Millennium: Model and experimental details

The Earth System Model:

The Earth System Model developed at the Max Planck Institute for Meteorology consists of the general circulation models for the atmosphere ECHAM5[1] and for the ocean MPIOM[2]. ECHAM5 is run at T31 resolution (3.75°) with 19 vertical levels and MPIOM applies a conformal mapping grid with a horizontal resolution ranging from 22 km to 350 km. This grid set-up is a low-resolution version of the model used for the CMIP3[3], including scenario simulations for the International Panel of Climate Change (IPCC) and C4MIP[4] simulations. Ocean and atmosphere are coupled daily without flux corrections. The carbon cycle model comprises the ocean biogeochemistry module HAMOCC5[5] and the land surface scheme JSBACH[4]. HAMOCC5 simulates inorganic carbon chemistry as well as phyto- and zooplankton dynamics in dependence of temperature, solar radiation and nutrients. It also considers the build-up of detritus, its sinking, remineralisation, and sedimentation. JSBACH distinguishes 12 plant functional types (PFTs) and organic carbon on land occurs in specified vegetation and soil carbon pools. Three-dimensional transport of carbon within the ocean and the atmosphere as well as the exchange between atmosphere and land biosphere are calculated each time step so that the daily and seasonal cycle of the atmospheric CO_2 concentrations are resolved. The carbon flux between the ocean and the atmosphere is determined at each coupling time step.

External forcing

Land-cover changes: Anthropogenic land cover change is considered by applying the reconstruction of global agricultural areas and land cover[6]. The global maps with a spatial resolution of 0.5° and an annual timescale contain 14 vegetation types and discriminate between the agricultural categories cropland, and C3 and C4 pastures. The reconstruction merges published maps of agriculture from AD1700 to 1992 and a population-based approach to quantify agriculture from AD 800 to 1700. This approach captures the expansion of agriculture but also regionally confined historical events, such as warfare and epidemics[7].

Orbital forcing: The ECHAM5 model contains a precise representation of periodic changes of the Earth's orbit around the Sun on all frequencies, including short term variations beyond a few years. It uses the Variation Seculaires des Orbites Planetaires (VSOP) analytical solution[8] and determines today's orbit for an interval -4000 to 8000 years with respect to the year 2000 accurately. Additionally, the nutation, a small wobble of the Earth's rotational axis with a period of 18.6 years is represented in the model[1].

Solar forcing: Total solar irradiance forcing (figure S1) used for ensemble E1 (the standard forcing) exhibits a total increase in TSI of 0.1% from the Maunder Minimum to today, which is in agreement with recent evaluations[9,10,11]. The data set has daily sampling from 1627 AD onward[12,13]. In this period, the 11-year activity cycle is included since solar irradiance was reconstructed from historical records of sunspot numbers, where a simple physical model is first used to calculate variations in the solar photospheric magnetic field. Prior to the Maunder Minimum, no direct estimates of solar variability, such as sunspot observations, are available. The TSI time series for the period 800 AD to the Maunder Minimum is reconstructed from estimates of the solar open magnetic flux based on cosmogenic isotope ^{14}C measurements from Antarctic ice cores[14,15,16]. The original time series has a resolution of about 10 years. In order to derive a consistent time series applied as solar forcing for the model, the 11-years cycle has been artificially over-imposed onto the time beyond the Maunder Minimum. The amplitude was estimated from the analysis of the relationship between the cycle amplitude and overall solar activity, as represented by the 11-year running mean of the TSI between 1700 and 1880 AD. The TSI series (figure S1) used for ensemble model experiments E2 is based on another compilation of ^{14}C and ^{10}Be production rates[17] from which an annual data set was derived[18]. Both TSI forcing series are fitted by adding a constant in order to start with a solar constant of 1367 W/m^2 that is used in the control run for the coupled model.

Volcanic forcing: The volcanic forcing is calculated online in the model using time series of aerosol optical depth (AOD) at 0.55μm and of the effective radius (R_{eff})[19]. The time resolution of the series is ten days and the data are provided at four equal area latitude bands (Figure S2). AOD estimates are based on a correlation between sulphate in Antarctic ice cores and satellite data[20]. R_{eff} growth and decay is based on satellite observations of the Pinatubo eruption in 1991, with eruptions larger than that of Pinatubo (maximum is 0.15) being scaled by the theoretical calculations for very large eruptions[21]. In the model AOD is distributed between 20-86 hPa over three vertical levels, with a maximum at 50 hPa. Sensitivity experiments for the model response to the Pinatubo eruption yield an average global temperature change (0.4 K) comparable to observations. For the largest eruption of the last millennium, the 1258 AD eruption, a NH summer temperature anomaly over land of 1.2 K is found in agreement with reconstructions[22].

Greenhouse gas forcing: The carbon dioxide concentration is calculated interactively within the model. The concentrations of the next two major greenhouse gases, methane (CH_4) and nitrous oxide (N_2O) are prescribed[23]. The data sets are applied to the model using annual resolution, where a simple spline function is used for smoothing the data. The projection of these greenhouse gases into the future, as well as a number of chlorofluorocarbons (CFC) that are considered in the model, follows the IPCC scenario A1B, which is defined in the Special Report on Emission Scenarios (SRES)[24]. For all simulations, present day ozone climatology[25] is prescribed.

Aerosol forcing: The climatology of background aerosol distribution[26] distinguishes time independent spatial distributions of the optical thickness of sea, land, urban, and desert aerosols, and well mixed tropospheric and stratospheric background aerosols. The spatially varying aerosols are described by a maximum optical thickness at 0.55µm, normalized horizontal distributions, normalized vertical integrals, and a troposphere stratosphere discrimination factor. The optical depth at 0.55µm is rescaled to the spectral intervals of the ECHAM radiation scheme[1].

The natural and anthropogenic sulphate dry mass are provided as monthly means in µg SO4 m^{-3}, every 10 years for 1750 (i.e. natural preindustrial distribution), 1850, 1900, 1920 to 1980, and 1990 to 2100 and converted online in optical parameters. The 1850 to 1980 sulphate fields uses historical reconstructions[27]. The projection from 1990 to 2100 follows the A1B scenario. The sulphur emission scenarios[24] are based on model simulations[28,29].

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