

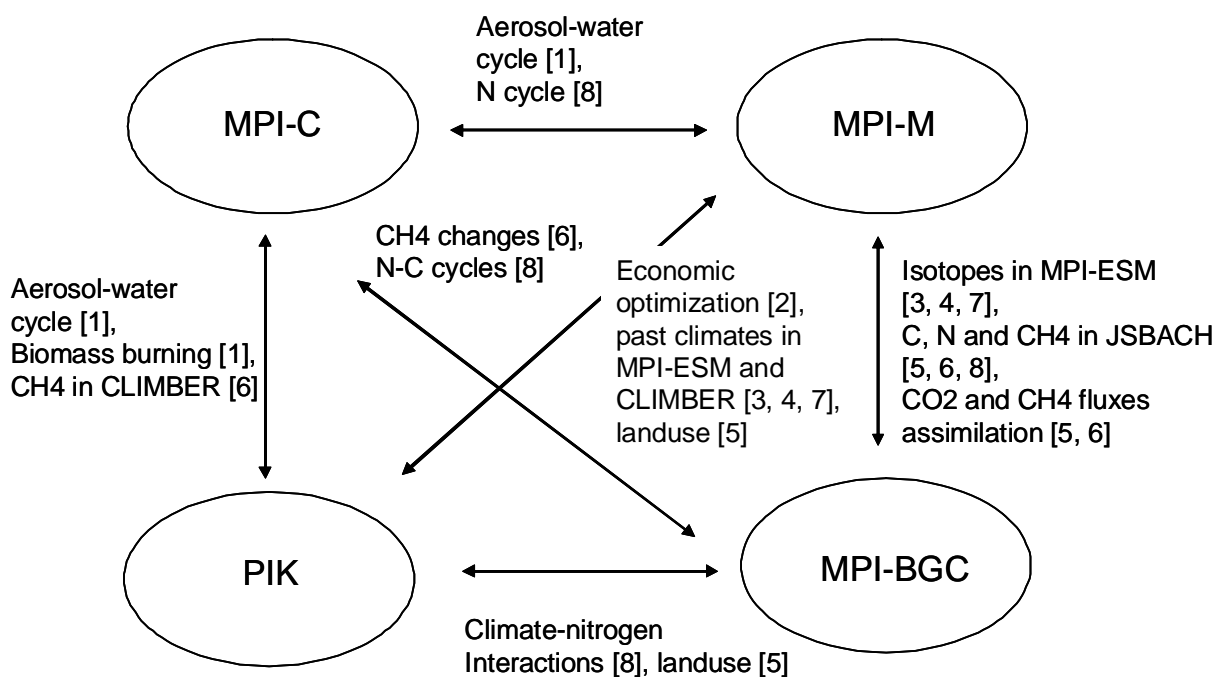
# ENIGMA - Earth System Network of Integrated Modelling and Assessment

## Project summary

Third draft by Stefan Hagemann, 2.3.2012

ENIGMA has intensified and extended the ESRP cooperation towards a better understanding of biospheric control mechanisms of climate and how they are affected by the numerous and strong human influences on terrestrial and marine ecosystems. This led to a collective development of a comprehensive Earth system model, in which the representation of ecosystem feedbacks is improved. Eight major work packages were set up within ENIGMA:

1. Aerosols and the water cycle
2. Climate modules for economic optimisation
3. Glacial cycles
4. Holocene climate and carbon cycle
5. Land use, the biosphere, and the Earth system
6. Methane changes since the pre-industrial era
7. Millennium simulations
8. Nitrogen-Carbon (N-C) cycles



**Figure 1** Interactions within ENIGMA. Work package numbers are mentioned in brackets.

All work packages have shown good progress and have significantly enhanced the cooperation among the ENIGMA partners. During ENIGMA, a 9<sup>th</sup> work package on land data assimilation was initiated. Here, a strategy for data assimilation of FLUXNET data, remote sensing observations, and data from ecosystem manipulation experiments has been developed and led to the joint FINALACE initiative between MPI-BGC and MPI-M where currently

large effort is undertaken to use a multitude of data streams for data assimilation into the JSBACH land surface model. In addition, the cross-cutting topic of land surface hydrology has led to productive common activities across work packages 3, Glacial cycles; 4, Holocene; and 6, Methane changes. In general, ENIGMA has led to a significantly increased communication among the partners that is forming the basis for further future cooperation and common projects.

Integration of physical-chemical and biospheric components of the Earth system is a quickly growing, dynamic area of Earth system science. The ENIGMA project provided a unique opportunity for the ESRP institutes to perform research at the frontier of this innovative scientific domain. The added value of ENIGMA was the further development of scientific collaboration through the ENIGMA work packages. This collaborative network is schematically summarized in Figure 1.

