

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

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Abstract

The scientific understanding of the Earth's climate system, including the central question of how the climate system is likely to respond to human-induced perturbations, is comprehensively captured in GCMs and Earth System Models (ESM). Diagnosing the simulated climate response, and comparing responses across different models, is crucially dependent on transparent assumptions of how the GCM/ESM has been driven – especially because the implementation can involve subjective decisions and may differ between modelling groups performing the same experiment. This paper outlines the climate forcings and setup of the Met Office Hadley Centre ESM, HadGEM2-ES for the CMIP5 set of centennial experiments. We document the prescribed greenhouse gas concentrations, aerosol precursors, stratospheric and tropospheric ozone assumptions, as well as implementation of land-use change and natural forcings for the HadGEM2-ES historical and future experiments following the Representative Concentration Pathways. In addition, we provide details of how HadGEM2-ES ensemble members were initialised from the control run and how the palaeoclimate and AMIP experiments, as well as the “emission-driven” RCP experiments were performed.

1 Introduction

Phase 5 of the Coupled Model Intercomparison Project (CMIP5) is a standard experimental protocol for studying the output of coupled ocean-atmosphere general circulation models (GCMs). It provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. The purpose of these experiments is to address outstanding scientific questions that arose as part of the IPCC Fourth Assessment report (AR4) process, improve understanding of climate, and to provide estimates of future climate change that will be useful to those considering its possible consequences and the effect of mitigation strategies.

CMIP5 began in 2009 and is meant to provide a framework for coordinated climate change experiments over a five year period and includes simulations for assessment in

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



the IPCC Fifth Assessment Report (AR5) as well as others that extend beyond the AR5. The IPCC's AR5 is scheduled to be published in September 2013. CMIP5 promotes a standard set of model simulations in order to:

- evaluate how realistic the models are in simulating the recent past,
- provide projections of future climate change on two time scales, near term (out to about 2035) and long term (out to 2100 and beyond), and
- understand some of the factors responsible for differences in model projections, including quantifying some key feedbacks such as those involving clouds and the carbon cycle.

A much more detailed description can be found on the CMIP5 project webpages (see URL 1 in Appendix A) and in Taylor et al. (2009).

There are a number of new types of experiments proposed for CMIP5 in comparison with previous incarnations. As in previous intercomparison exercises, the main focus and effort rests on the longer time-scale (“centennial”) experiments, including now emission-driven runs of models that include a coupled carbon-cycle (ESMs). These centennial experiments are being performed at the Met Office Hadley Centre with the HadGEM2-ES Earth System model (Collins et al., 2011; Martin et al., 2011); a configuration of the Met Office’s Unified Model. Figure 1 outlines the main experiments and groups them into categories: “realistic” above the line (with studies of the past to the left and future projections to the right) and “idealised” or process-understanding studies below the line. The central pink area shows simulations regarded as “core” with the priority nominally decreasing to tier-1 (yellow) and then tier-2 (green).

In the following, we briefly describe HadGEM2-ES ESM, which is documented in detail in Collins et al. (2011). HadGEM2-ES is a coupled AOGCM with atmospheric resolution of N96 ($1.875^\circ \times 1.25^\circ$) with 38 vertical levels and an ocean resolution of 1° (increasing to $1/3^\circ$ at the equator) and 40 vertical levels. HadGEM2-ES also represents interactive land and ocean carbon cycles and dynamic vegetation with an option

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

to prescribe either atmospheric CO₂ concentrations or to prescribe anthropogenic CO₂ emissions and simulate CO₂ concentrations as described in Sect. 2. An interactive tropospheric chemistry scheme is also included, which simulates the evolution of atmospheric composition and interactions with atmospheric aerosols. The model timestep is 30 min (atmosphere and land) and 1 h (ocean). Extensive diagnostic output is being made available to the CMIP5 multi-model archive. Output is available either at certain prescribed frequencies or as time-average values over certain periods as detailed in the CMIP5 output guidelines (see URL 2 in Appendix A).

The CMIP5 simulations include 4 future scenarios referred to as “Representative Concentration Pathways” or RCPs (Moss et al., 2010). These future scenarios have been generated by four integrated assessment models (IAMs) and selected from over 300 published scenarios of future greenhouse gas emissions resulting from socio-economic and energy-system modelling. These RCPs are labelled according to the approximate global radiative forcing level in 2100 for RCP8.5 (Riahi et al., 2007), during stabilisation after 2150 for RCP4.5 (Clarke et al., 2007; Smith and Wigley, 2006) and RCP6 (Fujino et al., 2006) or the point of maximal forcing levels in the case RCP3-PD (van Vuuren et al., 2006, 2007), with PD standing for “Peak and Decline”. The latter scenario has previously been known as RCP2.6, as radiative forcing levels decline towards 2.6 Wm⁻² by 2100. Note that these radiative forcing levels are illustrative only, because greenhouse gas concentrations, aerosol and tropospheric ozone precursors are prescribed, resulting in a wide spread in radiative forcings across different models.

The experimental protocol involves performing a historical simulation (defined for HadGEM2-ES as 1860 to 2005) using the historical record of climate forcing factors such as greenhouse gases, aerosols and natural forcings such as solar and volcanic changes. The model state at 2005 is then used as the initial condition for the 4 future RCP simulations. Further extension of the RCP simulations to 2300 is also implemented as detailed in the RCP White Paper (see URL 3 in Appendix A) and Meinshausen et al. (2011).

Many of these experiments require technical implementation by means of either or both of the following:

- time-varying boundary conditions such as concentrations of greenhouse gases or emissions of reactive chemical species or aerosol pre-cursors. These may be given as single, global-mean numbers, or supplied as 2-D or 3-D fields of data,
- code changes to alter the scientific behaviour of the model, such as to decouple various feedbacks and interactions (e.g. the “uncoupled” carbon cycle experiments).

This paper presents in detail the technical aspects of how these model forcings are implemented in HadGEM2-ES. It is not our intention here to present scientific results from the experiments. This analysis will be left for subsequent work.

The CMIP5 experiments performed with HadGEM2-ES are listed in Table 1 along with the relevant forcings for each experiment. How these forcings are then implemented is detailed in the following sections with Sect. 2 describing the atmospheric CO₂ concentrations for the concentration-driven runs as well as the CO₂ emission assumptions for the emission-driven experiments. Section 3 details the boundary conditions of atmospheric concentrations of the other well-mixed greenhouse gases. Tropospheric and stratospheric ozone assumptions are detailed in Sect. 4. Section 5 details the treatment of aerosols, while Sect. 6 documents that applied to land use pattern changes. Natural forcings, both solar and volcanic, are described in Sect. 7. Apart from these recent history, centennial 21st century and longer-term experiments, we describe as well the setup for the palaeoclimatic runs in Sect. 8. The more general issue of how the ensemble members are branched off the control run is described in Sect. 9, and Sect. 10 concludes. A list of URL locators for websites holding relevant data is included as an Appendix.

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



2 Carbon dioxide

2.1 CO₂ concentration

For simulations requiring prescribed atmospheric CO₂ concentrations, a single global 3-D constant provided as an annual mean mass mixing ratio was used – linearly interpolated in the model at each timestep. This prescribed CO₂ concentration is then passed to the model’s radiation scheme, and constitutes a boundary condition for the terrestrial and ocean carbon cycle. The oceanic partial pressure of CO₂, $p\text{CO}_2$, is always simulated prognostically from this, i.e. it is not itself prescribed.

The CO₂ concentrations used were taken from the CMIP5 dataset (see URL 4 in Appendix A). The historical part of the concentrations (1860–2005) is derived from a combination of the Law Dome ice core (Etheridge et al., 1996), NOAA global mean data (see URL 5 in Appendix A) and measurements from Mauna Loa (Keeling et al., 2009). After 2005, CO₂ concentrations recommended for CMIP5 were calculated for the 21st century from harmonized CO₂ emissions of the four IAMs that underlie the four RCPs. Beyond 2100, these concentrations were extended, so that the CO₂ concentrations under the highest RCP, RCP8.5, stabilize just below 2000 ppm by 2250. Both the medium RCPs smoothly stabilize around 2150, with RCP4.5 stabilizing close to the 2100 value of the former SRES B1 scenario (~540 ppm). The lower RCP, RCP3-PD, illustrates a world with net negative emissions after 2070 and sees declining CO₂ concentrations after 2050, with a decline of 0.5 ppm yr⁻¹ around 2100 (see Fig. 2). These CO₂ concentrations are prescribed in HadGEM2-ES’s historical, AMIP, RCP simulations and the carbon-cycle uncoupled experiments. The detection and attribution experiments with time varying CO₂ also use these values, but the detection and attribution experiments with fixed CO₂ levels use a constant, pre-industrial value of 286.3 ppm. This CMIP5 dataset also provides the CO₂ concentration used for the pre-industrial control simulation (taken here to be 1860 AD), which is 286.3 ppm. CO₂ for the palaeoclimate

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



simulations is described in Sect. 8. More details on the CMIP5 CO₂ concentrations and how they were derived are provided in Meinshausen et al. (2011).

