Exchanges

- Selected Research Papers -

Modelling the Late Maunder Minimum with a 3-dimensional OAGCM[1]

Irene Fischer-Bruns[1], Ulrich Cubasch[1], Hans von Storch[2], Eduardo Zorita[2], J. Fidel Gonzáles-Rouco[3] and Jürg Luterbacher[4]

[1] Modelle und Daten, Max-Planck-Institut für Meteorologie, Hamburg, Germany
[2] GKSS, Institut für Küstenforschung Geesthacht, Germany
[3] Depto. de Astrofísica y Ciencias de la Atmósfera Universidad Complutense de Madrid, Spain
[4] Nationaler Forschungsschwerpunkt Klima, Universität Bern, Switzerland
corresponding e-mail: fischer-bruns@dkrz.de

Abstract

A fully coupled OAGCM has been forced with the solar variability, the volcanism and the greenhouse gas concentrations for the last 450 years. The simulation shows almost global cooling during the Late Maunder Minimum (LMM, 1675-1715) with the lowest values in the North Atlantic. This is consistent with the available historic reconstructions. The rate of cooling at the onset of the LMM and the rate of warming at the end of the LMM are in the same range or even larger than what has been experienced since the industrialization. During the first half of the LMM the NAO has a negative phase allowing cold Siberian air to penetrate deeply into Europe. During the second half, the NAO shifts into a positive phase, thus contributing to the warming, which eventually marked the end of the LMM. The North Atlantic experiences a "Great Salinity Anomaly", which leads to an increased ice-coverage in the Denmark Straight.

1. Introduction

So far, fully coupled 3-dimensional OAGCM's have successfully simulated the present day climate, the climate since the beginning of the industrialization, and have been used to calculate future climates (IPCC, 2001). In the study presented here, such a model is used to simulate the climate since 1550. These simulations are performed in response to the discussion about the attribution of the recently observed climate change to anthropogenic factors. In this context it is debated whether the climate change experienced since the beginning of industrialization is unique in its rate and magnitude, and how this change compares to the climate change during the Little Ice Age (LIA). It is also an interesting test for the models, where we can gain more confidence in their ability to simulate a future climate, if we can calculate realistically historic climate events. Furthermore such a simulation can be used to validate historic climate reconstructions, for example from tree rings.

Cubasch et al. (1997) and Cubasch and Voss (2000) performed the first numerical experiments of this kind. They forced an earlier version of the model, which has been used to run climate change simulations with the solar variability since the 17th century. They found a significant response to long periodic large amplitude variations of the solar radiation. These data where further analysed by Hegerl et al. (1997). They could distinguish between a natural forcing signal and a greenhouse gas signal and could prove that during the recent decades the anthropogenic signal was significantly larger than the natural forcing signal. Tett et al. (1999, 2000) extended this approach running multiple experiments and the inclusion of volcanic forcing. They confirmed the results of Hegerl et al. (1997) and Cubasch et al. (1997) that the natural forced variability is smaller than the anthropogenically forced climate change and does not explain the temperature increase recently observed. Both sets of experiments did, however, not go far back enough in time to be able to simulate the LIA.

Crowley (2000) performed a simulation starting at the year 1000, but using only a 1-dimensional energy balance model. Shindell et al. (2001) performed an equilibrium study with an atmosphere model coupled to a mixed layer ocean for the LMM.

In the present study the natural and anthropogenic forcing described by Crowley (2000) has been used to drive a fully coupled 3-dimensional ocean atmosphere in a transient mode, i.e. the time evolution of the climate before, during and after the LMM is calculated.

The experimental set up and the model used are described in section 2, the results are discussed in section 3. Besides an analysis of the temperature evolution, particular emphasis has been placed on the investigation of the role of the NAO during this time. This is followed by a general discussion in section 4.