Interactions between aerosols and the water cycle including biomass burning were explored in the collaboration between MPI-C, MPI-M, and PIK in WP1 “Aerosols and the water cycle”, while feedbacks between methane emissions and atmospheric chemistry were investigated in cooperation among MPI-BGC, MPI-C, and MPI-M in WP6 “Methane changes since the preindustrial era”. Within WP2 “Climate modules for economic optimisation”, a collaboration between PIK with strong expertise in energy economic modelling, MPI-M and MPI-C aimed at cost-optimal, low-impact, dynamically consistent mitigation scenarios. Analysis of past climates (Holocene, glacial cycle, Millennium) was mostly going on within MPI-M and PIK, but some aspects of past changes, such as changes in atmospheric CH<sub>4</sub> concentration, were of interest for the MPI-C, while MPI-BGC added a strong expertise in modelling <sup>18</sup>O and <sup>13</sup>C isotope cycles which are of key importance for constraining the past dynamics. Last but not least, ENIGMA enhanced discussions of the cross-cutting issues such as terrestrial hydrology, permafrost, and dynamic wetlands.

The topic of wetlands and methane was connecting all ESRP partners, and particularly contributing to the work packages 4 “Holocene climate and carbon cycle” and 6 “Methane changes since the preindustrial era”, while the whole methane cycle was also tackled in WP2 “Climate modules for economic optimisation” and WP5 “Land use, the biosphere, and the Earth system”. This is reflected by the conducted and ongoing development and implementation of wetland hydrology and biogeochemistry into JSBACH, measurement and modelling of methane emissions from wetlands at MPI-BGC and MPI-M, understanding and modelling of methane related processes in wetlands (such as anoxic decomposition) at MPI-BGC, measurement (MPI-C) and modelling of atmospheric transport of methane within EMICs (PIK) and ESMs (MPI-C). The enhanced communication through ENIGMA on this topic, such as realised in a workshop on wetlands, has avoided parallel development and formed a knowledge base that allows for common future model developments including the definition of model routine interfaces, such as required for bringing together modelling parts of wetland hydrology and biogeochemistry.

Within WP8 “Nitrogen-Carbon (N-C) cycles”, the initiative of ENIGMA participants has led to the development of coupled climate-carbon cycle model that include nitrogen cycle feedback (Churkina et al., 2009). The model results suggest that incorporation of nitrogen cycle (which is still missing in most of the state-of-the-art models) may alter the sign of feedback between climate and terrestrial carbon cycle from positive to negative. Recent simulations by several other groups support this important result.

Also under the same work package, an active collaboration between MPI-M and MPI-C has been developed with the aim to explicitly calculate mass exchanges of trace species between

the ocean and atmosphere. The effort was led by MPI-C and MPI-M. It required the combined expertise of atmospheric chemistry and oceanic biogeochemistry modellers. The ocean model MPIOM and the biogeochemical model HAMOCC (both developed at MPI-M) have been coupled with ECHAM5 including full chemistry within the MESSy framework (MPI-C) to facilitate the efficient exchange of large numbers of chemical tracers. The newly developed version of the chemistry-climate model, EMMAC (ECHAM5-MPIOM-HAMOCC/MESSy Atmospheric Chemistry), is the first climate model that enables a direct physical and chemical coupling of the ocean and atmosphere.

The Millennium project (WP2) delivered the first simulations of historical climate evolution in an Earth system context using a comprehensive general circulation model including the carbon cycle. This accomplishment is based substantially on the development of the advanced land surface module JSBACH including the terrestrial carbon cycle and surface energy feedbacks. This advance of JSBACH was only possible due to the shared expertise from ENIGMA partners within WP 5 “Land use, the biosphere, and the Earth system”. The new reconstruction of land cover changes (WP5, Pongratz et al., 2008) made new analyses possible, focusing on biogeophysical and biophysical effects of anthropogenic land use and its effect on climate and the carbon cycle. Moreover, the land-cover-change reconstructions will be used by the Paleo Modelling Intercomparison Project (PMIP) community for upcoming millennium simulations.

Within WP5, the trio of MPI-M, MPI-BGC and PIK have organised a series of annual meetings of biosphere and land use modellers that led to the formation of the GINKGO network (GINKGO is a network for climate and global ecosystem modelling) and the successful initiation of the TERRABITES EU COST networking action on the topic of land in the Earth System and land surface modelling in the Earth system. For the latter, MPI-M is coordinating the activity while PIK is heading one of the four work packages, the one on land use.

One of the ENIGMA goals is to pursue further development of the Earth System models, the major tools that scientists have for projecting climate and biogeochemistry changes in the future. The current strategy is to support the development of a spectrum of Earth System models of different complexity which is necessary to address interactions between Earth System components on different spatial and temporal scales. The ENIGMA project is of special significance to move toward a coherent and harmonized set of models on national scale within Germany, including models of full complexity such as MPI-ESM, intermediate complexity models such as CLIMBER, and special models for interactions between several components, such as biospheric model LPJ and atmospheric dynamics-chemistry models EMAC and ECHAM-HAM.