Aside from these centennial simulations, idealized experiments are performed with HadGEM2-ES for CMIP5 in order to estimate, inter alia, transient and equilibrium climate sensitivity and the climate-carbon cycle feedback. For the idealised annual 1% increase in CO₂ concentration, we start from the control-run level of 286.3 ppm in 1859 up to 4 × CO₂ (1144 ppm) after 140 yr (experiment 6.1). Equivalently, our instantaneous quadrupling to 4 × CO₂ uses a concentration of 1144 ppm in order to allow diagnosis of short-term forcing adjustments and equilibrium climate sensitivities (experiment 6.3).

2.1.1 Decoupled carbon cycle experiments

Using additional code modifications to the appropriate modules of the HadGEM2-ES model, it is possible to decouple different carbon-cycle feedbacks. For the decoupled carbon cycle experiments (5.4, 5.5) we decoupled the climate and carbon cycle in 2 different ways. The C4MIP intercomparison exercise (Friedlingstein et al., 2006) defined an “UNCOUPLED” methodology in which only the carbon cycle component responded to changes in atmospheric CO₂ levels. Gregory et al. (2009) additionally describe the counterpart experiment where only the model’s radiation scheme responds to changes in CO₂. Gregory et al. (2009) recommend performing both experiments (as the results may not combine linearly to give the fully coupled behaviour) and labelling such experiments in terms of what *is* rather than *is not* coupled.

Hence we performed the biogeochemically coupled (“BGC”) experiments (5.4) in which the models biogeochemistry is coupled (i.e., the biogeochemistry modules respond to the changing atmospheric CO₂ concentration) and the radiation scheme is uncoupled (and uses the preindustrial level of CO₂ which is held constant) and also radiatively coupled (“RAD”) experiments (5.5) in which the model’s radiation scheme is allowed to respond to changes in atmospheric CO₂ levels, but the biogeochemistry components (land vegetation and ocean chemistry and ecosystem) use a constant CO₂ level, again set to the preindustrial value. We performed both BGC and RAD

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



experiments for the idealised (1%) and transient, multi-forcing (historical/RCP4.5) scenarios.

2.2 CO₂ emissions

2.2.1 Emissions data

In addition to running with prescribed atmospheric CO₂ concentrations, HadGEM2-ES can be configured to run with a fully interactive carbon cycle. Here, atmospheric CO₂ is treated as a 3-D prognostic tracer, transported by atmospheric circulation, and free to evolve in response to prescribed surface emissions and simulated natural fluxes to and from the oceans and land. This approach is required for the “Emission-driven” simulations (5.1–5.3) shown in green text in Fig. 1, and it also allows additional model evaluation by comparison with flask and station measuring sites such as at Mauna Loa (e.g. Law et al., 2006; Cadule et al., 2010).

A 2-D timeseries of total anthropogenic emissions was constructed by summing contributions from fossil fuel use and land-use change. For the historical simulation, annual mean emissions from fossil fuel burning, cement manufacture, and gas-flaring were provided on a 1° × 1° grid from 1850 to 1949 (Boden et al., 2010), with monthly means from 1950 to 2005 (Andres et al., 2011). For the RCP8.5 simulation, the harmonized fossil fuel emissions for 2005 to 2100 were used (as available in the RCP database, see URL 6 in Appendix A). The land use change (LUC) emissions are based on the regional totals of Houghton (2008), which were provided as annual means of the period 1850–2005. Within each of the ten regions the emissions were linearly weighted by population density on a 1° × 1° grid (for more information, see URL 7 in Appendix A). These population data were also used by Klein Goldewijk (2001) and are linearly interpolated between the years 1850, 1900, 1910, 1920, 1930, 1940, 1950, 1960, 1970, 1980, and 1990. After the year 1990 population density is assumed to stay constant. Additionally, high population density was set to a limit of 20 persons per km² to avoid

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



large emissions in urban centres. The weighting with population data inhibits land use change emissions in deserts and high northern latitudes, which improves the latitudinal distribution of the emissions. However, the method is insufficient to provide realistic local land use change emissions (e.g. in tropical forests).

The gridded ($1^\circ \times 1^\circ$) fossil fuel and land-use emissions data, originally provided as a flux per gridbox, were converted to flux per unit area, then regridded as annual means onto the HadGEM2-ES model grid. A small scaling adjustment was made after regridding to ensure the global totals matched those of the $1^\circ \times 1^\circ$ data exactly. The CO_2 emissions are updated daily in the model by linearly interpolation between the annual values (or monthly, from 1950 onwards). HadGEM2-ES has the functionality to interactively simulate land-use emissions of CO_2 directly from a prescribed scenario of land-use change and simulated vegetation cover and biomass (see Sect. 6). However, the model has not been fully evaluated in this respect, so for CMIP5 experiments we disable this feature and choose rather to prescribe reconstructed land-use emissions from Houghton (2008). By simulating changes in carbon storage due to imposed land use change, but imposing land-use CO_2 emissions to the atmosphere from an external dataset we introduce some degree of inconsistency in this simulation. Work is required to evaluate and improve the simulation of land-use emissions so that they can be used interactively in such simulations in the future.

The uncertainty in annual land-use emissions of $\pm 0.5 \text{ GtC}$ (cf. Le Quéré et al., 2009) is relatively large compared to the total land use emissions (an estimated 1.467 GtC in 2005, Houghton, 2008). The RCP scenarios have been harmonised towards the average LUC emission value of all four original IAM emission estimates, i.e., 1.196 GtC in 2005. This is substantially lower than the value calculated by Houghton (2008) of 1.467 GtC in the same year, although still within the uncertainty. The climate-carbon cycle modelling community preferred to use the original Houghton (2008) estimates for historical emissions. A smooth transition between the historical and the RCP simulations was ensured by scaling the last five years of the historical LUC emissions to factor in a linearly-increasing contribution from the harmonised RCP values. In 2001 the two

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



values were combined in the ratio 80%:20% (Houghton: RCP), followed by 60%:40% in 2002, and so on until 0%:100% (i.e. the RCP value) in 2005, as shown in Fig. 3.

By rescaling the Houghton (2008) data between 2000 and 2005 to merge smoothly with the RCP value in 2005, we lower total emissions in this period by 0.94 GtC compared to the original Houghton estimates (Table 2). In the presence of fossil emissions of more than 40 GtC in this period this difference is small. Total emissions and the relative contribution of fossil fuel and LUC are shown in Fig. 4.

2.2.2 Carbon conservation

In the emissions-driven experiments, conservation of carbon in the earth system is required. The concentration of atmospheric CO₂ influences the carbon exchange with the oceans and terrestrial biosphere. Any drift in atmospheric CO₂ will modify these fluxes accordingly, and thereby impact the land and ocean carbon stores as well as the climate itself. While the transport of atmospheric tracers in HadGEM2-ES is designed to be conservative, the conservation is not perfect and in centennial scale simulations this non-conservation becomes significant. This has been addressed by employing an explicit “mass fixer” which calculates a global scaling of CO₂ to ensure that the change in the global mean mass mixing ratio of CO₂ in the atmosphere matches the total flux of CO₂ into or out of it each timestep (Corbin and Law, 2010).

Figure 5 demonstrates HadGEM2-ES’s ability to conserve atmospheric CO₂, following implementation of the mass fixer scheme described here. The evolution of the atmospheric CO₂ burden calculated by the model matches almost exactly the accumulation over time of the CO₂ flux to the atmosphere. The lower panel of Fig. 5 shows the difference between the two. This residual difference is most likely explained by changes in the total mass of the atmosphere in HadGEM2-ES over time, since CO₂ mass mixing ratio is conserved rather than CO₂ mass. CO₂ is chemically inert in HadGEM2-ES so all of the changes in its concentration are driven by surface emissions or sinks.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



3 Non-CO₂ well mixed Greenhouse Gases

Specification of the following non-CO₂ well-mixed greenhouse gases is required in HadGEM2-ES: CH₄, N₂O and halocarbons. For the control run, historical and RCP simulations they are implemented as described below and shown in Fig. 2. The CO₂ emissions-driven experiment and the historical/RCP decoupled carbon cycle experiments also use these time varying values, as do the AMIP runs and the detection and attribution experiments which require time variation of GHGs. GHG concentrations during the palaeo-climate simulations are described in Sect. 8.

3.1 CH₄ concentration

Atmospheric methane concentrations were prescribed as global mean mass mixing ratios. For experiments with time-variable CH₄ concentrations (historical RCP experiments), these were linearly interpolated from the annual concentrations for every time step of the model. These interpolated CH₄ concentrations were then passed to the tropospheric chemistry scheme in HadGEM2-ES (United Kingdom Chemistry and Aerosols: UKCA, O'Connor et al., 2011). Within UKCA, the surface CH₄ concentration was forced to follow the prescribed scenario and surface CH₄ emissions were decoupled. CH₄ concentrations above the surface were calculated interactively, and the full 3-D CH₄ field was then passed from UKCA to the HadGEM2-ES radiation scheme.