[1]Published in Exchanges No. 25, September 2002

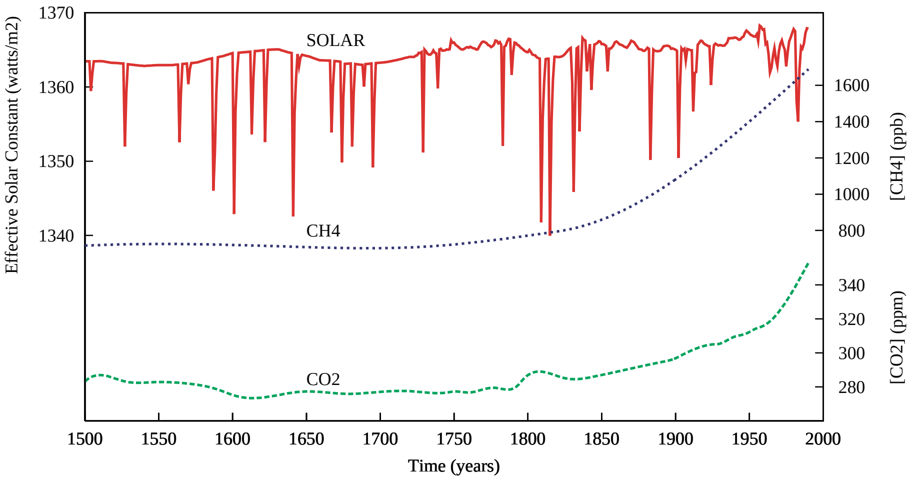

Fig. 1: Effective solar output (in W/m²) and concentrations of CO_2 and methane (CH_4) from 1500 to 2000 used to force the climate model.

2. The model and the experimental set up

The T30 version of the ECHAM4 atmosphere model (Roeckner et al., 1992) coupled to the HOPE ocean model (Wolff et al., 1997; Legutke and Maier-Reimer, 1999; Legutke and Voss, 1999) is used for the simulation. The ocean model has a resolution of 2.8° which increases to 0.5° near the equator in order to be able to simulate ENSO events. Two simulations have been performed: a 1000 year long control simulation, in which the solar and greenhouse gas forcing have been held fixed to present day conditions, and a historic climate change simulation with time dependent forcing. For the latter experiment, the solar forcing (reconstructed from ^{10}Be data), the volcanic forcing and the greenhouse gas forcing have been prescribed using the same data, which Crowley (2000) applied in his experiments. The albedo effect of the volcanoes is implemented as a reduction of the solar forcing. Fig. 1 shows the different forcings prescribed during the forced simulation. The simulation starts from present-day forcing conditions. These are slowly changed in 35 model years to the estimated values for year 1500 AD. This time period is not sufficient to obtain a deep ocean circulation at equilibrium with the forcing, but it is long enough to obtain a realistic response in the top layers of the ocean and in the atmosphere. The model achieves a stable state around year 1550 AD.

3. Results

Temperature Evolution

The mean temperature evolution can be found in Fig. 2. In order to make it comparable to the observational data by Mann et al. (1998), for the years prior to

