European Commission's 7th Framework Programme
Grant Agreement No. **226520**

Project acronym: **COMBINE**

Project full title: **Comprehensive Modelling of the Earth System for Better Climate Prediction and Projection**

Instrument: Collaborative Project & Large-scale Integrating Project

Theme 6: *Environment* Area 6.1.1.4: *Future Climate*

ENV.2008.1.1.4.1: *New components in Earth System modelling for better climate projections*

Start date of project: 1 May 2009 Duration: 48 Months

Deliverable reference number and title: D2.4: Role of chemistry-aerosol-cloud-interaction for the radiative forcing at $2xCO_2$

Lead work package for this deliverable: WP2

Organization name of lead contractor for this deliverable: CNRS

Due date of deliverable: Month 24
Actual submission date: Month 30

Project co-funded by the European Commission within the Seven Framework Programme (2007-2013)		
Dissemination Level PU		
PU	Public	PU
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the Consortium (including the Commission Services)	

1. Motivation

Long-lived greenhouse gases (LLGHG) such CO_2, methane or N_2O are well mixed in the atmosphere due to there very long lifetimes than can exceed 50 years. Their radiative forcing presents homogeneous patterns, some of them zonal (Ramaswamy et al., 2001). Forster et al. (2007) estimate the radiative forcing of CO_2, CH_4 and N_2O between 1750 and 2005 to be 1.75, 0.5 and 0.2 $W.m^{-2}$ respectively. Aerosols have a much shorter tropospheric lifetime from days to a few weeks, hence their geographical distribution show much larger gradients than the LLGHG. Aerosols can absorb or scatter the incoming solar flux and thus change the planetary shortwave albedo, this is the “aerosol direct effect”. Sea-salt, sulfate and organic carbon (OC) tend to cool the atmospheric column whereas dust can either warm or cool the atmosphere depending on the underlying surface albedo; black carbon (BC) tends to have a warming effect over all surfaces. Moreover the increase in aerosol number induces an enhancement of the cloud droplet number concentration which increased the cloud reflectivity through the so-called “1st aerosol indirect effect” (Twomey, 1974), which tend to cool climate. The present overall radiative forcing for aerosols is estimated to be -1.2 Wm^{-2} (Forster et al., 2007), when considering both the direct and the 1st indirect effect.

This work pertains to the anthropogenic aerosols (BC, OC and sulfate). We focus our study on present-day (2000) emission levels and on future (2020 and 2050) scenarios in order to assess how the cloud-aerosols interaction will change between these two periods. In the case of the RCP8.5 scenario, a level of CO_2 twice that of pre-industrial level (560 ppm) is reached in 2050. The aerosols loads being lower than the ones we have experienced in 2000. Following the Representation Concentrations Pathways (RCPs) scenarios considered for the Assessment Report 5, the LLGHG concentrations continue to increase during the 21st century. Meanwhile the aerosols emissions increase until 2020-2030 and then decrease due to the set up of mitigation policies.

2. Simulations

2.1 Aerosol Direct Effect

We estimate the aerosol radiative effects using the IPSL coupled model (Marti et al., 2010) based upon the CMIP5 simulations from 1850 to 2100. This coupled model reads in monthly aerosol fields previously calculated by the INteractive Chemistry Aerosol module, INCA (Textor et al., 2006). The aerosol direct forcing for the whole aerosol burden in 2000 and 2050 is estimated to be -0.29 Wm^{-2} and -0.20 Wm^{-2}, respectively (Figure 1).