As CH₄ concentrations were only prescribed at the surface, CH₄ in HadGEM2-ES above the surface is free to evolve in a non-uniform structure and may differ from prescribed, well-mixed historical or RCP CH₄ concentrations. The impact of passing a full 3-D CH₄ field from UKCA to the radiation scheme rather than passing a uniform concentration everywhere was evaluated in a present-day atmosphere-only configuration of the HadGEM1 model (Johns et al., 2006; Martin et al., 2006). The full 3-D CH₄ field lead to the extra-tropical stratosphere being cooler by 0.5–1.0 K, thereby reducing the warm temperature biases in the model (O'Connor et al., 2009).

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The CMIP5 dataset provided concentrations of 27 halocarbon species, more than GCMs generally represent separately (for example, HadGEM2-ES explicitly represents the radiative forcing of 6 of these species). The data is therefore also supplied aggregated into concentrations of “equivalent CFC-12” and “equivalent HFC-134a”, representing all gases controlled under the Montreal and Kyoto protocols respectively. These equivalent concentrations were used in HadGEM2-ES (Fig. 2d). Halocarbon concentrations were set to zero for the pre-industrial control run.

The CMIP5 “equivalent” concentrations of CFC12 and HFC134a were derived by simply summing the radiative forcing of individual species and assuming linearity of the relationship between the concentration and radiative forcing for a single species and additivity of multiple species. To quantify the difference between using equivalent CFC-12 and HFC-134a and the full set of possible species a set of five test simulations was completed:

1. Control: halocarbons assumed zero, CO₂ at 1 × CO₂ (286.3 ppm).
2. Halocarbons assumed zero, CO₂ at 2100 RCP8.5 concentrations (936 ppm).
3. Halocarbons assumed constant at 2100 RCP8.5 concentrations (aggregated as CFC-12eq and HFC-134Aeq), CO₂ at 1 × CO₂.
4. Halocarbons assumed constant at 2100 RCP8.5 concentrations with Montreal species split (i.e., CFC-11, CFC-12, CFC-113 and HCFC-22, remaining gases aggregated as CFC-12eq and HFC-134Aeq), CO₂ at 1 × CO₂.
5. Halocarbons assumed constant at RCP8.5 2100 concentrations with Kyoto species split (i.e., HFC-134a and HFC125 and remaining gases aggregated as CFC-12eq and HFC-134Aeq), CO₂ at 1 × CO₂.

Upward and downward fluxes of longwave radiation were saved on all vertical levels in the atmosphere after the first model timestep (so that the meteorology is identical).

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



It should be noted that species not available in HadGEM2-ES are combined into either HFC-134a or CFC-12 according to their classification. Species are combined into equivalent HFC-134a and CFC-12 by summing their radiative forcing consistently with the CMIP5 methodology. Figure 6 shows excellent agreement between the “equivalent” gases and the more detailed representation from experiments 3, 4, 5 above. Zonal mean differences are within 1 mWm^{-2} everywhere showing that the use of 2 CFC equivalent species in CMIP5 is justified.

4 Ozone

4.1 Tropospheric ozone pre-cursor emissions and concentrations

Tropospheric ozone (O_3) is a significant greenhouse gas due to its absorption in the infrared, visible, and ultraviolet spectral regions (Lacis et al., 1990). It has increased substantially since pre-industrial times, particularly in the northern mid-latitudes (e.g. Staelin et al., 2001), which has been linked by various studies to increasing emissions of tropospheric O_3 pre-cursors: nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$), carbon monoxide (CO), methane (CH_4), and non-methane volatile organic compounds (NMVOCs; e.g. Wang and Jacob, 1998). As a result, the tropospheric chemistry configuration of the UKCA model (O'Connor et al., 2011) was implemented in HadGEM2-ES and used in all CMIP5 simulations to simulate the time evolution of tropospheric O_3 interactively rather than having it prescribed. The UKCA chemistry scheme includes a description of inorganic odd oxygen (O_x), nitrogen (NO_y), hydrogen (HO_x), and CO chemistry with near-explicit treatment of CH_4 , ethane (C_2H_6), propane (C_3H_8), and acetone (Me_2CO) degradation (including formaldehyde (HCHO), acetaldehyde (MeCHO), peroxy acetyl nitrate (PAN), and peroxy propionyl nitrate (PPAN). It makes use of 25 tracers and represents 41 species, which participate in 25 photolytic reactions, 83 bimolecular reactions, and 13 uni- and termolecular reactions. Wet and dry deposition is also taken into account. Emissions from surface sources and aircraft were prescribed as monthly

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

mean fields and lightning emissions were computed interactively. A full description and evaluation of the chemistry scheme in HadGEM2-ES can be found in O'Connor et al. (2011). Although transport and chemistry were calculated up to the model lid, boundary conditions were applied within UKCA. In the case of O₃, it was overwritten in those model levels which were 3 levels (approximately 3–4 km) above the diagnosed tropopause (Hoerling et al., 1993) using the stratospheric O₃ concentration dataset described in Sect. 4.2. It is this combined O₃ field which is then passed to the model's radiation scheme. Furthermore, oxidation of sulphur dioxide and dimethyl sulphide (DMS) into sulphate aerosol (described in Sect. 5) involves hydroxyl (OH), hydroperoxyl (HO₂), hydrogen peroxide (H₂O₂), and O₃, whose concentrations are provided to the model's sulphur cycle from UKCA.

No prescribed tropospheric ozone abundance data were used within HadGEM2-ES. Instead, the tropospheric evolution of ozone was simulated using surface and aircraft emissions of tropospheric ozone precursors and reactive gases. It is these emissions, rather than tropospheric ozone concentrations which are held constant in the pre-industrial control simulation. For the palaeoclimate simulations, the same pre-industrial emissions are also used as described in Sect. 8. For the historical and future simulations (including the emissions driven and decoupled carbon cycle experiments, and AMIP runs) a time-varying data set of emissions is used. As the time evolution of tropospheric ozone is simulated rather than prescribed, it may diverge from historical or RCP supplied tropospheric ozone (Lamarque et al., 2011).

The emissions data used by HadGEM2-ES has been supplied for CMIP5 by Lamarque et al. (2010) and by the IAMs for the 4 RCPs. Speciated surface emissions were provided for the following sectors: land-based anthropogenic sources (agriculture, agricultural waste burning, energy production and distribution, industry, residential and commercial combustion, solvent production and use, land-based transportation, and waste treatment and disposal), biomass burning (forest fires and grass fires), and shipping. They were valid for the specific year provided with a time resolution of 10 yr in the case of anthropogenic and shipping emissions but as decadal means for biomass

burning. This was considered appropriate for biomass burning emissions due to their substantial inter-annual variability both globally and regionally (Lamarque et al., 2010). All surface emissions were provided as monthly means on a $0.5^\circ \times 0.5^\circ$ grid. In the case of aircraft emissions, they were provided as monthly means on a $0.5^\circ \times 0.5^\circ$ horizontal grid and on 25 levels in the vertical, extending from the surface up to 15 km.

For the UKCA tropospheric chemistry scheme used in HadGEM2-ES, surface emissions for the following species were considered: C_2H_6 , C_3H_8 , CH_4 , CO , $HCHO$, Me_2CO , $MeCHO$, and NO_x . For the CMIP5 simulations, the spatially uniform surface CH_4 concentration is prescribed (as described in Sect. 3.1), and hence the surface CH_4 emissions are essentially redundant in this case. For each species the provided emissions were re-gridded onto the model's N96 grid ($1.75^\circ \times 1.25^\circ$). A small adjustment was made after re-gridding to ensure the global totals matched those of the original data.

For emissions of C_2H_6 , it was decided to combine all C2 species (C_2H_6 , ethene (C_2H_4), and ethyne (C_2H_2)) and treat as emissions of C_2H_6 . These were each converted to $kg(C_2H_6)m^{-2}s^{-1}$, added together, and then regridded. For C_3H_8 , the C3 species (propane and propene (C_3H_6)) were similarly combined and treated as emissions of C_3H_8 .

For CO , emissions from land-based anthropogenic sources, biomass burning, and shipping were taken for the historical period from Lamarque et al. (2010). These were added together and re-gridded on to an intermediate $1^\circ \times 1^\circ$ grid in terms of $kg(CO)m^{-2}s^{-1}$. Oceanic CO emissions were also added ($45Tg(CO)yr^{-1}$), and their spatial and temporal distribution were provided by the Global Emissions Inventory Activity (see URL 10 in Appendix A), based on distributions of oceanic VOC emissions from Guenther et al. (1995). In the absence of an isoprene (C_5H_8) oxidation mechanism in the UKCA tropospheric chemistry scheme used in HadGEM2-ES, an additional $354Tg(CO)yr^{-1}$ was added based on a global mean CO yield of 30 % from C_5H_8 from a study by Pfister et al. (2008) and a global C_5H_8 emission source of $506TgCyr^{-1}$ (Guenther et al., 1995). It is distributed spatially and temporally using C_5H_8 emissions

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



from Guenther et al. (1995) and added to the other monthly mean emissions on the $1^\circ \times 1^\circ$ grid before regridding.

For HCHO emissions, the monthly mean land-based anthropogenic sources were combined with monthly mean biomass burning emissions from Lamarque et al. (2010a) for the historical period and re-gridded. Similar processing was applied to the future emissions supplied by the IAMs for the 4 RCPs.

