A new version of the CNRM Chemistry-Climate Model, CNRM-CCM: description and improvements from the CCMVal-2 simulations

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1. *Introduction*

Three-dimensional atmospheric circulation models with a fully interactive representation of stratospheric ozone chemistry are known as stratosphere-resolving Chemistry-Climate Models (CCMs). They are key tools for the attribution and projection of stratospheric ozone changes arising from the combined effects of changes in the amounts of greenhouse gases and ozone-depleting substances. We present here results of a modelling activity that lead to the definition and implementation of a new version of the Météo-France CNRM CCM, "CNRM-CCM".

2. *Description of the CNRM-CCM Model and of the simulations performed*

2.1 *From CNRM-ACM to CNRM-CCM*

The new model version CNRM-CCM is an evolution of the previous version CNRM-ACM, largely evaluated in the context of the CCMVal-2 activity, both in terms of their underlying General Circulation Model (GCM), as well as in the way these CCMs deal with the chemistry part through the interactions between chemical, radiative and dynamical processes. A number of minor differences exist between the dynamical/physical components of the CNRM-ACM GCM and that of the CNRM-CCM GCM (ARPEGE-Climat version 5.2). However, a major evolution concerns their radiation scheme, both in the SW spectrum with 2 and 6 bands respectively, and above all in the LW spectrum. A second major difference between CNRM-ACM and CNRM-CCM is that the chemistry of CNRM-CCM is so-called "on-line": the simulation of gaseous chemistry has been directly integrated within the GCM code. Chemical routines are a subset of the entire set of model routines, and chemical species are considered as prognostic variables of the model. The advection scheme is thus the same for meteorological and for chemical variables, avoiding inconsistencies with transport. More details can be found in [Michou et al., GMD, 2011].

2.2 *Simulations and diagnostics analysed*

We analysed a 47-yr transient simulation (1960–2006) defined as the CCMVal-2 REF-B1 simulation. The diagnostics considered appear in Table 1. For further details see [Michou et al., GMD, 2011]

Table 1. Diagnostics considered in this study.

Process	Diagnostics	Variables	Observations
Dynamics	High lat. strat. biases	T (Temperature)	ERA-40; Uppala et al. (2005)
	Winter, spring		ERA-Interim; Simmons et al. (2006)
			NCEP, UKMO reana.; Eyring et al. (2006)
	Easterlies at 60S	U (zonal wind)	ERA-40, ERA-Interim
	SH and NH Night Polar Jet	U	ERA-40
Transport	Tape recorder	H_2O	HALOE; Grooß and Russel (2005)
	Latitu. profiles at 0.5, 10 and 50 hPa	Age of air	Various; Eyring et al. (2006)
	Vert. and latitu. profiles	CH_4	HALOE
	Seasonal cycles	O_3, H_2O	HALOE, MIPAS; SPARC (2010)
	at 100, 200 hPa and	HNO_3	MIPAS
	at 40° N–60° N, 60° S–40° S		
UTLS	Seasonal cycles	T	ERA-40, ERA-Interim
	at 100 hPa Equator	O_3, H_2O	HALOE
	Latitu. profiles ANN, DJF, JJA	Tropo. pressure	ERA-40, ERA-Interim
Natural variability	Anom. at 50 hPa	T	ERA-40, ERA-Interim
Chemistry	Vert. and latitu. profiles	H_2O, O_3, HCl	HALOE
	Time ser. at 50 hPa, 80° S	Cl_y	Various; Eyring et al. (2006)
	Seasonal cycles	CH_4, H_2O, O_3, HCl	HALOE
	at 50, 1hPa and	HNO_3, NO_2, N_2O_5	MIPAS
	at 30° N–60° N,	BrO	SCIAMACHY; SPARC (2010)
	30° S–60° S, 15° S–15° N		
		$ClONO_2$	MIPAS
		CO	MLS; Lee et al. (2011)
	Total column 1980–1990, 1990–2000	O_3	BSv2.7; Bodeker et al. (2005)

3. *Results*

3.1 *Overview*

As an overall picture of the agreement between the observations and the CNRM model outputs, we plotted a Taylor diagram of all the diagnostics analysed (see Fig.13). Interesting outcomes can be made: a number of diagnostics have poor skills, either because of a very low correlation with observations and/or because of an amplitude of the signal far from that of the observations. In contrast, a substantial number of dots lie in the portion of the diagram close to the REF line, and delimited by a correlation coefficient higher than 0.9. It appears that CNRM-CCM has a larger number of satisfactory dots than CNRM-ACM. To assess whether both model versions were statistically different, we performed a one-sample Student t Test to test whether the differences of the two sample means were significantly different from zero. Overall, we show that CNRM-ACM and CNRM-CCM are significantly different in most of the cases studied (see Table 1). For argument's sake, this is not the case, for example, for the equatorial temperature and water vapor at 100 hPa.