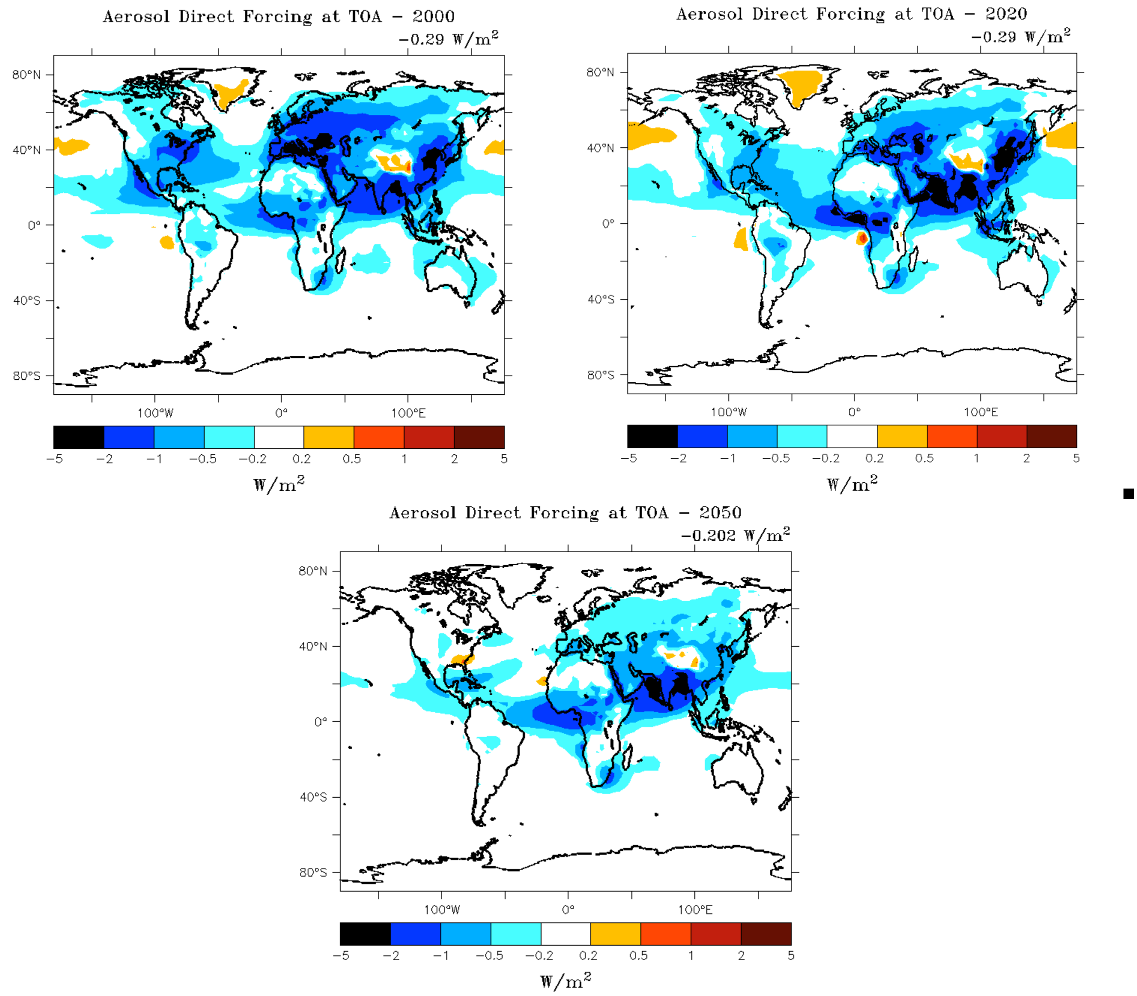

Figure 1*: Aerosol radiative forcing at TOA for the whole aerosol burden for 2000 and 2050.*

The radiative forcing tends to decrease between 2000 and 2050 due to the mitigation policy relative to the aerosol emissions according the RCP8.5 scenario.

The radiative impact of anthropogenic aerosols was assessed separately, using the LMDZORINCA model, a GCM interactively coupled to INCA (Textor et al., 2006). To better represent surface fluxes, this model is coupled to the land-vegetation module ORCHIDEE (Krinner et al., 2005). Simulations are performed following the RCP8.5 scenario for the years 2000 and 2050 respectively. CMIP3 Sea Surface Temperatures (SST) issued from the IPSL coupled model are used as boundary conditions.

With this model, we also assess the radiative impact of several economic sectors following the RCP8.5 prescription emissions. We performed simulations for 2000, 2020 and 2050.

Table 1 presents the direct radiative forcing for the three main sectors: energy, shipping and industry.

Year	*Energy sector*	*Shipping*	*Industry*
2000	-0.214 W m^{-2}	-0.018 W m^{-2}	-0.074 W m^{-2}
2020	-0.201 W m^{-2}	-0.019 W m^{-2}	-0.111 W m^{-2}
2050	-0.054 W m^{-2}	-0.007 W m^{-2}	-0.089 W m^{-2}

Table 1: *Direct radiative forcing for the three main activity sectors for present-day (2000) emissions and for 2020 and 2050 RCP8.5 scenario.*

2.2 Aerosol Indirect Effect

The 1st aerosol indirect effect (AIE) has been implemented following the empirical relationship of Boucher and Lohmann (1995) between the aerosol mass and the cloud droplet number concentration. This relationship was updated using observational constraints from MODIS observations (Quaas et al., 2006). Lohmann et al. (2009) show how the use of such observational constraints leads to a lower estimate of the 1st indirect effect compared to prognostic methods. The assessment of the 1st AIE for several economic sectors has been performed for sulfate only following the approach of Deandreis et al. (2011). In order to be consistent we need to keep the same meteorological fields for the study of each economic sector. The economic sectors follow the division that was decided upon in the preparation of the emission data for the 5th Assessment Report. These sectors are respectively: Land Transport, Energy, Residential and Commercial, Industry, Shipping, Waste, Agriculture Waste Burning, Grass fires and Forest fires.