For MeCHO, the monthly mean NMVOC biomass burning emissions from Lamarque et al. (2010) for the historical period were used. Using different emission factors from Andreae and Merlet (2001) for grass fires, tropical forest fires, and extra-tropical forest fires, emissions of NMVOCs were converted into emissions of MeCHO (i.e. $\text{kg}(\text{MeCHO}) \text{m}^{-2} \text{s}^{-1}$). Surface emissions of Me_2CO were taken from land-based anthropogenic sources and biomass burning from Lamarque et al. (2010, 2011). These were added together and re-gridded on to an intermediate $1^\circ \times 1^\circ$ grid in terms of $\text{kg}(\text{Me}_2\text{CO}) \text{m}^{-2} \text{s}^{-1}$. Then, the dominant source of Me_2CO from vegetation was added, based on a global distribution from Guenther et al. (1995) and scaled to give a global annual total of $40.0 \text{Tg}(\text{Me}_2\text{CO}) \text{yr}^{-1}$. The total monthly mean emissions were then re-gridded on to the model's N96 grid. For future emissions, the processing was identical.

Finally for NO_x surface emissions, contributions from land-based anthropogenic sources, biomass burning, and shipping from Lamarque et al. (2010a) were added together and re-gridded on to an intermediate $1^\circ \times 1^\circ$ grid in terms of $\text{kg}(\text{NO}) \text{m}^{-2} \text{s}^{-1}$. Added to these were a contribution from natural soil emissions, based on a global and monthly distribution provided by GEIA on a $1^\circ \times 1^\circ$ grid (see URL 10 in Appendix A), and based on the global empirical model of soil-biogenic emissions from Yienger and Levy II (1995). These were scaled to contribute an additional $12 \text{Tg}(\text{NO}) \text{yr}^{-1}$. A similar approach was adopted when processing the future emissions. All emissions provided were processed as above for the years supplied and a linear interpolation applied between years to produce emissions for every year. Figure 7 shows the time evolution of tropospheric O_3 pre-cursor surface emissions over the 1850–2100 time period. After 2100, tropospheric ozone precursor emissions were kept constant.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



In the case of NO_x emissions, 3-D emissions from aircraft were also considered. These were supplied as monthly mean fields of either NO or NO₂ on a 25 level (L25) 0.5 × 0.5 grid by Lamarque et al. (2010) for the historical period. For HadGEM2-ES we used the NO emissions. They were first re-gridded on to an N96 × L25 grid and then projected on to the model's N96 × L38 grid, ensuring that the global annual total emissions were conserved. A similar approach was adopted when processing the future emissions.

No additional coding in the HadGEM2-ES or UKCA models was necessary for the treatment of tropospheric ozone pre-cursor emissions. The only code change was required for the Detection and Attribution “greenhouse gases only” simulation (7.2). In this case, the UKCA model was modified to maintain the global mean surface CH₄ concentration at pre-industrial levels i.e. 805.25 ppb. This was to ensure that the increase in CH₄ concentration as seen by the radiation scheme did not affect concentrations of tropospheric oxidants, thereby influencing the rate of sulphate aerosol formation.

4.2 Stratospheric ozone concentration

HadGEM2-ES requires stratospheric ozone to be input as monthly zonal/height ancillary files. CMIP5 recommends the use of the AC&C/SPARC ozone database (Cionni et al., 2011) which covers the period 1850 to 2100 and can be used in climate models that do not include interactive chemistry. The pre-industrial dataset consists of a repeating seasonal cycle of ozone values, and this is also used for the palaeoclimate simulations described in Sect. 8. For the historical and future simulations (including the emissions driven and decoupled carbon cycle experiments, and AMIP runs) a time-varying data set of stratospheric ozone is used.

The historical part of the AC&C/SPARC ozone database spans the period 1850 to 2009 and consists of separate stratospheric and tropospheric data sources. The future part of the AC&C/SPARC ozone database covers the period 2010 to 2100 and seamlessly extends the historical database also including separate stratospheric and

tropospheric data sources based on 13 CCMs that performed a future simulation until 2100 under the SRES A1B GHG scenario.

The AC&C/SPARC ozone is provided on pressure levels between 1000–1 hPa. The UK National Centre for Atmospheric Science (NCAS) has produced an updated version of the SPARC ozone dataset as follows.

A multiple-linear regression was performed on the historical raw pressure-level data between 1000–1 hPa consistent with the Randel and Wu (1999) method used to construct the timeseries. The ozone was then represented as: $O_3(t) = a \cdot \text{SOL} + b \cdot \text{EESC} + \text{seasonal_cycle} + \text{residuals}$. For consistency, the indices of 11-yr solar cycle (SOL) and total equivalent chlorine (EESC) are identical to those used to prepare the original dataset. The SOL index is a 180.5 nm timeseries provided by Fei Wu at NCAR. The standard SPARC ozone dataset which extends into the future does not include solar cycle variability post-2009. For production of a dataset extending into the future including an 11-yr ozone solar cycle, the solar regression index is used to build a future time series consistent with a repeating solar irradiance compiled by the Met Office Hadley Centre (see Sect. 7.1) and is modelled as a sinusoid with a period of 11 yr, with mean and max-min values corresponding to solar cycle 23 normalised against the 180.5 nm timeseries used in the historical ozone. There is no solar ozone signal in the high latitudes.

The data were then horizontally interpolated onto a N96 grid. Vertical interpolation was achieved by hydrostatically mapping the SPARC ozone data from pressure surfaces onto pressure surface equivalent levels corresponding to the height-based grid used by HadGEM2-ES using a scale height of 7 km.

5 Tropospheric aerosol forcing

HadGEM2-ES simulates concentrations of six tropospheric aerosol species: ammonium sulphate, fossil-fuel black carbon, fossil-fuel organic carbon, biomass-burning, sea-salt, and mineral dust aerosols (Bellouin et al., 2007; Collins et al., 2011). Although

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**

C. D. Jones et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

an ammonium nitrate aerosol scheme is available to HadGEM2-ES, it was still in its developmental version when CMIP5 simulations started, hence nitrate aerosols are not included in the CMIP5 simulations. In addition, secondary organic aerosols from biogenic emissions are represented by a fixed climatology. All aerosol species can exert a direct effect by scattering and absorbing shortwave and longwave radiation, and a semi-direct effect whereby this direct effect modifies atmospheric vertical profiles of temperature and clouds. In HadGEM2-ES all aerosol species, except fossil-fuel black carbon and mineral dust, also contribute to both the first and second indirect effects on clouds, modifying cloud albedo and precipitation efficiency, respectively. Changes in direct and indirect effects since 1860 are termed aerosol radiative forcing. The magnitude of this forcing depends on changes in aerosols, which are due in part to changes in emissions of primary aerosols and aerosol precursors. Changes in emission rates are either derived from external datasets or due to changes in the simulated climate. Here we document how any changes in emission rates are implemented in the HadGEM2-ES CMIP5 centennial experiments. In the control run we specify a repeating seasonal cycle of 1860 emissions, and this is also used in the palaeoclimate simulations (Sect. 8). Historical and future simulations (including the emissions-driven and decoupled carbon cycle experiments and AMIP runs) use time-varying emissions as described in this section.

In HadGEM2-ES sea-salt and mineral dust aerosol emissions are computed interactively, whereas emission datasets drive schemes for sulphate, fossil-fuel black and organic carbon, and biomass aerosols. Unless otherwise stated, datasets are derived from the historical and RCP time series prepared for CMIP5. All non-interactive emission fields are interpolated by the model every five simulated days from prescribed monthly-mean fields. Timeseries of non-interactive emissions are shown in Fig. 10. Aircraft emissions of aerosol precursors and primary aerosols are not included in the model.

The sulphur cycle, which provides concentrations of ammonium sulphate aerosols, requires emissions of sulphur dioxide (SO₂) and dimethyl-sulphide (DMS). Sulphur

**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**C. D. Jones et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

dioxide emissions are derived from sector-based emissions. Emissions for all sectors are injected at the surface, except for energy emissions and half of industrial emissions which are injected at 0.5 km to represent chimney-level emissions. Sulphur dioxide emissions from biomass burning are not included. The model accounts for three-dimensional background emissions of sulphur dioxide from degassing volcanoes, taken from Andres and Kasgnoc (1998). This represents a constant rate of $0.62 \text{ Tg[S] yr}^{-1}$ on a global average, independent of the year simulated and is not part of the implementation of volcanic climate forcing which we discuss in Sect. 7.2. Similarly, land-based DMS emissions do not vary in time and give 0.86 Tg yr^{-1} (Spiro et al., 1992). Oceanic DMS emissions are provided interactively by the biogeochemical scheme of the ocean model as a function of local chlorophyll concentrations and mixed layer depth (based on Simo and Dachs, 2002). In an objective assessment against ship-board and time-series DMS observations, the HadGEM2-ES interactive ocean DMS scheme performs with similar skill to that found in the widely used Kettle et al. (1999) climatology (Halloran et al., 2010). The primary differences between the model-simulated and the climatology-interpolated surface ocean DMS fields are; lower model Southern Hemisphere summer Southern Ocean DMS concentrations, higher model annual equatorial DMS concentrations, and a reduced model seasonal cycle amplitude. Oxidation of sulphur-dioxide and DMS into sulphate aerosol involves hydroxyl (OH), hydroperoxyl (HO_2), hydrogen peroxide (H_2O_2), and ozone (O_3): concentrations for those oxidants are provided by the tropospheric chemistry scheme.