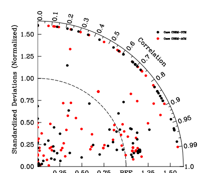

Fig. 13. Taylor diagram (*Taylor*, 2001) of the diagnostics presented in the various paragraphs of the paper, red dots for CNRM-ACM, black dots for CNRM-CCM.

Table 1. Results of the t-Tests conducted on each month of the annual cycle of a given chemical compound, hn1: 30° N–60° N at 1 hPa, hs1: 30° S–60° S at 1 hPa, hn50: 30° N–60° N at 50 hPa, hs50: 30° S–60° S at 50 hPa, trop1: 30° S–30° N at 1 hPa, trop50: 30° S–30° N at 50 hPa. A ✓ indicates where a significant difference ($p < 0.05$) has been found.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
BrO-hn1				✓	✓	✓	✓	✓				
BrO-hn50	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
BrO-hs1	✓	✓					✓			✓	✓	✓
BrO-hs50	✓	✓	✓	✓		✓	✓	✓				✓
BrO-trop1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
BrO-trop50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hn1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hn1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hn50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hn50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hs1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hs1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hs50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-hs50	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-trop1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-trop1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CH4-trop50	✓	✓	✓	✓	✓	✓					✓	✓
CH4-trop50	✓	✓	✓	✓	✓	✓					✓	✓
ClONO2-hn1	✓			✓	✓	✓	✓	✓	✓		✓	✓
ClONO2-hn50	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
ClONO2-hs1	✓	✓			✓	✓			✓	✓	✓	✓
ClONO2-hs50	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
ClONO2-trop1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
ClONO2-trop50	✓	✓	✓								✓	✓

3.2 *Main improvements: dynamics*

Stratospheric temperature biases in spring and winter at high latitudes are smaller or comparable to those of the CCMVal-2 models (see Fig.1), and the temperature anomalies linked to volcanic eruptions follow those of the ERA-40 reanalysis (see Fig.10). The other dynamical features analysed, transition to easterlies at 60° S, strength and position of the stratospheric jets (see Fig.3) and pressure of the tropopause, compare favorably to the ERA-40 and ERA-Interim reanalyses. The characteristics of the transport appear to be quite accurately reproduced throughout the stratosphere, even though it is somewhat too rapid (see Fig.4).

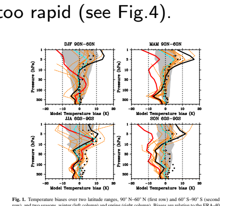

Fig. 1. Temperature biases over two latitude ranges, 90° N–60° N (first row) and 60° S–90° S (second row), and two seasons, winter (left column) and spring (right column). Biases are relative to the ERA-40 1980–2001 monthly reanalysis, for CNRM-ACM (red line), CNRM-CCM (black line) and CCMVal-2 REF-B1 models (dashed orange lines), and for ERA-Interim (dashed cyan line), NCEP (dots), and UKMO (crosses) reanalyses. The grey area shows ERA-40 ±1 standard deviation.

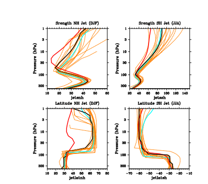

Fig. 3. Strengths ($m\,s^{-1}$) and latitudes of the maximum of the climatological zonal wind in DJF (first column) and JJA (second column). Climatologies (1980–2001) are for ERA-40 (cyan line), CNRM-ACM (red line), CNRM-CCM (black line), and CCMVal-2 REF-B1 models (dashed orange lines).

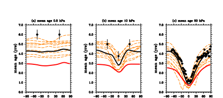

Fig. 4. Mean age of air at **(a)** 0.5, **(b)** 10, and **(c)** 50 hPa, observations (black dots $\pm 1\sigma$, set text), CNRM-ACM (red line), CNRM-CCM (black line) and CCMVal-2 REF-B1 models (dashed orange lines). Model outputs are from the 1980–2001 period.