The radiative code is therefore called twice at each time step. *Table 2* presents the decrease in the first indirect effect that would take place if no aerosol were produced by one of the three economic sectors that influence mostly the indirect effect. Contrary to the direct effect, the 1st indirect forcing is not linearly related to the aerosol mass emission.

Year	*Energy power*	*Shipping*	*Industry*
2000	22.1	18.0	12.7
2020	15.7	18.0	16.0
2050	13.1	12.9	20.0

Table 2*: Reduction in % in the 1st aerosol indirect effect if emissions are set to zero in a sector, for the three most important sectors.*

From the Boucher and Lohmann (1995) relationship, the cloud droplet number concentration is much more sensitive in a clean atmosphere, where sulfate concentration is lower than the threshold of 0.8μg(SO_4)/m^3 ; which correspond to oceanic regions. Moreover the indirect forcing mainly occurred in regions where the lower level clouds are persistent, as shown in Figure 2 for the year 2020.

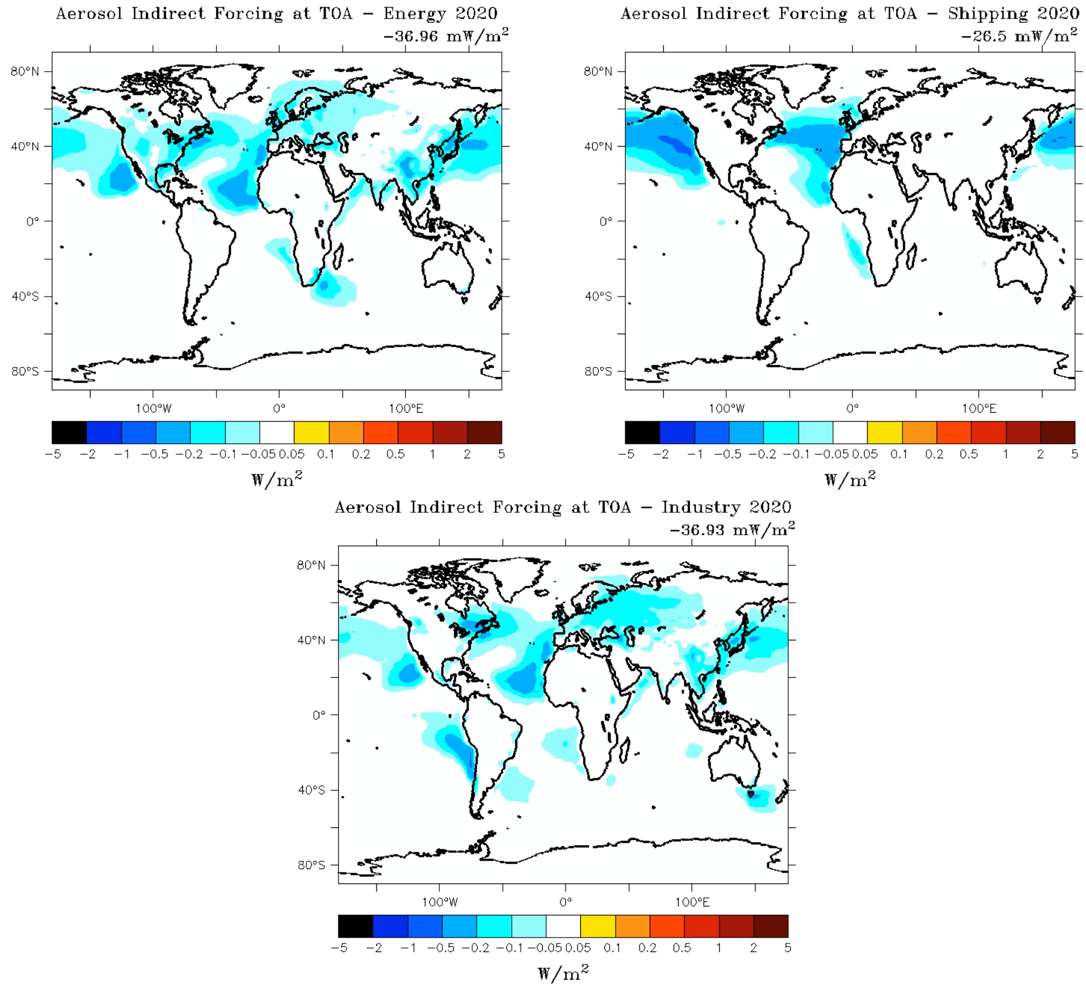

***Figure 2**: Predicted 2020 Aerosol indirect forcing at TOA due to the energy, international shipping and industry sectors.*

While studying the indirect effect, we also analyzed how the indirect forcing varied with respect to the preindustrial aerosol levels. In particular, volcanic emissions play an important role in the indirect forcing calculation. We considered the estimate of 29 Tg (SO_2)/yr for volcanic emissions (Dentener et al., 2006) while the anthropogenic emissions in 1750 and 1850 are estimated to 2 and 4 Tg (SO_2)/yr respectively. We identified the need to define a common preindustrial level for future multi-model intercomparisons in order to be able to compare indirect forcing.