Emissions of primary black and organic carbon from fossil fuel and biofuel are injected at 80 m. Emissions of biomass-burning aerosols are the sum of the biomass-burning emissions of black and organic carbon. Grassfire emissions are assumed to be located at the surface, while forest fire emissions are injected homogeneously across the boundary layer (0.8 to 2.9 km).

Sea-salt emissions are computed interactively over open oceans at each model time step from near-surface (10 m) wind speeds (Jones et al., 2001). Mineral dust emissions are also interactive, and depend on near-surface wind speed, land cover and soil

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

properties. The scheme is described in Woodward (2011). It is based on that designed for HadAM3 (Woodward, 2001) with major developments including the modelling of particles up to 2 mm in the horizontal flux, threshold friction velocities based on Bagnold (1941), a modified version of the Fécan et al. (1999) soil moisture treatment and the utilisation of a preferential source multiplier similar to that described in Ginoux et al. (2001).

Finally, secondary organic aerosols from biogenic emissions are represented by monthly distributions of three-dimensional mass-mixing ratios obtained from a chemistry transport model (Derwent et al., 2003). These distributions are constant for all simulated years.

6 Land-use and land-use change

The HadGEM2-ES land-surface scheme incorporates the TRIFFID DGVM (Cox, 2001), and as such simulates internally the land cover (and its evolution) in response to climate (and climate change). Hence we do not directly impose prescribed land-cover or vegetation types, but rather provide a fractional mask of anthropogenic disturbance as a boundary condition to the dynamic vegetation scheme. Previous Met Office Hadley Centre coupled climate-carbon cycle simulations (e.g. Cox et al., 2000; Freidlingstein et al., 2006) used a static (present day) agricultural mask. However the dynamic vegetation scheme, TRIFFID has now been updated to allow time-varying land-use distributions in the CMIP5 simulations.

TRIFFID represents the fractional coverage in each grid cell of 5 plant functional types (PFTs: broadleaf tree, needleleaf tree, C3 grass, C4 grass, shrub) and also bare soil. Prescribed fractions of urban areas, lakes and ice are also included from the IGBP land cover map (Loveland et al., 2000) and do not vary in time. The summed fractional coverage of crop and pasture is provided as a time-varying input. Within a grid box tree and shrub PFTs are excluded from this fraction allowing natural grasses to grow and represent “crops”. Abandonment of crop land removes this constraint on

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



trees and shrubs but we do not specify instant replacement by these woody PFTs, but rather their regrowth is simulated by the model's vegetation dynamics. If woody vegetation cover reduces because of a land use change, vegetation carbon from the removed woody PFTs goes partially to the soil carbon pool and partially to a series of wood products pools. These wood products pools have turnover rates of 1, 10 and 100 yr and are not sensitive to environmental conditions. The fraction of vegetation carbon directed into the wood products pool is proportional to the ratio of above ground and below ground carbon pools ((leaf carbon + stem carbon)/root carbon). Distribution of disturbed biomass into the different carbon pools depends on the vegetation type consistent with McGuire et al. (2008) and is shown in Table 3.

HadGEM2-ES is therefore able to simulate both biophysical and biogeochemical effects of land-use change as well as natural changes in vegetation cover in response to changing climate and CO₂. In this version of the model only anthropogenic disturbance in the form of crop and pasture is represented. Data on within-grid-cell transitions due to shifting cultivation or the impact of wood harvest are not yet used. As described in Sect. 2.2, CO₂ emissions from land-use change can be simulated by HadGEM2-ES but are not used interactively in the emissions driven experiment.

The biophysical impacts of land use change include the direct effect of changes to surface albedo and roughness due to land-cover change and also changes to the hydrological cycle due to changes in evapotranspiration and runoff. There is also an indirect physical effect due to changes in surface emissions of mineral dust caused by changes in bare soil fraction, windspeed and soil moisture, which has a radiative effect in the atmosphere.

Historic and future simulations (including the emissions-driven and decoupled carbon cycle simulations and AMIP runs) use time varying disturbance from the Hurtt et al. (2010) dataset described below. The pre-industrial control simulation uses an agricultural disturbance mask, fixed in time at 1860 values in this same dataset. The natural and GHG detection and attribution simulations (7.1, 7.2) also use a fixed, pre-industrial land-use disturbance mask, but the land-use only simulations (7.3) use the

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

time varying historical data as in the full historical simulation. For the mid-Holocene and LGM experiments, there is no agricultural disturbance (which therefore differs from the control run where a pre-industrial disturbance mask is used). The Last Millennium and AMIP simulations do not use the dynamic vegetation scheme of HadGEM2-ES and instead directly prescribe land-cover as described in Sects. 8 and 9 respectively.

The historical land use data is based on the HYDE database v3.1 (Klein Goldewijk et al., 2010, 2011), whilst the future RCP land use scenarios were produced by the respective IAMs and are thus internally consistent with the socio-economic storylines and carbon emissions of the scenarios. A harmonization manipulation was performed, as described in Hurtt et al. (2009, 2010), that attempts to preserve gridded and regional IAM crop and pasture changes as much as possible while minimizing the differences between the historical estimates and future projections (in 2005). The harmonization procedure employs the Global Land-use Model (GLM) that ensures a smooth and consistent transition in the harmonization year, grids (or re-grids) the data when necessary, spatially allocates national/regional wood harvest statistics, and computes all the resulting land-use states and transitions between land-use states annually from 1500–2100 at half-degree (fractional) spatial resolution, including the effects of wood harvesting and shifting cultivation. Both historical and future scenarios were made available at $0.5^\circ \times 0.5^\circ$ resolution with annual increments and were downloaded (see URL 11 in Appendix A).

The crop and pasture fraction is re-gridded onto the HadGEM2-ES grid using area average re-gridding. Crop and pasture are then combined to produce a combined “agriculture” mask. It is assumed crop and pasture both mean “only grass, no tree or shrub”. This assumption is simplistic as in some regions of the world “pasture” refers to rangeland where animals are allowed to graze on whatever natural vegetation exists there (which may include trees and shrub). Similarly, woody biofuel crops are treated (erroneously in this case) as non-woody crops. As noted by Hurtt et al. (2010), the definition and reporting of biofuel differs even within the IAMs producing the 4 RCP scenarios. However, the necessary data to avoid these problems are not available

and we expect the impact of any inconsistency to be minor. It remains an outstanding research activity to improve past and present reconstructions of land-cover which can account for temporally and regionally varying changes in definitions and terminology.

An additional uncertainty in reporting the land use carbon fluxes is that the wood products pools are assumed to be zero everywhere at 1860 whilst the terrestrial carbon cycle (carbon content and vegetation fractions) have been run to equilibrium with 1860 climate and anthropogenic disturbance. Changes in land use cover prior to 1860 involve land use expansion and hence both direct emissions prior to 1860 and some legacy emissions post-1860 due to inputs of disturbed biomass to the soil carbon. No attempt has been made to include these effects in our output but future work will assess and quantify this effect.

7 Natural climate forcing

HadGEM2-ES can simulate the climate response to two aspects of natural climate forcing: changes in solar irradiance and stratospheric volcanic aerosol. In the control experiment these forcings are kept constant in time. For the historical experiments (including the emissions-driven and decoupled carbon cycle simulations and AMIP runs) they are varied due to observed reconstructions. For simulations of future periods, where natural forcings are not known, they are varied as described here to minimise the impact of possibly incorrect assumptions about the natural forcings. See Sect. 8 for details on the solar and volcanic forcings applied to the palaeoclimate simulations.

7.1 Total solar irradiance

The way the model deals with variations in total solar irradiance (TSI) is the same as in earlier generations of Hadley Centre models, HadCM3 (Stott et al., 2000, Tett et al., 2002) and HadGEM1 (Stott et al., 2006). Annual mean variations in TSI are partitioned across the six shortwave spectral bands (0.2–10 μm) to estimate the associated

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



spectral changes with TSI variations (Lean et al., 1995a). With the changes across the spectral bands the Rayleigh scattering and ozone absorption properties are also varied. See Stott et al. (2006) for further details.

The TSI data used for the historic period were recommended by CMIP5 (Lean et al., 2009 – L09) and are created from reconstructions of solar cycle and background variations in TSI. The solar cycle component is produced from a multiple regression of proxy measures of bright and dark regions of the Sun with satellite reconstructions of TSI (Fröhlich and Lean, 2004). Background variations in TSI are produced from a model of solar magnetic flux incorporating historic sunspot numbers (Wang et al., 2005). The annual mean TSI was processed to force the mean of the 1700–2004 period to be the same as the model control solar constant value (1365 Wm^{-2}).