The development of Earth System models is going on so rapidly today that there is a constant need to discuss a recent state of research going on in the partner institutes. These discussions help to harmonize model development and avoid parallel developments as well as keep a balance between different model components. Periodic work package meetings, workshops on cross-cutting issues, and annual ESRP meetings in Ringberg were important instruments to pursue effective communication within ENIGMA. In addition, a joint summer school on boundary layer processes in the Earth system was organized in 2010. This communication ensured that project partners use the most recent model approaches, observational datasets, and the best available expertise to be successful in integrated modelling and assessment.

## **ENIGMA publications involving members from at least 2 partner institutes**

### **MPI-BGC/MPI-C**

- Andreae, M. O., Artaxo, P., Beck, V., M. Bela, Gerbig, C., Longo, K., Munger, J. W., Wiedemann, K. T., and Wofsy, S. C., Carbon monoxide and related trace gases and aerosols over the Amazon Basin during the wet and dry seasons: *Atmos. Chem. Phys. Discuss.*, 2012, to be submitted.
- Beck, V., Chen, H., Gerbig, C., Bergamaschi, P., Bruhwiler, L., Houweling, S., Röckmann, T., Kolle, O., Steinbach, J., Koch, T., Sapart, C. J., van der Veen, C., Frankenberg, C., Andreae, M. O., Artaxo, P., Longo, K. M., and Wofsy, S. C., Methane airborne measurements and comparison to global models during BARCA: *J. Geophys. Res.*, 2012, submitted.
- Clement, L.W., S.C.W. Koppen, W.A. Brand, and M. Heil, 2008: Strategies of a parasite of the ant-Acacia mutualism. *Behavioral Ecology and Sociobiology*, 62, 953-962. doi: 10.1007/s00265-007-0520-1.
- Corazza, M., P. Bergamaschi, A.T. Vermeulen, T. Aalto, L. Haszpra, F. Meinhardt, S. O'Doherty, R. Thompson, J. Moncrieff, E. Popa, M. Steinbacher, A. Jordan, E. Dlugokencky, C. Bruhl, M. Krol, and F. Dentener, 2011: Inverse modelling of European N(2)O emissions: assimilating observations from different networks. *Atmospheric Chemistry and Physics*, 11, 2381-2398. doi: 10.5194/acp-11-2381-2011.
- Desai, A.R., A.D. Richardson, A.M. Moffat, J. Kattge, D.Y. Hollinger, A. Barr, E. Falge, A. Noormets, D. Papale, M. Reichstein, and V.J. Stauch, 2008: Cross-site evaluation of eddy covariance GPP and RE decomposition techniques. *Agricultural and Forest Meteorology*, 148, 821-838. doi: 10.1016/j.agrformet.2007.11.012.
- Kuhn, U., M.O. Andreae, C. Ammann, A.C. Ara'ujo, E. Brancaleoni, P. Ciccioli, T. Dindorf, M. Frattoni, L.V. Gatti, L. Ganzeveld, B. Kruijt, J. Lelieveld, J. Lloyd, F.X. Meixner, A. D. Nobre, U. Pöschl, C. Spirig, P. Stefani, A. Thielmann, R. Valentini, and J. Kesselmeier, 2007: Isoprene and monoterpene fluxes from Central Amazonian rainforest inferred from tower-based and airborne measurements, and implications on the atmospheric chemistry and the local carbon budget. *Atmos. Chem. Phys.* 7, 2855-2879.
- Kuhn, U., L. Ganzeveld, A. Thielmann, T. Dindorf, G. Schebeske, M. Welling, J. Sciare, G. Roberts, F.X. Meixner, J. Kesselmeier, J. Lelieveld, O. Kolle, P. Ciccioli, J. Lloyd, J. Trentmann, P. Artaxo, and M.O. Andreae, 2010: Impact of Manaus City on the Amazon Green Ocean atmosphere: ozone production, precursor sensitivity and aerosol load. *Atmospheric Chemistry and Physics*, 10, 9251-9282. doi: 10.5194/acp-10-9251-2010.
- Lavric, J. V., Heimann, M., Gerbig, C., Winderlich, J., Schulze, E.-D., Andreae, M. O., Onuchin, A. A., and Panov, A. V., Walk Tall: A Look up at the Zotino Tall Tower Observatory: *Meteorol. Technol. Intl.*, 6-10, 2011.
- Lloyd, J., O. Kolle, H. Fritsch, S.R. de Freitas, M. Dias, P. Artaxo, A.D. Nobre, A.C. de Araujo, B. Kruijt, L. Sogacheva, G. Fisch, A. Thielmann, U. Kuhn, and M.O. Andreae, 2007: An airborne regional carbon balance for Central Amazonia. *Biogeosciences*, 4, 759-768.
- Luyssaert, S., M. Reichstein, E.D. Schulze, I.A. Janssens, B.E. Law, D. Papale, D. Dragoni, M.L. Goulden, A. Granier, W.L. Kutsch, S. Linder, G. Matteucci, E. Moors, J.W. Munger, K. Pilegaard, M. Saunders, and E.M. Falge, 2009: Toward a consistency cross-check of eddy covariance flux-based and biometric estimates of ecosystem carbon balance. *Global Biogeochemical Cycles*, 23, Gb3009. doi: 10.1029/2008gb003377.
- Moffat, A.M., D. Papale, M. Reichstein, D.Y. Hollinger, A.D. Richardson, A.G. Barr, C. Beckstein, B.H. Braswell, G. Churkina, A.R. Desai, E. Falge, J.H. Gove, M. Heimann, D.F. Hui, A.J. Jarvis, J. Kattge, A. Noormets, and V.J. Stauch, 2007: Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. *Agricultural and Forest Meteorology*, 147, 209-232. doi: 10.1016/j.agrformet.2007.08.011.
- Mraja, A., S.B. Unsicker, M. Reichelt, J. Gershenson, and C. Roscher, 2011: Plant Community Diversity Influences Allocation to Direct Chemical Defence in *Plantago lanceolata*. *Plos One*, 6, e28055. doi: 10.1371/journal.pone.0028055.
- Peylin, P., F.M. Breon, S. Serrar, Y. Tiwari, A. Chedin, M. Gloor, T. Machida, C. Brenninkmeijer, A. Zahn, and P. Ciais, 2007: Evaluation of Television Infrared Observation Satellite (TIROS-N) Operational Vertical Sounder (TOVS) spaceborne CO(2) estimates using model simulations and aircraft data. *Journal of Geophysical Research-Atmospheres*, 112, D09313. doi: 10.1029/2005jd007018.
- Richardson, A.D., M.D. Mahecha, E. Falge, J. Kattge, A.M. Moffat, D. Papale, M. Reichstein, V.J. Stauch, B.H. Braswell, G. Churkina, B. Kruijt, and D.Y. Hollinger, 2008: Statistical properties of random CO2 flux