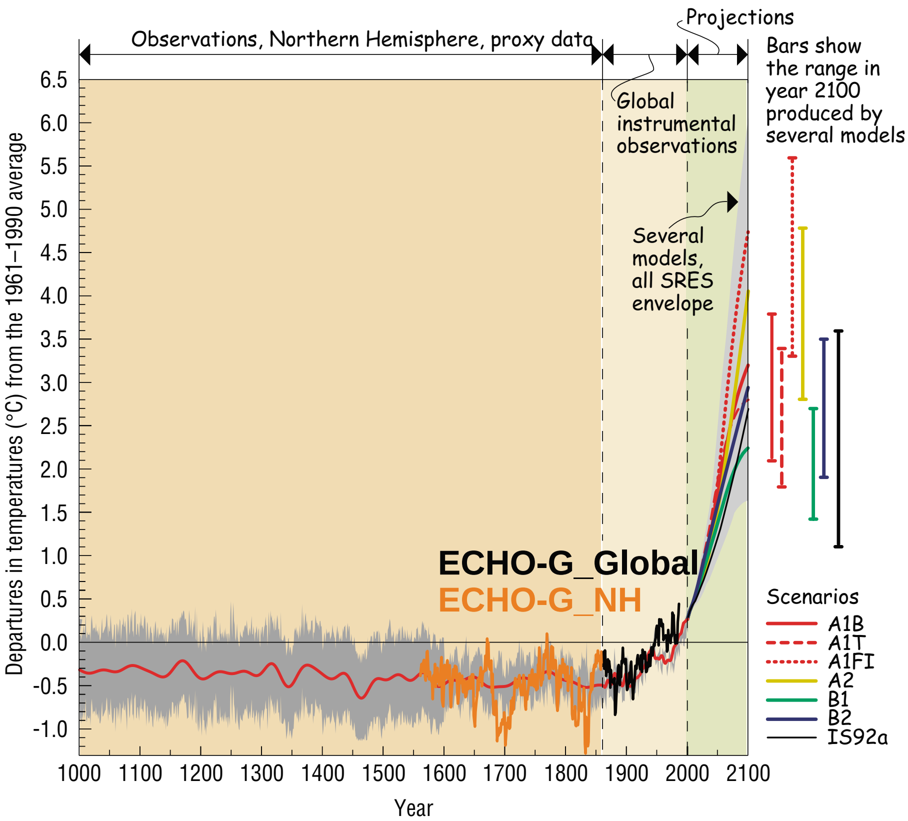

Fig. 2: Time series of mean temperature anomalies simulated in the 1550-1860 run for the NH (orange), for the whole globe from 1860 to 1990. These curves have been superimposed on the diagram of the IPCC synthesis report (Albritton et al., 2001) showing the temperature evolution according to Mann et al. (1998) and the projections up to the year 2100.

1860 only the Northern Hemisphere (NH) has been displayed. The temperature has two distinct minima, one during the LMM, and one during the Dalton Minimum (circa 1780-1829). These minima have a larger amplitude than in the reconstruction by Mann et al. (1998). Their amplitude is more comparable to the recent reconstructions by Esper (2002). It is interesting to note that the warming (cooling) rates are in the same range or even larger than what has been observed during the 20th century.

The global mean temperature change for the LMM period shows a cooling over the whole globe with the lowest temperatures in the NH, and particularly in the North Atlantic region (Fig. 3). This is in contrast to the findings by Shindell et al. (2001) and Cubasch et al. (1997), which more or less obtain the global warming pattern with an inverse sign once the solar input is reduced. This shows the importance of the volcanic forcing, which had been neglected in these two studies, as Shindell (pers. com.) has been able to show.

The largest cooling can be found in the western North Atlantic, where south of Greenland and close to Iceland a large ice covered area emerges. This ice cover diminishes the heat flow of the ocean into the atmosphere. It bears the signature of a "Great Salinity Anomaly" (GSA) as described by Dickson et al. (1988) and Mysak et al. (1990). Such an anomaly has been found in simulations by Hall and Stouffer (2001), where it has been generated by non-linear dynamics without additional forcing. In the case presented here it is caused by increased precipitation in the years before the LMM. The LMM simulation by Shindell et al. (2001) cannot simulate a GSA since it is a transient feature and demands a fully interactive ocean, because it needs the dynamical interplay of atmosphere, ocean and sea-ice.

North Atlantic Oscillation

The North Atlantic Oscillation (NAO) characterizes atmospheric variability at monthly to decadal time scales. Since the interdecadal variability appears to be most evident during the winter season, an EOF analysis of the mean sea level pressure anomalies for the North Atlantic region based on winter data (DJF) has been performed. The model produces a realistic representation of the winter NAO pattern (Fig. 4) in the historic climate change simulation (1550-1990).