The annual mean TSI and variations across the UV, visible and IR bands are shown in Fig. 13. For comparison the TSI used in previous model simulations are also shown. The TSI now recommended for use in CMIP5 studies is consistent with the latest assessment of TSI variations by the IPCC's Fourth Assessment report – AR4 – (Forster et al., 2007) which estimated the solar radiative forcing to be 50% of that given in the previous report. The increase in TSI for L09 between the Maunder minimum in the 17th century and the average over the last 2 solar cycles of the 20th century is 1.11 Wm^{-2} . This compares to 2.73 Wm^{-2} for the TSI used in the HadGEM1 simulations (Stott et al., 2006) and 2.95 Wm^{-2} in the HadCM3 simulations (Stott et al., 2000).

7.2 Stratospheric volcanic aerosol

How HadGEM2-ES incorporates changes in stratospheric volcanic aerosol is the same as in the HadGEM1 model (Stott et al., 2006). Aerosols in the troposphere are linked to emission sources and sulphur and chemistry feedbacks. Aerosols in the stratosphere are separated from these processes and are prescribed. Stratospheric aerosol concentrations are varied across four equal area latitudinal zones on a monthly timescale. The aerosol is distributed vertically above the tropopause such that the mass mixing

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



ratio is constant across the levels. In this version of the model, volcanic aerosol is not related to, and does not interact with, other simulated aerosol behaviour.

The dataset used for the historic period was monthly stratospheric optical depths, at 550 nm, from 1850 to 2000 (Sato et al., 1993, see URL 12 in Appendix A) which was averaged over the four equal area latitudinal zones and converted into aerosol concentrations (Stott et al., 2006 and figures therein).

In a previous study (Stott et al., 2006) the data was extended past 2000 by continuing an assumed 1 yr timescale decay, from 1997, to a minimum and then keeping concentrations constant. There is some evidence that background aerosol concentrations are not as low as this assumes (Thomason et al., 2008). Also future volcanic activity is likely to introduce further aerosol into the stratosphere. There was no specific CMIP5 recommendations, apart from suggesting that the same concentration of stratospheric aerosol is present in the future simulations as in the control (Taylor et al., 2009), being aware of any step-change in aerosol.

The future dataset of optical depth is constructed as follows. The 1 yr decay timescale constructed for the post 1997 period appears to give a break point in the data. We re-construct the data, to remove the break point, from 1997 to 2002 by continuing the decay timescale of 3.3 yr seen in the 1995–1997 period of the data. A value of stable observed optical depth at 1020 nm since 2000 was found to be 0.001 (Thomason et al., 2008). As optical depth is estimated to vary inversely with wavelength, this suggests a minimum of global stratospheric aerosol optical depth of 0.002 at 550 nm, approximately 20 times more than used in the HadGEM1 study. During the period 2020–2040 concentrations were increased to match those in the control simulation (optical depth 0.0097). This compromise was an attempt to balance the lack of knowledge of when large eruptions would occur in the future with the unlikely possibility of no major volcanic eruptions significantly influencing aerosol amounts in the stratosphere for 100 yr. The global mean of the stratospheric optical depth is shown in Fig. 14, compared with what was used in the HadGEM1 simulation.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



8 Palaeoclimate boundary conditions, including geophysical changes

In order to complete the palaeo-climate simulations (3.4–3.6) a number of modifications need to be made to the model. The mid-Holocene simulation (3.4) required GHG concentrations of CH₄ (650 ppb) and N₂O (270 ppb), and halocarbon concentrations of zero (as in the pre-industrial control simulation). Stratospheric Ozone and pre-cursor emissions of tropospheric ozone remain the same as the pre-industrial control run, as do concentrations of CO₂ and the land sea mask. Because tropospheric Ozone is calculated interactively in HadGEM2-ES, Ozone concentrations in the palaeo simulations may not be identical to those in the pre-industrial control simulation: it is the pre-cursor emissions which we keep the same as the control run. This is also the case for dust and ocean DMS emissions which are simulated interactively and may differ due to changes in the simulated climate or vegetation cover.

8.1 Mid-Holocene (6 kya)

In the mid-Holocene, Earth's orbit differed from present day affecting the timing and magnitude of solar energy reaching the surface. Orbital parameters were modified to correspond to those required by the PMIP3 protocol (see URL 13 in Appendix A). Figure 15 shows the monthly anomalies of TOA SW radiation relative to the present day for the official PMIP3 requirements (black) and as calculated within HadGEM2-ES (red). The land use disturbance mask is set to zero everywhere for the mid-Holocene thus assuming that there is no human activity which would displace forests in any location.

8.2 Last glacial maximum (LGM, 21 kya)

The LGM simulation (3.5) setup requires major changes to the geophysical state of the land and ocean bed. The land sea mask and orography are changed to increase ice sheet volumes and to represent the associated decreased sea level. The bathymetry of the ocean model is also changed to reflect the decreased sea-level. Figure 16

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



shows how the land-sea mask changes. GHG concentrations are prescribed as, CO₂ of 185 ppm, CH₄ of 350 ppb, N₂O of 200 ppb. Halocarbons are zero (as in the pre-industrial control setup) and O₃ is treated the same as in the pre-industrial control run by using the same stratospheric ozone concentrations and tropospheric ozone precursor emissions. Boundary condition files were downloaded from the PMIP3 website (see URL 13 in Appendix A). Orbital parameters are changed to the required configuration and the river routing ancillary was also updated to take into account changes in the land sea mask.

8.3 Last Millennium (800 AD–present)

Different from the centennial simulation, in the Last Millennium simulation no anthropogenic disturbance is used to update the land cover boundary conditions. Instead the land cover is updated from historical land cover reconstruction data from Pongratz et al. (2008, hereafter P08). The original data are on a grid of 0.5° × 0.5° and provide the spatial distribution of 14 vegetation types from the present day back to year 800 AD. The vegetation types in the P08 database are mapped into the 5 TRIFFID vegetation classes. The details of the reclassification are shown in Table 4. In case of no one-to-one mapping, the following rules are applied:

- C3/C4 pasture is treated as natural C3/C4 grass.
- Tundra is treated as mixture of shrubs, grass and bare soil. The mixture is chosen to match as close as possible the distribution obtained in Essery et al. (2003) in tundra regions for the present time.
- Crops are treated as in Essery et al. (2003), as a mixture of C3/C4 grass and soil. The ratio between C3 and C4 grass is used as threshold to discriminate between C3 and C4 grass to be used in crop.

After the application of inland water mask and ice mask, the unclassified fraction of each grid cell is filled with the soil land class. For the urban land class we used the data

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**C. D. Jones et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

from HYDE3.1 (Goldewijk et al., 2010a, b). The data provide the urban/built-up area on a grid cell of $0.083^\circ \times 0.083^\circ$. We used local area-averaging interpolation to regrid HYDE 3.1 data into the P08 grid. In the coastal areas only the grid cells where at least 30% of the original data showed urban coverage were considered as urban. The half-degree historical land cover data is then re-gridded onto the HadGEM2-ES grid using area average re-gridding. Figure 17 shows the total woodland (needle leaf + broad leaf trees) reduction with respect to year 800 respectively in year 1000, 1500 and 1990 on the HadGEM2 grid.

For the volcanic forcing we use the reconstruction of aerosol optical depth (AOD) provided by Crowley et al. (2008) and we maintain the same latitudinal distribution as described in Sect. 7.2. The reconstruction is based on ice-core records from Antarctic and Greenland calibrated based on the Pinatubo eruption and is validated by comparison to the 20th century instrumental records. The data closely match the Sato et al. (1993) reconstruction for the 20th century. Figure 18 shows the volcanic aerosol optical depth at $0.55 \mu\text{m}$ integrated across the lower stratosphere between 15 and 25 km for the 4 latitudinal bands from the year 800 to 2000.

For the solar forcing up to 1810 we implemented the data of Steinhilber et al. (2009), a Total Solar Irradiance (TSI) reconstruction based on the cosmogenic radionuclide ^{10}Be measured in ice cores. The TSI was calculated using the observed correlation between open solar flux and TSI derived by Fröhlich (2009). Because cosmogenic nuclide based reconstructions do not perfectly match the instrumentally observed TSI changes from 1976 onwards, for the period 1810–2000 we used the solar reconstruction of Wang et al. (2005), which is based on a flux transport model of the open and closed flux which used the observed sunspot record as the main input. For consistency between the two forcings, the Steinhilber et al. (2009) reconstruction was normalised to the Wang et al. (2005) values from 1976–2006 and also had a synthetic 11 yr cycle overlaid, according to the PMIP3 guidelines (Schmidt et al., 2011). To get the two different reconstructions to match up, a linear combination of the Wang et al. (2005) reconstruction with background and without background was used so that the mean values

of the two reconstructions were identical between 1810 and 1820. Eventually the whole TSI has been normalized to a mean value over the whole period of 1365 Wm^{-2} . The forcing over the total duration of the simulation runs is shown in Fig. 19, with different colours to highlight the two reconstructions used.