measurement uncertainty inferred from model residuals. *Agricultural and Forest Meteorology*, 148, 38-50. doi: 10.1016/j.agrformet.2007.09.001.

Rockmann, T., C.X.G. Alvarez, S. Walter, C. van der Veen, A.G. Wollny, S.S. Gunthe, G. Helas, U. Poschl, F. Keppler, M. Greule, and W.A. Brand, 2010: Isotopic composition of H<sub>2</sub> from wood burning: Dependency on combustion efficiency, moisture content, and delta D of local precipitation. *Journal of Geophysical Research-Atmospheres*, 115, D17308. doi: 10.1029/2009jd013188.

Schulze, E.D., P. Ciais, S. Luyssaert, M. Schrumpf, A.A. Janssens, B. Thiruchittampalam, J. Theloke, M. Saurat, S. Bringezu, J. Lelieveld, A. Lohila, C. Rebmann, M. Jung, D. Bastviken, G. Abril, G. Grassi, A. Leip., A. Freibauer, W. Kutsch, A. Don, J. Nieschulze, A. Börner, J. Gash and A.J. Dolman, 2010: The European carbon balance. Part 4: Integration of carbon and other trace-gas fluxes. *Glob. Change Biol.* 16, 1451-1469.

Ulman, M., K. Bielawska, B. Lozowicka, M. Heimann, J. Kesselmeier, G. Schebeske, K.S. Katrynski, and Z. Chilmonczyk, 2007: Determination of volatile organic compounds (VOCs) in the atmosphere over central Siberian forest and southern part of European Taiga in Russia. *Chemia Analityczna*, 52, 435-451.

Vasileva, A. V., Moiseenko, K. B., Mayer, J.-C., Jürgens, N., Panov, A., Heimann, M., and Andreae, M. O., Assessment of the regional atmospheric impact of wildfire emissions based on CO observations at the ZOTTO tall tower station in Central Siberia: *J. Geophys. Res.*, 116, D07301, doi:10.1029/2010JD014571, 2011.

Vigano, I., R. Holzinger, T. Rockmann, A. van Dijk, F. Keppler, M. Greule, W.A. Brand, H. van Weelden, and J. van Dongen, 2009: UV light induces methane emission from plant biomass: Mechanism and isotope studies. *Geochimica Et Cosmochimica Acta*, 73, A1382-A1382.

Vogt, M., S. Turner, N. Yassaa, M. Steinke, J. Williams, and P. Liss, 2008: Laboratory inter-comparison of dissolved dimethyl sulphide (DMS) measurements using purge-and-trap and solid-phase microextraction techniques during a mesocosm experiment. *Marine Chemistry*, 108, 32-39. doi: 10.1016/j.marchem.2007.10.001.