The NAO index is defined as the difference between the area averaged and normalized mean sea-level pressure anomalies representing the teleconnectivity centres located northwest of Portugal and over Iceland (Ulbrich and Christoph, 1999, Portis et al., 2001). The principal component time series corresponding to the leading EOF is highly correlated (r=0.92) with the NAO index in the simulation. The simulated NAO index has also been compared with the reconstructed NAO index by Luterbacher et al. (1999, 2002), who used long-term instrumental time series and high-resolution documentary proxy data for his reconstruction. Both time series show considerable variability and differences in phase. They never enter a quasi-permanent low index phase during the LMM associated with weaker mean westerlies over the North Atlantic as suggested by Shindell et al. (2001).

Furthermore, an analysis of the modelled annual global mean temperature in relation to the modelled NAO index for the time period 1550-1800 reveals that during approximately the first half of the LMM (LMM1, 1671-1684) the NAO index is negative, together with a sharp drop in temperature in Europe, while it turns positive approximately during in the second half of the LMM (LMM2, 1685-1708) with an increase in temperature (Fig. 5). During the first phase of the LMM the advection of continental cold air dominates in central Europe, while in the second phase the NAO contributes with an en-

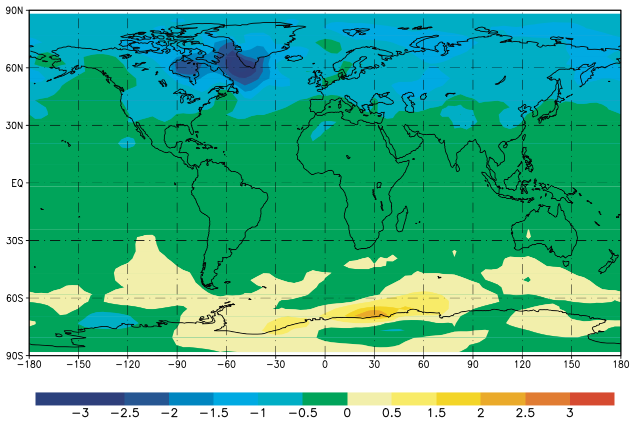

Fig. 3: Difference in annual mean near-surface air temperature, simulated during the Late Maunder Minimum event, 1675-1710, and the mean in 1550-1800 AD, in the forced simulation.

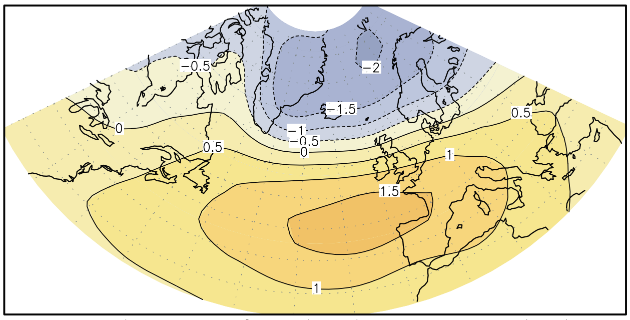

Fig. 4: Leading EOF of North Atlantic mean sea level pressure anomalies based on winter means (DJF) of the historic climate change simulation (1550-1990) explaining 38% of the total variance.

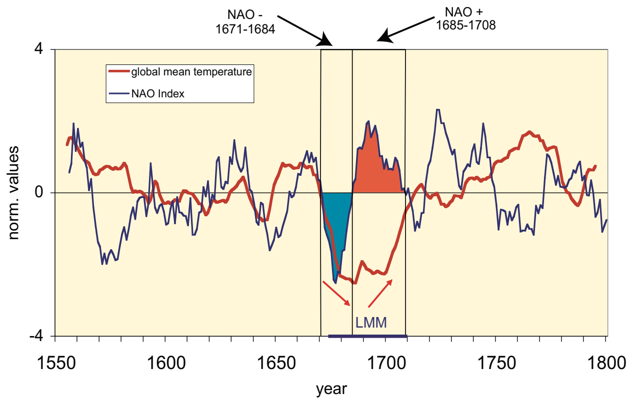

Fig.5: Modeled annual global mean temperature and NAO index (1550-1800, normalized time series, 11 year moving average). In the LMM1 period (1671-1684, cooling phase) the NAO index is negative, in the LMM2 period (1685-1708, warming phase) the NAO index is positive.

hanced advection of warmer Atlantic air masses to the decay of the LMM. This cooling-warming transition can be verified with the temperature reconstruction of van den Dool et al. (1978).