UKCA is included in these simulations allowing the simulation of a 3-D methane field and interaction with O_3 and aerosols, but with the concentrations of well-mixed GHGs CO_2 , CH_4 and N_2O prescribed. The set up follows the PMIP3 standard (Schmidt et al., 2011): data over the post-1860 industrial period (Hansen and Sato, 2004) are linked with splines through the ice core results of the last 2 millennia.

For the pre-1860 period, black carbon aerosols are set to zero, while the biomass burning is kept constant at the pre-industrial, 1860 value.

9 Ensemble initialisation

9.1 HadGEM2-ES coupled model historical simulations (3.2E)

CMIP5 requests initial-condition ensembles of simulations of some experiments in order to be able to estimate any component of apparent changes in climate which may be due to internal variability in the model. In order to produce an ensemble of initial condition members for the historical simulations it is necessary to somehow perturb the initial conditions. A standard technique for this is simply to choose different points on the control run from which to take the initial conditions for a simulation. GCMs possess sufficient sensitivity to initial conditions that for even a small perturbation, their day-to-day weather will soon diverge. But they may also possess some long-term “memory” which may mean ensemble members taken too close together in the control simulation, or from widespread but similar initial states, are not fully independent.

Extensive evidence exists from previous long control simulations showing simulated climate possesses large-scale variations on decadal to centennial timescales (Delworth et al., 1993; Delworth and Mann, 2000; Latif et al., 2004; Knight et al., 2005).

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Typically, these variations are associated with the principal modes of decadal variability of the climate system – the Atlantic Multidecadal Oscillation (AMO) (Enfield et al., 2001) and the Pacific Decadal Oscillation (PDO), sometimes referred to as the Interdecadal Pacific Oscillation (IPO) (Power et al., 1999). The AMO is a North Atlantic-centred mode in which sea surface temperatures (SSTs) vary coherently within the basin on multidecadal to centennial timescales, and which can have far reaching climate impacts (Knight et al., 2006). The PDO/IPO has a characteristic pattern of anomalously warm and cool SSTs in the Pacific Ocean that resembles a modified El Niño pattern, and typically has a shorter timescale of about two decades (Kwon and Deser, 2007). So-called “perfect model” experiments (Collins and Sinha, 2003), in which sections of model control simulations are repeated after small initial perturbations, demonstrate the potential for multidecadal oceanic processes to provide a long-term memory of the initial state. This is undesirable as we would like the ensemble mean to provide an unbiased estimate of the model’s response to imposed forcings. In terms of the initialisation of the transient simulations from the model control described here, this implies that care needs to be taken in choosing a sufficient range of initial states with respect to decadal modes.

North Atlantic and Pacific patterns of the decadal-centennial variability in the HadGEM2-ES control simulation were derived from a principal component analysis of low-pass filtered simulated annual mean SST data in each basin. The filter half-power timescales were chosen to preserve only the decadal and longer components of the variability. The patterns derived bear a strong resemblance to those seen in observations (Parker et al., 2007). Projecting these patterns from 500 yr of the control run against the low-pass filtered SST fields, indices of Atlantic and Pacific decadal variability were derived (Fig. 20). The Atlantic index (labelled “AMO”) has considerable variability on decadal to centennial timescales, whereas the Pacific mode (labelled “IPO”) tends towards variations on shorter timescales. Despite long-term variability, neither index exhibits a long-term drift.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Figure 21 shows the trajectory of the control model in the space defined by these two indices, as well as the points at which the ensemble members of the transient simulation were initialised. We wanted to retain an objective method for selecting initial conditions rather than using this metric to subjectively choose years from the control run. As such we select initial conditions at 50 yr intervals from the control run (as indicated by red dashed lines in Fig. 20), and use these indices of long-term variability to monitor whether these initial states are independent as desired. The range of initial states selected possesses an average that is close to zero compared to the variability in both indices. This indicates that there is no mean signal of the AMO or IPO in the initial conditions, giving confidence that the net long-term signal from the initial state has been minimised in the transient ensemble. We note that the 4 ensemble members chosen span a reasonable range of the IPO variability but a relatively narrow range of AMO variability, clustered close to zero. Future work may explore the response of extra ensemble members which start from deliberately chosen high or low AMO states.

9.2 Atmosphere only model (AMIP) simulations (3.3E)

Traditionally, AMIP experiments (Gates, 1992) comprise the atmosphere-only version of a GCM forced only by time-varying fields of prescribed sea-surface temperatures (SSTs) and sea-ice. The atmospheric component of GCMs generally includes the land-surface model which means that surface properties such as soil temperature and moisture are simulated in AMIP experiments, but the land-cover would be prescribed from a climatology and held constant in time.

For CMIP5 the AMIP experiments, 3.3(E), use time-varying datasets of SST and sea-ice at monthly resolution as recommended by CMIP5 (Hurrell et al., 2008). The experiment design also recommends time varying forcing of the other climate drivers such as GHGs, aerosols and natural forcing as imposed in the coupled historical simulation, 3.2. For ESMs such as HadGEM2-ES which include dynamic vegetation there is a decision to make regarding whether to prescribe or simulate the land cover, and if the latter how to initialise it for the start of the AMIP period (1979–2010). For the HadGEM2

timescales (Koster and Suarez, 2001). Hence these two approaches to initialising AMIP ensemble members can be later analysed as two sub-ensembles to assess the importance of land-surface state for predictability on seasonal to decadal timescales.

10 Discussion and concluding comments

5 Arbitrary or subjective decisions in experimental design can cause differences in results which hamper attempts to quantify and understand model spread and uncertainty in future climate projections. CMIP5 represents a coordinated attempt to define a common modelling protocol by which modelling centres worldwide can abide, in order to facilitate comparison of complex GCM experiments and thus avoid the impacts of subjective decisions. However, by necessity there may still be a number of subjective decisions required when elements of the experimental protocol are not applicable to a certain model or model configuration. It is our hope that any such occurrences with HadGEM2-ES will not have a large impact on the interpretation of the results, but we discuss here for completeness some possible impacts.

15 In the HadGEM2-ES earth system model (Collins et al., 2011), some of the components of the earth system are now simulated interactively by the model rather than being prescribed as external boundary conditions. For example, HadGEM2-ES includes interactive tropospheric chemistry and hence can simulate the evolution of atmospheric methane and ozone concentration in response to meteorological conditions and emissions of reactive gases. Therefore atmospheric composition may not follow exactly the CMIP5-prescribed values. In our experiments we have forced the surface methane concentrations to follow the CMIP5 values in order to reduce any model drift away from the scenarios, but there may still be differences in CH₄ concentrations in the free atmosphere away from the surface.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



Similarly, simulated tropospheric ozone may not follow the exact CMIP5-prescribed concentrations. In general, we see this enhanced, process-based functionality of the model as a benefit – the rationale behind developing such a complex earth system model is precisely to study these interactions and allow them to change consistently with future climate in a way not possible with prescribed concentrations. But we do acknowledge that these differences also represent a divergence from the precise CMIP5 protocol which should be borne in mind during subsequent multi-model analysis.

Other areas where a divergence may occur due to the structure of the ESM include land-use forcing and set-up of detection and attribution experiments.

By prescribing anthropogenic disturbance in addition to simulated, dynamic vegetation we risk diverging from the intended impact of the prescribed land-use change. For example, if the model initially simulates too much or too little forest in a region to be deforested then the impact of this deforestation on both carbon storage and physical surface properties will be too great or too little. We mitigate the risk of this impact in the emission-driven experiments by overwriting the land-use flux seen by the atmosphere by the CMIP5-prescribed land-use emissions dataset. However, the issue remains for any biophysical effect of land-use change. Future work is required to quantify the impact of this effect.

Detection and attribution studies aim to attribute changes in observed climate to driving processes. Model experiments are designed to do this by varying or holding constant separate forcings such as natural, greenhouse gases or aerosols. In this way the characteristic spatial or temporal patterns of response to each forcing can be derived and an optimal scaling found to best match observations. The scaling is then used to deduce if the signal for the forcing is detected and if the scaled response is consistent with the original signal, thus providing confidence for an attribution statement. In GCMs to date the distinction between, say, natural and greenhouse gas forcing is clear, and it is easy in the model to hold one fixed whilst varying the other. However, in an ESM where simulated GHG concentrations (such as methane or ozone) or aerosols may respond to climate, this distinction becomes slightly blurred. If natural forcings af-

fect atmospheric processes which alter GHG or aerosol amounts then should these be allowed to vary or not in the “natural” detection and attribution experiment? Or should the HadGEM2-ES “natural” simulations be forced to solely consider the direct radiative effects of the natural forcings?

5 In the HadGEM2-ES natural experiment we varied the TSI and stratospheric volcanic aerosol concentrations as per the historical simulation, kept all other emissions/concentrations the same as in the control simulation and allowed the earth system processes to vary as normal. We decided on a more complicated set up for the GHG only forced run. Concentrations of the greenhouse gases (CO₂, CH₄, N₂O and the halocarbon species) were prescribed throughout the atmosphere for the radiation scheme. However, prescribing the methane seen by the chemistry scheme would influence the chemistry and thus species like ozone, which we did not want to be varied in this experiment. So in the interactive chemistry part of the model, the set up was as in the control, i.e. methane emissions at surface and concentrations in the atmosphere as in the control simulation. This “chemistry methane” does not interact with the radiation scheme. Our choice to do this was therefore a pragmatic compromise between the ESM part of the model and the needs of a detection and attribution study.