#### **MPI-BGC/MPI-M/PIK**

Churkina, G., Brovkin, V., von Bloh, W., Trusilova, K., Jung, M., and Dentener, F., 2009. Synergy of rising nitrogen depositions and atmospheric CO<sub>2</sub> on land carbon uptake offsets global warming, *Global Biogeochem. Cycles*, v. 23, doi:10.1029/2008GB003291.

#### **MPI-BGC/MPI-M**

Arneth, A., S.P. Harrison, S. Zaehle, K. Tsigaridis, S. Menon, P.J. Bartlein, J. Feichter, A. Korhola, M. Kulmala, D. O'Donnell, G. Schurgers, S. Sorvari, and T. Vesala, 2010: Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience*, 3, 525-532. doi: 10.1038/ngeo905.

Beer, C., M. Reichstein, P. Ciais, D.E. Leopold, P. Oliveira, S. Piao, T. Raddatz, E. Tomelleri, N. Viovy, 2012: Evaluation of process-based water use efficiency by a data-driven global map. *Geophys. Res. Lett.*, in prep.

Brovkin V, P van Bodegom, T Kleinen, C Wirth, W Cornwell, HJC Cornelissen, J Kattge (2012) Plant-driven variation in decomposition rates improves projections of global litter stock distribution. *Biogeosciences* 9:565-576

Demuzere, M., M. Werner, N.P.M. van Lipzig, and E. Roeckner, 2009: An analysis of present and future ECHAM5 pressure fields using a classification of circulation patterns. *International Journal of Climatology*, 29, 1796-1810. doi: 10.1002/joc.1821.

Goll, D.S., V. Brovkin, B. R. Parida, C. H. Reick, J. Kattge, P. B. Reich, P. M. van Bodegom, and U.Niinemets, Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling, *Biogeosciences*, submitted

Kattge J, Knorr W, Raddatz T, Wirth C (2009) Quantifying photosynthetic capacity and nitrogen use efficiency for global-scale terrestrial biosphere models. *Global Change Biology* 15(4):976-991.

Mantlana, K.B., A. Arneth, E.M. Veenendaal, P. Wohland, P. Wolski, O. Kolle, and J. Lloyd, 2008: Seasonal and inter-annual photosynthetic response of representative C(4) species to soil water content and leaf nitrogen concentration across a tropical seasonal floodplain. *Journal of Tropical Ecology*, 24, 201-213. doi: 10.1017/s0266467408004859.

- Mantlana, K.B., A. Arneeth, E.M. Veenendaal, P. Wohland, P. Wolski, O. Kolle, M. Wagner, and J. Lloyd, 2008: Photosynthetic properties of C4 plants growing in an African savanna/wetland mosaic. *Journal of Experimental Botany*, 59, 3941-3952.
- Petersen, A.K., T. Warneke, C. Frankenberg, P. Bergamaschi, C. Gerbig, J. Notholt, M. Buchwitz, O. Schneising, and O. Schrems, 2010: First ground-based FTIR observations of methane in the inner tropics over several years. *Atmospheric Chemistry and Physics*, 10, 7231-7239. doi: 10.5194/acp-10-7231-2010.
- Raddatz, T.J., C. Reick, W. Knorr, J. Kattge, E. Roeckner, R. Schnur, K.-G. Schnitzler, P. Wetzel and J. Jungclaus, 2007: Is the tropical land biosphere dominating the carbon cycle - climate feedback during the 21st century? *Climate Dynamics* 29, 565-574 (doi 10.1007/s00382-007-0247-8).
- Scholze, M., P. Ciais, and M. Heimann, 2008: Modeling terrestrial C-13 cycling: Climate, land use and fire. *Global Biogeochemical Cycles*, 22, Gb1009. doi: 10.1029/2006gb002899.
- Schultz, M.G., A. Heil, J.J. Hoelzemann, A. Spessa, K. Thonicke, J.G. Goldammer, A.C. Held, J.M.C. Pereira, and M. van het Bolscher, 2008: Global wildland fire emissions from 1960 to 2000. *Global Biogeochemical Cycles*, 22, Gb2002. doi: 10.1029/2007gb003031.
- Trusilova, K., Jung, M., Churkina, G., Karstens, U., Heimann, M., Claussen, M., 2008: Urbanization impacts on the climate in Europe: Numerical experiments by the PSU/NCAR Mesoscale Model (MM5). *J. Appl. Met. Clim.* 47, 1422-1455.
- Wohlfahrt, J., S.P. Harrison, P. Braconnot, C.D. Hewitt, A. Kitoh, U. Mikolajewicz, B.L. Otto-Bliesner, and S.L. Weber, 2008: Evaluation of coupled ocean-atmosphere simulations of the mid-Holocene using palaeovegetation data from the northern hemisphere extratropics. *Climate Dynamics*, 31, 871-890. doi: 10.1007/s00382-008-0415-5.
- Wu, J., L. Van Der Linden, G. Lasslop, N. Carvalhais, K. Pilegaard, C. Beier, and A. Ibrom, 2012: Effects of climate variability and functional changes on the interannual variation of the carbon balance in a temperate deciduous forest. *Biogeosciences*, 9, 13-28.

