model trend in the strength of the Brewer-Dobson circulation. Further inter-comparison of models, including detailed diagnosis of the stratospheric momentum budget, should be carried out to try to understand this trend. Additional observational constraints on the processes involved are also needed.
- In order to better simulate tropical stratospheric variability and its links to the extra-tropics CCMs should move towards simulating a physically realistic, internally generated QBO.
- There are persistent dynamical weaknesses in CCMs (*e.g.*, the timing of the break-down of the polar vortex) which require further work to understand both the resolved and parameterised (gravity-wave) forcing from the troposphere.

CHAPTER 5

- The following features are essential for realistic model transport, particularly for simulation of the Antarctic ozone hole: 1) local conservation of chemical family mixing ratios (*e.g.*, Cl_y), 2) realistic tropical ascent in the lower stratosphere, 3) realistic mixing between the tropics and extra-tropics, 4) close agreement with *all* mean age diagnostics, and 5) generation of an isolated Antarctic vortex in the lower stratosphere. Models that reasonably represent these essential attributes have enhanced credibility for prediction of future stratospheric composition.
- Transport improvement efforts should concentrate on the tropical lower stratosphere. The ability to reproduce the observed tracer-derived vertical velocities and to maintain the correct degree of tropical isolation

seem to be key to the accurate simulation of transport throughout the stratosphere.

CHAPTER 6

- All CCM groups should participate in the PhotoComp 2008 and PSS process diagnostics. These are fundamental diagnostics that will, after successful competition, provide confidence that these models have an accurate representation of chemical processes.
- CCM groups should monitor their sulfate SAD distributions. This chapter has shown that there is a wide variation in what models are using (even though it was prescribed).
- Models must conserve atoms of key chemical families. For example, there are several cases where the stratospheric total inorganic chlorine (or bromine) abundance is much greater than that specified at the surface. This is not necessarily a chemistry issue; it may be due to non-conservation in the CCM tracer advection scheme. However, non-conservation of ozone depleting substances will clearly affect the accuracy of modelled ozone distributions and trends.
- The community must address the issue of how to include very short-lived (VSL) organic bromine species into the boundary condition and chemical mechanism of CCMs. The measurement community has confirmed that these species are important for stratospheric inorganic bromine loading. Comparisons with measured BrO show higher abundances in the atmosphere than are found in all of the standard model simulations. Validation of model bromine chemistry and ozone loss using observations is not possible without a realistic description of the past/present atmosphere. Not including these VSL sources of inorganic bromine also makes interpretation of model derived ozone trends more uncertain. Models also need to be consistent in following the prescribed scenarios of long-lived halocarbons.
- One of the most notable differences between the models was the abundance of Cl_y at the tropopause and throughout the troposphere. Some models have near zero (<< 50 ppt) values of Cl_y in these regions of the atmosphere, while other models have much larger values (>> 50 ppt). Models with high levels of Cl_y at the tropopause tend to have excess Cl_y throughout the lower stratosphere. We postulate these differences are due to various representations of Cl_y uptake and removal. In the future, attention should be devoted to model representation of Cl_y in the troposphere, tropopause, and lower stratosphere regions because models with the higher values of Cl_y may display a different sensitivity to future changes in stratospheric H_2O and temperature (*i.e.*, more chlorine available to be activated) than models with lower values of Cl_y.
- CCM groups should continue to pay attention to how water vapour is coupled to the stratospheric chemistry schemes. GCMs contain a water vapour field which should be coupled to and used by the chemistry module. The dynamics of the GCM, however, needs to be sufficiently realistic to give accurate stratospheric H_2O abundances.
- The next generation of CCMs should also include a better representation of tropospheric chemical processes (*e.g.*, non-methane hydrocarbons; lighting NO_x production; detail inclusion of dry and wet deposition processes). This is certainly important for science studies in the troposphere and UTLS region, but also may be important in better representing the overall climate system.

CHAPTER 7

- The quantitative evaluation of the models has been found to be difficult for some diagnostics due to limited representativeness or low accuracy of observations in the UTLS. It will be necessary to compare the UTLS metrics with future measurements to reduce uncertainty in the model comparison associated with potential measurement errors. For this purpose, the observational database for the UTLS should be expanded by measurements with both higher spatial and temporal resolution and sampling, but also reasonable accuracy.
- New observations are needed especially for O_3 and H_2O in the UTLS with a vertical resolution better than 1 km and a horizontal resolution better than 100 km, especially in the SH and the tropics.
- Evaluating chemical processes in the UTLS should be part of future model validation efforts, including

tropospheric CCMs used for the IPCC. However, to do this properly, future model development is needed that brings together tropospheric and stratospheric chemistry models.

- Part of this model development should include the representation of very short-lived (VSL) species that also represent major sources of bromine in the stratosphere. These VSL provide a range of lifetimes and can discriminate transport from marine and continental source regions into the UTLS.

CHAPTER 8

- The evaluation of the sensitivity of the SH large-scale dynamics to the parameterisation of non-orographic gravity wave drag and its implication for the interannual variability in ozone should be included in future assessments.
- Models should use spectrally resolved solar irradiance data and a suitable radiation and photolysis code. More detailed inter-comparison of radiation and photolysis codes as well as sensitivity studies to understand the complex non-linear interactions of the solar signal with other natural variability signals are needed.
- The simulation of the QBO in CCMs is an outstanding challenge. It is a problem that needs to be addressed comprehensively, because of the dependence of the modelled QBO on the representation of a number of processes, ranging from convective processes to the vertical propagation of atmospheric waves. A successful simulation needs to assess both meteorological and chemical fields.
- The parameterisation of volcanic effects has to be advanced as well as the understanding of observed variations in response to volcanic eruptions.

CHAPTER 9

- The simulation of the Antarctic ozone hole needs to be improved in most models. This can be achieved by improving the simulation of polar stratospheric clouds and their activation of chlorine, and by reducing overall ozone biases.
- 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.
- Simulations with different halogen and GHG scenarios need to be completed to complement the simulations in which these quantities are fully varying. While multi-linear regression has been effective in determining the importance of these factors in controlling ozone in the middle and upper stratosphere, the technique is less effective in the lower stratosphere where the dynamical and chemical time scales have periods of a month or more and the causality of the relationships is less clear.

CHAPTER 10

- More CCMs should be coupled to dynamical oceans. This is necessary in order to reliably simulate the tropospheric response to stratospheric perturbations, otherwise it is constrained by the prescribed SSTs.
- Model runs with fixed ODS and both fixed and different GHG scenarios are needed to allow the influences of greenhouse gas changes and ozone depleting substances on tropospheric climate to be separated.