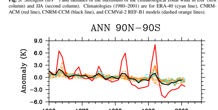

Fig. 10. Anomalies of annual mean global temperature at 50 hPa for ERA-40 (cyan solid line), ERA-Interim (dashed cyan line), CNRM-ACM (red line), CNRM-CCM (black line) and CCMVal-2 REF-B1 models (dashed orange lines). Anomalies are those w.r.t. the 1980–1989 period.

3.3 *Main improvements: chemical species*

The distributions of long-lived species, including CH_4 and HCl are well captured. Both the amplitude and the phase of the annual cycles of chemical species like O_3 and H_2O are well simulated in the UTLS where the effects of transport dominate. For the several other chemical species investigated, i.e. CO, $ClONO_2$, BrO and HNO_3, the results do not reveal any major weakness in the model. Finally, our first analysis of the simulation of the ozone distribution and of the total column ozone is quite encouraging (see Fig. 11 and 18).

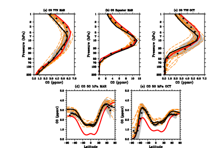

Fig. 11. Climatological (1992–2001) zonal-mean O_3 mixing (ppmv), for HALOE observations (black dots, with grey area showing $\pm 1\sigma$), CNRM-ACM (red line), CNRM-CCM (black line), and CCMVal-2 REF-B1 models (dashed orange lines). Vertical profiles at **(a)** 77° N in March, **(b)** 0° N in March, and **(c)** 77° S in October. Zonal-means at 50 hPa in **(d)** March and **(e)** October.

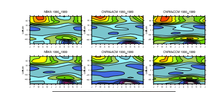

Fig. 18. Climatological monthly zonal total column ozone (DU) over two 10-yr periods, 1980–1989 (first row) and 1990–1999 (second row), for BSv2.7 observations (left column), CNRM-ACM (middle column) and CNRM-CCM (right column) simulations.

3.4 *Remaining weaknesses*

Stratospheric temperatures are too low at the equatorial tropopause and too high in the upper stratosphere between 5 and 1 hPa warm (5 to 9 K). This warm bias extends to all latitudes, is permanent throughout the year and simulations performed with no retroaction with the chemistry onto the radiative scheme reveal that it is intrinsic to the GCM itself (see Fig.14). In the end, a number of biases appear in the chemistry of the upper stratosphere. The model produces not enough O_3, but too much NO_2 and N_2O_5 at 1 hPa and is then at the high end of the CCMVal-2 models (see Fig.15).

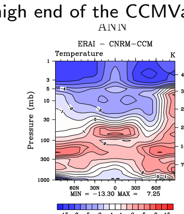

Fig. 14. Latitude-pressure cross-sections of differences in annual temperature between ERA-Interim and CNRM-CCM (1989-2000 period).

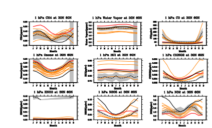

Fig. 15. Mean annual cycle at 50 hPa over 30° N–60° N for CH_4 (ppmv), H_2O (ppmv), CO (ppbv), O_3 (ppmv), HCl (ppbv), $ClONO_2$ (ppbv), HNO_3 (ppbv), N_2O_5 (ppbv) and NO_2 (ppbv). Observations (dashed black line, $\pm 1\sigma$, see text), CNRM-ACM (red line), CNRM-CCM (black line) and CCMVal-2 REF-B1 models (dashed orange lines).

4. *Future*

We suggest that some of the chemical problems addressed above may be tackled by addressing issues related to the dynamics and the physics of the model. CNRM-CCM does not simulate at this stage intrinsically the QBO of the lower stratospheric equatorial winds (nor do most current CCMs). This has been identified as a major shortcoming by the CCMVal-2 project. Furthermore, the temperature of the higher stratosphere should be adjusted, possibly through the implementation of a more accurate radiation scheme in the short wavelengths. Further developments of the model will also include the non-orographic aspects of the gravity waves, as well as the short-lived source gases containing bromine. CNRM-CCM is planned for use in a variety of projects linked with the interactions between chemistry and climate, in particular in seasonal and decadal predictions, where it could possibly be coupled to an interactive ocean.

Michou, M., D. Saint-Martin, H. Teyssèdre, A. Alias, F. Karcher, D. Olivié, A. Voldoire, V.-H. Peuch, H. Clark, J.N. Lee and F. Chéroux: A new version of the CNRM Chemistry-Climate Model, CNRM-CCM: description and improvements from the CCMVal2 simulations, Geosci. Model Dev., 4, 128, 2011, www.geosci-model-dev.net/4/1/2011, /doi:10.5194/gmd-4-1-2011