The NAO index calculated here is positively correlated with the North Atlantic storm track (defined as the 2.5 to 6 day band pass filtered variance of the 500 hPa geopotential height) with a maximum correlation of 0.6 in the central North Atlantic (cf. Osborn et al., 1999). During the first half of the LMM a significant decrease of storm track activity in the North Atlantic and West European region is found, while for the second half of the LMM an significant increase of storm track activity over the European continent is simulated.

4. Discussion

The model simulation presented here agrees with the equilibrium mixed layer model simulation of Shindell et al. (2001) by simulating a distinct Maunder Minimum with a global drop of temperature and a particularly large drop of temperature over Europe. Contrary to the simulation by Shindell et al. (2001), it shows a large cooling connected to a GSA in Denmark Strait. Also, its NAO is variable, which agrees well with the observational reconstructions. The more stable NAO in Shindell et al.'s calculation might be caused by their experimental design, but might also be caused by their more elaborate representation of the stratosphere.

It has to be stressed that our result is just one realization. Multiple experiments have to be run to enhance the significance of the findings. The excessive amount of computing resources was so far prohibitive.

Acknowledgement

The model simulations have been performed by GKSS at the DKRZ computing center. Irene Fischer-Bruns has been supported by the SFB 512 sponsored by the DFG. The experiments have been part of the KIHZ-project of the Helmholtz-Society. The authors also wish to express thank to D. Shindell for the useful discussion during the AGU Spring Meeting in Washington (2002), and to T. Crowley for making the data available.

References

Albritton, D.L., T. Barker, I.A. Bashmakov, O. Canziani, R. Christ, U. Cubasch, O. Davidson, H. Gitay, D. Griggs, J. Houghton, J. House, Z. Kundzewicz, M. Lal, N. Leary, C. Magadza, J.J. Mccarthy, J.F.B. Mitchell, J.R. Moreira, M. Munasinghe, I. Noble, R. Pachuri, B. Pittock, M. Prather, R.G. Richels, R.B. Robinson, J. Sathaye, S. Schneider, R. Scholes, T. Stocker, N. Sundararaman, R. Swart, T. Taniguchi, and D. Zhou, 2001: Climate Change 2001: Synthesis Report. R.T. Watson ed., Cambridge University Press, 200pp.

Crowley, T.J., 2000: Causes of climate change over the past 1000 years. *Science*, **289**, 270-277

Cubasch, U., G.C. Hegerl, R. Voss, J. Waszkewitz, and T.C. Crowley, 1997: Simulation with an O-AGCM of the influence of variations of the solar constant on the global climate. *Climate Dynamics*, **13**, 757-767

Cubasch, U., and R. Voss, 2000: The influence of total solar irradiance on climate. *Space Science Reviews*, **94**, 185-198.

Dickson, R.R., J. Meincke, S.-A. Malmberg, and A.J. Lee, 1988: The „Great Salinity Anomaly“ in the Northern North Atlantic 1968-1982. *Prog. Oceanog.*, **20**, 103-151.

Esper, J., E.R. Cook, and F.H. Schweingruber, 2002: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science*, **295**, 2250-2254.

Hall, A., and R.J. Stouffer, 2001: An abrupt climate event in a coupled ocean-atmosphere simulation without external forcing. *Nature*, **409**, 171-174.

Hegerl, G.C., K. Hasselmann, U. Cubasch, J.F.B. Mitchell, E. Roeckner, R. Voss, and J. Waszkewitz, 1997: Multi-fingerprint detection and attribution analysis, of greenhouse gas, greenhouse gas-plus-aerosol and solar forced climate change. *Climate Dynamics*, **13**, 613-634.