#### **MPI-BGC/PIK**

- Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M. and Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13 (3): 679-706.

#### **MPI-C/MPI-M**

- Austin, J., K. Tourpali, E. Rozanov, H. Akiyoshi, S. Bekki, G. Bodeker, C. Bruhl, N. Butchart, M. Chipperfield, M. Deushi, V.I. Fomichev, M.A. Giorgetta, L. Gray, K. Kodera, F. Lott, E. Manzini, D. Marsh, K. Matthes, T. Nagashima, K. Shibata, R.S. Stolarski, H. Struthers, and W. Tian, 2008: Coupled chemistry climate model simulations of the solar cycle in ozone and temperature. *Journal of Geophysical Research-Atmospheres*, 113, D11306. doi: 10.1029/2007jd009391.
- Braesicke, P., C. Bruhl, M. Dameris, R. Deckert, V. Eyring, M.A. Giorgetta, E. Mancini, E. Manzini, G. Pitari, J.A. Pyle, and B. Steil, 2008: A model intercomparison analysing the link between column ozone and geopotential height anomalies in January. *Atmospheric Chemistry and Physics*, 8, 2519-2535.
- Butchart, N., I. Cionni, V. Eyring, T.G. Shepherd, D.W. Waugh, H. Akiyoshi, J. Austin, C. Bruhl, M.P. Chipperfield, E. Cordero, M. Dameris, R. Deckert, S. Dhomse, S.M. Frith, R.R. Garcia, A. Gettelman, M.A. Giorgetta, D.E. Kinnison, F. Li, E. Mancini, C. McLandress, S. Pawson, G. Pitari, D.A. Plummer, E. Rozanov, F. Sassi, J.F. Scinocca, K. Shibata, B. Steil, and W. Tian, 2010: Chemistry-Climate Model Simulations of Twenty-First Century Stratospheric Climate and Circulation Changes. *Journal of Climate*, 23, 5349-5374. doi: 10.1175/2010jcli3404.1.
- Ellingsen, K., M. Gauss, R. Van Dingenen, F.J. Dentener, L. Emberson, A.M. Fiore, M.G. Schultz, D.S. Stevenson, M.R. Ashmore, C.S. Atherton, D.J. Bergmann, I. Bey, T. Butler, J. Drevet, H. Eskes, D.A. Hauglustaine, I.S.A. Isaksen, L.W. Horowitz, M. Krol, J.F. Lamarque, M.G. Lawrence, T. Van Noije, J. Pyle, S. Rast, J. Rodriguez, N. Savage, S. Strahan, K. Sudo, S. Szopa, and O. Wild, 2008: Global ozone and air quality: A multi-model assessment of risks to human health and crops. *Atmospheric Chemistry and Physics Discussions*, 8, 2163-2223. (Kein "Final Paper" in ACP)
- Funke, B., A. Baumgaertner, M. Calisto, T. Egorova, C.H. Jackman, J. Kieser, A. Krivolutsky, M. Lopez-Puertas, D.R. Marsh, T. Reddmann, E. Rozanov, S.M. Salmi, M. Sinnhuber, G.P. Stiller, P.T. Verronen, S. Versick, T. von Clarmann, T.Y. Vyushkova, N. Wieters, and J.M. Wissing, 2011: Composition changes after the "Halloween" solar proton event: the High Energy Particle Precipitation in the Atmosphere (HEPPA)

model versus MIPAS data intercomparison study. *Atmospheric Chemistry and Physics*, 11, 9089-9139. doi: 10.5194/acp-11-9089-2011.

Funke, B., A. Baumgaertner, M. Calisto, T. Egorova, C.H. Jackman, J. Kieser, A. Krivolutsky, M. López-Puertas, D.R. Marsh, T. Reddman, E. Rozanov, S.M. Salmi, M. Sinnhuber, G.P. Stiller, P.T. Verronen, S. Versick, T. Von Clarmann, T.Y. Vyushkova, N. Wieters, and J.M. Wissing, 2011: Composition changes after the "halloween" solar proton event: The high energy particle precipitation in the atmosphere (HEPPA) model versus MIPAS data intercomparison study. *Atmospheric Chemistry and Physics*, 11, 9089-9139.

Guglielmo, F., I. Stemmler, and G. Lammel, 2012: The impact of organochlorines cycling in the cryosphere on their global distribution and fate - 1. Sea ice. *Environmental Pollution*, 162, 475-481.