Present vs 1750 with volcano	-0.655 W m^{-2}
Present vs 1850 with volcano	-0.589 W m^{-2}
Present vs 1850 no volcano	-0.855 W m^{-2}
Present vs 1750 no volcano	-1.001 W m^{-2}

Table 3: *Effect of Pre-Industrial levels of sulfate on the first indirect effect. This study is conducted only with the sulfate aerosols.*

We are currently running simulations for the whole economic sectors defined by the RCPs including all the anthropogenic aerosols for 2000, 2020 and 2050. According to the RCPs scenarios, aerosol emissions in Asia keeps increasing from 2000 to a maximum in 2020; while emissions elsewhere around the world decrease at the beginning of the 21th century.

3. References

Boucher, O., and U. Lohmann: The sulfate-CCN-cloud albedo effect: A sensitivity study with two general circulation models, Tellus, 47B, 281-300, 1994.

Deandreis, C., Y. Balkanski and J.L. Dufresne: Radiativeforcing estimates in coupled-chemistry models with emphasis on the role of the temporal variability, Atmos. Chem. Phys, 11, 24313–24364, 2011.

Dentener, F., Kinne, S., Bond, T., Boucher, O., Cofala, J., Generoso, S., Ginoux, P., Gong, S.,Hoelzemann, J., Ito, A., Marelli, L., Penner, J., Putaud, J.-P., Textor, C., Schulz, M., Werf,G.v.d , and J. Wilson: Emissions of primary aerosol and precursor gases in the year 2000 and 1750 prescribed data-sets for AeroCom, Atmos. Chem. Phys., 6, 4321-4344, 2006.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., and R. Van Dorland: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Krinner, G., Viovy, N., de Noblet-Ducoudre´, N., Ogee, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S. and I. Colin Prentice: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system , Glo. Biogeochem. Cycles, 19, 2005.

Lamarque J.-F., T. C. Bond, V. Eyring, C. Granier, A. Heil, Z. Klimont, D. Lee, C. Liousse, A. Mieville, B. Owen, M. G. Schultz, D. Shindell, S. J. Smith, E. Stehfest, J. Van Aardenne, O. R. Cooper, M. Kainuma, N. Mahowald, J. 1074 R. McConnell, V. Naik, K. Riahi, and D. P. van Vuuren, Historical (1850–2000) gridded anthropogenic and biomass burning emissions of 1076 reactive gases and aerosols: methodology and application, Atmos. Chem. Phys., 10, 7017-1077 7039, 2010.

Marti, O., Braconnot, P., Dufresne, J.L., Bellier, J., Benshila, R., Bony, S., Brockmann, P., Cadule, P., Caubel, A., Codron, F., de Noblet, N., Denvil, S., Fairhead, L., Fichefet,T., Foujols, M.A., Friedlingstein, P., Goosse, H., Granpeix, J.Y., Guilyardi, E., Hourdin, F., Idelkadi, A., Kageyama, M., Krinner, G., Lévy, C., Madec, G., Mignot, J., Musat, I., Swingedouw, D. and C. Talandier : Key feature of theIPSL ocean atmosphere model and its sensitivity at the atmospheric resolution, Clim. Dyn., 34, 1-26, 2010.

Quaas J., Boucher O. and U. Lohmann U.: Constraining the total aerosol indirect effect in the LMDZ and ECHAM4 GCMs using MODIS satellite data, Atmos. Chem. Phys, 6, 947–955, 2006.

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G. Y., and S. Solomon: Radiative forcing of climate change, in Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental 5 Panel on Climate Change, edited by: Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., and Johnson, C. A., 349–416, Cambridge Univ. Press, New York, USA, 2001.

Textor, C., M. Schulz, S. Kinne, S. Guibert, S. Bauer, T. Berntsen, T. Berglen, O. Boucher, M. Chin, F. Dentener, T. Diehl, H. Feichter, D. Fillmore, S. Ghan, P. Ginoux, S. Gong, A. Grini, J. Hendricks, L. Horrowitz, I. Isaksen, T. Iversen, D. Koch, M. Krol, A. Lauer, J.F. Lamarque, X. Liu, V. Montanaro, G. Myhre, J. Penner, G. Pitari, S. Reddy, O. Seland, P. Stier, T. Takemura, and X. Tie: The effect of harmonized emissions on aerosol properties in global models – an AeroCom experiment, Atmos. Chem. Phys., 7, 4489-4501, 2007.

Twomey, S.: Pollution and planetary albedo, Atmos.Environ., 8, 1251-1256, 1974.