IPCC, 2001: Projections of future climate change. In: Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, and C.I. Johnson (eds.)]. Cambridge University Press, ISBN 0521 01495 6.

Legutke, S., and R. Voss, 1999: The Hamburg Atmosphere-Ocean Coupled Circulation Model ECHO-G. Technical Report No. 18, DKRZ, Hamburg.

Legutke, S., and E. Maier-Raimer, 1999: Climatology of the HOPE-G Global Ocean - Sea Ice General Circulation Model. Technical Report No. 21, DKRZ, Hamburg.

Luterbacher, J., C. Schmutz, D. Gyalistras, E. Xoplaki, and H. Wanner, 1999: Reconstruction of monthly NAO and EU indices back to AD 1675. *Geophys. Res. Lett.*, **26**, 2745-2748.

Luterbacher, J., E. Xoplaki, D. Dietrich, P.D. Jones, T.D. Davies, D. Portis, J.F. Gonzalez-Rouco, H. von Storch, D. Gyalistras, C. Casty, and H. Wanner, 2002: Extending North Atlantic Oscillation Reconstructions Back to 1500. *Atmos. Sci. Lett.*, **2**, 114-124.

Mann, M.E., R.S. Bradley, and M.K. Hughes, 1998: Global scale temperature patterns and climate forcing over the past six centuries. *Nature*, **392**, 779 – 787.

Mysak, L.A., D.K. Manak, and R.F. Marsden, 1990: Sea-ice anomalies observed in the Greenland and Labrador Seas during 1901-1984 and their relation to an interdecadal Arctic climate cycle. *Climate Dynamics*, **5**, 111-133.

Osborn T.J., K.R. Briffa, S.F.B. Tett, P.D. Jones, and R.M. Trigo, 1999: Evaluation of the North Atlantic Oscillation as simulated by a coupled climate model. *Climate Dynamics*, **15**, 685-702.

Portis, D.H., J.E. Walsh, M. El Hamly, and P.J. Lamb, 2001. Seasonality of the North Atlantic Oscillation. *J. Climate*, **14**, 2069-2078.

Roeckner, E., K. Arpe, L. Bengtsson, S. Brinkop, L. Dümenil, M. Esch, E. Kirk, F. Lunkeit, M. Ponater, B. Rockel, R. Sausen, U. Schlese, S. Schubert, and M. Windelband, 1992: Simulation of the present-day climate with the ECHAM model: Impact of model physics and resolution. Report No. 93, Max-Planck-Institut für Meteorologie, Bundesstr 55, Hamburg.

Shindell, D.T., G-A. Schmidt, M.E. Mann, D. Rind and A. Waple, 2001: Solar forcing of regional climate change during the Maunder minimum. *Science*, 294, 2149-2154.

Tett, S.F.B., P.A. Stott, M.R. Allen, W.J. Ingram und J.F.B. Mitchell, 1999: Causes of twentieth-century temperature change near the Earth's surface. *Nature*, **399**, 569 - 572.

Tett, S. F.B., G.S. Jones, P.A. Stott, D.C. Hill, J.F.B. Mitchell, M.R. Allen, W.J. Ingram, T.C. Johns, C.E. Johnson, A. Jones, D. L. Roberts, D.M.H. Sexton, and M.J. Woodage, 2000: Estimation of natural and anthropogenic contributions to 20th century. Hadley Centre Tech Note 19, Hadley Centre for Climate Prediction and Response, Meteorological Office, RG12 2SY, UK pp52.

Ulbrich, U., and M. Christoph, 1999: A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate Dynamics*, **15**, 551-559.

van den Dool, H.M., H.J. Krijnen, and C.J.E. Schuurmans, 1978: Average winter temperatures at De Bilt (The Netherlands): years 1634-1977. *Climatic Change*, **1**, 319-330.

Wolff, J.-O., E. Maier-Raimer, and S. Legutke, 1997: The Hamburg Ocean Primitive Equation Model HOPE, Technical Report No. 13, DKRZ, Hamburg.