Kulmala, M., A. Asmi, H.K. Lappalainen, U. Baltensperger, J.L. Brenguier, M.C. Facchini, H.C. Hansson, Ø. Hov, C.D. O'Dowd, U. Pöschl, A. Wiedensohler, R. Boers, O. Boucher, G. De Leeuw, H.A.C. Denier Van Der Gon, J. Feichter, R. Krejci, P. Laj, H. Lihavainen, U. Lohmann, G. McFiggans, T. Mentel, C. Pilinis, I. Riipinen, M. Schulz, A. Stohl, E. Swietlicki, E. Vignati, C. Alves, M. Amann, M. Ammann, S. Arabas, P. Artaxo, H. Baars, D.C.S. Beddows, R. Bergström, J.P. Beukes, M. Bilde, J.F. Burkhardt, F. Canonaco, S.L. Clegg, H. Coe, S. Crumeyrolle, B. D'Anna, S. Decesari, S. Gilardoni, M. Fischer, A.M. Fjaeraa, C. Fountoukis, C. George, L. Gomes, P. Halloran, T. Hamburger, R.M. Harrison, H. Herrmann, T. Hoffmann, C. Hoose, M. Hu, A. Hyvärinen, U. Hörrak, Y. Iinuma, T. Iversen, M. Josipovic, M. Kanakidou, A. Kiendler-Scharr, A. Kirkevåg, G. Kiss, Z. Klimont, P. Kolmonen, M. Komppula, J.E. Kristjánsson, L. Laakso, A. Laaksonen, L. Labonnote, V.A. Lanz, K.E.J. Lehtinen, L.V. Rizzo, R. Makkonen, H.E. Manninen, G. McMeeking, J. Merikanto, A. Minikin, S. Mirme, W.T. Morgan, E. Nemitz, D. O'Donnell, T.S. Panwar, H. Pawlowska, A. Petzold, J.J. Pienaar, C. Pio, C. Plass-Duelmer, A.S.H. Prévôt, S. Pryor, C.L. Reddington, G. Roberts, D. Rosenfeld, J. Schwarz, O. Seland, K. Sellegri, X.J. Shen, M. Shiraiwa, H. Siebert, B. Sierau, D. Simpson, J.Y. Sun, D. Topping, P. Tunved, P. Vaattovaara, V. Vakkari, J.P. Veefkind, A. Visschedijk, H. Vuollekoski, R. Vuolo, B. Wehner, J. Wildt, S. Woodward, D.R. Worsnop, G.J. Van Zadelhoff, A.A. Zardini, K. Zhang, P.G. Van Zyl, V.M. Kerminen, K.S. Carslaw, and S.N. Pandis, 2011: General overview: European Integrated project on Aerosol Cloud Climate and Air Quality interactions (EUCAARI)-integrating aerosol research from nano to global scales. *Atmospheric Chemistry and Physics*, 11, 13061-130143.

Kunze, M., P. Braesicke, U. Langematz, G. Stiller, S. Bekki, C. Bruhl, M. Chipperfield, M. Dameris, R. Garcia, and M. Giorgetta, 2010: Influences of the Indian Summer Monsoon on Water Vapor and Ozone Concentrations in the UTLS as Simulated by Chemistry-Climate Models. *Journal of Climate*, 23, 3525-3544. doi: 10.1175/2010jcli3280.1.

Lelieveld, J., C. Brühl, P. Jöckel, B. Steil, P.J. Crutzen, H. Fischer, M.A. Giorgetta, P. Hoor, M.G. Lawrence, R. Sausen, and H. Tost, 2007: Stratospheric dryness: model simulations and satellite observations. *Atmos. Chem. Phys.* 7, 1313-1332.

Morgenstern, O., M.A. Giorgetta, K. Shibata, V. Eyring, D.W. Waugh, T.G. Shepherd, H. Akiyoshi, J. Austin, A.J.G. Baumgaertner, S. Bekki, P. Braesicke, C. Bruhl, M.P. Chipperfield, D. Cugnet, M. Dameris, S. Dhomse, S.M. Frith, H. Garny, A. Gettelman, S.C. Hardiman, M.I. Hegglin, P. Jockel, D.E. Kinnison, J.F. Lamarque, E. Mancini, E. Manzini, M. Marchand, M. Michou, T. Nakamura, J.E. Nielsen, D. Olivie, G. Pitari, D.A. Plummer, E. Rozanov, J.F. Scinocca, D. Smale, H. Teyssedre, M. Toohey, W. Tian, and Y. Yamashita, 2010: Review of the formulation of present-generation stratospheric chemistry-climate models and associated external forcings. *Journal of Geophysical Research-Atmospheres*, 115, D00m02. doi: 10.1029/2009jd013728.

Pozzer, A., P. Jöckel, B. Kern, and H. Haak, 2011: The atmosphere-ocean general circulation model EMAC-MPIOM. *Geosci. Model Dev.*, 4, 771-784.

Tourpali, K., A.F. Bais, A. Kazantzidis, C.S. Zerefos, H. Akiyoshi, J. Austin, C. Bruhl, N. Butchart, M.P. Chipperfield, M. Dameris, M. Deushi, V. Eyring, M.A. Giorgetta, D.E. Kinnison, E. Mancini, D.R. Marsh, T. Nagashima, G. Pitari, D.A. Plummer, E. Rozanov, K. Shibata, and W. Tian, 2009: Clear sky UV simulations for the 21st century based on ozone and temperature projections from Chemistry-Climate Models. *Atmospheric Chemistry and Physics*, 9, 1165-1172.

#### **MPI-M/PIK**

Andreev A.A., Schirrmeyer, L., Tarasov, P.E., Ganopolski, A., Brovkin, V., Siebert, C., Hubberten H.-W., Vegetation and climate history in the Laptev Sea region (arctic Siberia) during Late Quaternary inferred from pollen records, 2011. *Quaternary Science Reviews*, 30, 2182-2199.

- Brovkin, V., Petoukhov, V., Claussen, M., Bauer, E., Archer, D., Jaeger, C., 2009: Geoengineering climate by stratospheric sulfur injections: Earth system vulnerability to technological failure. *Climatic Change* 92, 243-259, doi: 10.1007/s10584-008-9490-1.
- Brovkin, V., Ganopolski, A., Archer, D., and Munhoven, G., Glacial CO<sub>2</sub> cycle as a succession of key physical and biogeochemical processes, *Clim. Past*, 8, 251–264, 2012. doi:10.5194/cp-8-251-2012
- Calov, R., Ganopolski, A., Kubatzki, C., Claussen, M., 2009: Mechanisms and time scales of glacial inception simulated with an Earth system model of intermediate complexity. *Clim. Past* 5, 245-258.
- Claussen, M., Berger, A., Held, H., 2007: A survey of hypotheses for the 100 ka cycle. in: Sirocko, F., Claussen, M., Sanchez-Goni, M., Litt, T. (eds.) 2007: *The climate of past interglacials*. *Developments in Quaternary Science* 7, Elsevier Publisher, 29-35.
- Dakos, V., M. Scheffer, E. H. van Nes, V. Brovkin, V. Petoukhov, H. Held, 2008: Slowing down as an early warning signal for abrupt climate change, *PNAS* 105, 38, 14308-14312, doi/10.1073/pnas.0802430105.
- Ganopolski, A., Calov, R., Claussen, M., 2010: Simulation of the last glacial cycle with a coupled climate ice-sheet model of intermediate complexity. *Clim. Past*, 6, 229-244.
- Jin, L., Chen, F., Ganopolski, A., and Claussen, M., 2007: Response of East Asian climate to Dansgaard/Oeschger and Heinrich events in a coupled model of intermediate complexity. *Geophys. Res.*, 112, D06117, doi:10.1029/2007JD007317.
- Kubatzki, C., Claussen, M., Calov, R., Ganopolski, A., 2007: Modelling the end of an interglacial (MIS 1,5,7,9,11). in: Sirocko, F., Claussen, M., Litt, T., Sanchez-Goni, M. (eds.) 2007: *The climate of past interglacials*. Springer-Verlag, Berlin Heidelberg, 583-593.
- Pitman, A.J., deNoblet-Ducoudre, N., Cruz, F.T., Davin, E.L., Bonan, G.B., Brovkin, V., Claussen, M., Delire, C., Ganzeveld, L., Gayler, V., van den Hurk, B.J.J.M., Lawrence, P.J., van der Molen, M.K., Müller, C., Reick, C.H., Seneviratne, S.I., Strengers, B.J., Voldoire, A., 2009: Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophys. Res. Lett.*, 36, L14814, doi:10.1029/2009GL039076.
- Rietkerk, M., Brovkin, V., von Bodegom, P.M., Claussen, M., Dekker, S.C., Dijkstra, H.A., Gorayachin, S.V., Kabat, P., van Ness, E.H., Neutel, A.-M., Nicholson, S.E., Nobre, C., Petoukhov, V., Provenzale, A., Scheffer, M., and Seneviratne, S.I., 2011: Local ecosystem feedbacks and critical transitions in the climate. *Ecol. Complex.*, doi:10.1016/j.ecocom.2011.03.001
- M. Scheffer, J. Bascompte, W. Brock, V. Brovkin, S. Carpenter, V. Dakos, H. Held, E. van Nes, M. Rietkerk, G. Sugihara, 2009: Early warning signals for critical transitions, *Nature*, 461, 53-59, doi:10.1038/nature/08227.
- Schneider von Deimling, T., M. Meinshausen, A. Levermann, V. Huber, K. Frieler, D. M. Lawrence, and V. Brovkin, 2012. Estimating the near-surface permafrost-carbon feedback on global warming, *Biogeosciences*, 9, 649–665, doi:10.5194/bg-9-649-2012.