15 In this paper we have documented how we have implemented the CMIP5 experimental protocol for the centennial simulations in the Met Office HadGEM2-ES earth system model. We have successfully set-up and performed the experiments as described here and will make the results available via the PCMDI multi-model database. We hope these will form a valuable contribution to the CMIP5 modelling activity.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

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The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

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5

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Overview of CMIP5 experiments and their prescribed boundary conditions, i.e., atmospheric concentrations or emissions. This table lists the climate forcings required to be changed from the control run (experiment 3.1) in order to set-up and perform each CMIP5 experiment. The presence of a cross denotes that that forcing is changed, and is documented in the section listed in the column title. An absence of a cross does not mean that forcing is missing, but that it is kept the same as in the control run.

Experiment number ^a	Experiment name	2.1. CO ₂ concentration	2.2. CO ₂ emissions	3. well-mixed GHG ^b	4. Ozone	5. Aerosols	6. Land use	7. Natural ^c	8. Geophysical ^d
3.1	Pre-industrial control ^e	X		X	X	X	X	X	
3.2(E) ^f	historical	X		X	X	X	X	X	
3.3(E)	AMIP	X		X	X	X	X ^g	X	
3.4	Mid-Holocene	X		X			X	X ^h	
3.5	LGM	X		X			X	X	X
3.6	Last Millennium	X		X			X ^g	X	
4.1, 4.2, 4.3, 4.4	RCP projections to 2100	X		X	X	X	X	X	
4.1L, 4.2L, 4.3L	RCP extensions to 2300	X		X	X	X	X	X	
5.1	ESM control	X ⁱ							
5.2, 5.3	ESM historical/RCP		X	X	X	X	X	X	
6.1	Idealised 1%	X							
6.3, 6.3 E	Idealised 4 × CO ₂	X							
5.4(1), 5.5(1)	Carbon-cycle decoupled 1%	X							
5.4(2), 5.5(2)	Carbon-cycle decoupled Historical/RCP4.5	X		X	X	X	X	X	
7.1 (E)	D&A ^j Natural							X	
7.2 (E)	D&A GHG	X		X					
7.3	D&A "individual" LU – only						X		

^a Experiments are numbered as per Centennial experiments (Table B in Taylor et al., 2009). We explicitly don't consider the idealised SST experiments 6.2, 6.4, 6.5, 6.6, 6.7, 6.8 which will be documented elsewhere.

^b "Well mixed GHG" here covers CH₄, N₂O, and halocarbons, but not CO₂ which is treated in Sect. 2. "Ozone" covers tropospheric and stratospheric and includes emissions of pre-cursor gases which affect tropospheric ozone (see Sect. 4).

^c "Natural" forcing covers both solar and volcanic changes (Sect. 7).

^d "Geophysical" here is taken to include changes in: prescribed ice sheet extent (incl. height), land-sea mask, ocean bathymetry.

^e The control run does have "forcing" in that we prescribe several things to be constant. The relevant sections describe how each climate forcing is set up for the control run. The table then lists aspects which differ from the control (either by being time varying in scenarios, or by being held constant at different values such as in the 4 × CO₂ simulation).

^f "(E)" denotes that an initial-condition ensemble is required for these experiments. Section 9 describes how the initial conditions are derived.

^g Land-use in the AMIP and last millennium experiments is described in their respective Sects. 9.2, 8.3 rather than the land-use Sect. 6.

^h Palaeoclimate orbital forcing is described in Sect. 8 rather than under solar forcing in Sect. 7.1.

ⁱ The "ESM control" simulation actually has an absence of forcing as CO₂ is simulated in this experiment, not prescribed.

^j "D&A" stands for detection and attribution.

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

Table 3. Allocation of aboveground displaced carbon to the different wood products pools, based on the values given in McGuire et al. (2008) but recalculated to be applied to just the aboveground carbon flux.

	1 yr	10 yr	100 yr
Broadleaf tree	60%	30%	10%
Needleleaf tree	60%	40%	0%
Shrub	80%	20%	0%

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

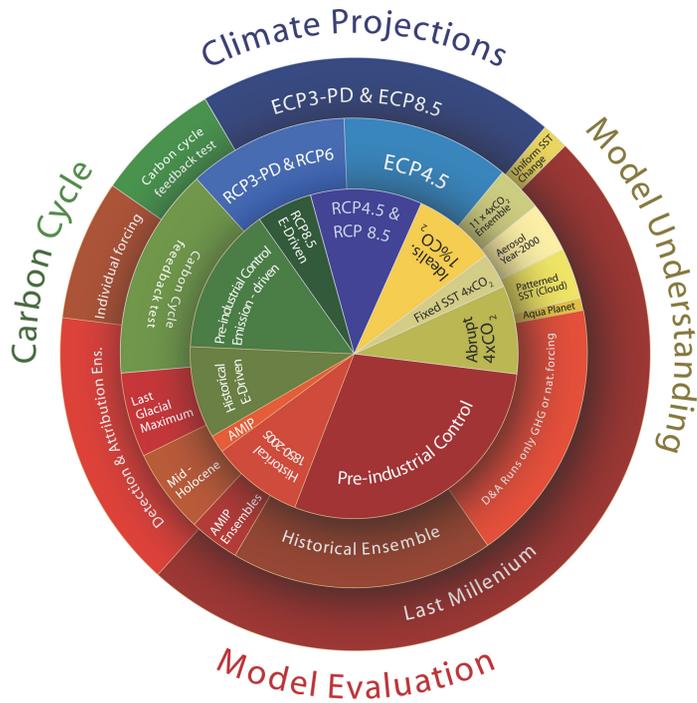
[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

Table 4. Mapping of the P08 land classes into MOSES2 vegetation types.

Classification in P08	Classification in MOSES2
Tropical evergreen forest	Broadleaf trees
Tropical deciduous forest	Broadleaf trees
Temperate evergreen broadleaf forest	Broadleaf trees
Temperate/boreal deciduous broadleaf forest	Broadleaf trees
Temperate/boreal evergreen conifers	Needle leaf trees
Temperate/boreal deciduous conifers	Needle leaf trees
Raingreen shrub	Shrubs
Summergreen shrub	Shrubs
C3 natural grasses	C3 grasses
C4 natural grasses	C4 grasses
Tundra	multiple mapping
Crop	multiple mapping
C3 pasture	C3 grasses
C4 pasture	C4 grasses



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Fig. 1. Schematic of CMIP5 centennial simulations, adapted from Taylor et al. (2009) with each experiment being represented by an area that is proportional to the experiment’s length in model years. The inner circle denotes “core” priority experiments with tier 1 (middle circle) and tier 2 (outer circle) having successively lower priority. Experiments are split between climate projections (blue), idealised experiments aimed at elucidating process understanding in the models (yellow), model evaluation, including pre-industrial control runs and historical experiments (red), and additional experiments for models with a coupled carbon cycle (green). See CMIP5 project webpage (Appendix A) for more detailed information. (D&A: detection and attribution, ECP: extended RCP simulations to 2300).

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#) | [Introduction](#)

[Conclusions](#) | [References](#)

[Tables](#) | [Figures](#)

[⏪](#) | [⏩](#)

[◀](#) | [▶](#)

[Back](#) | [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



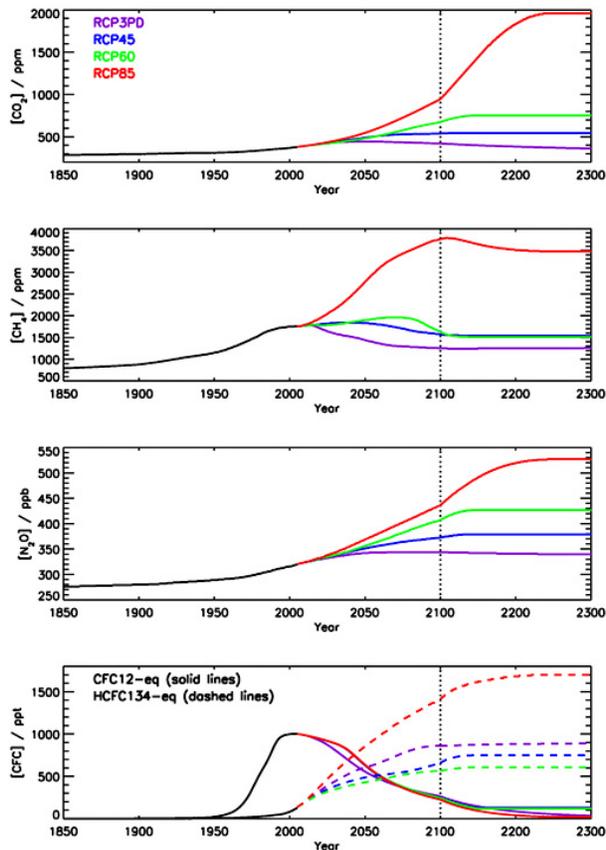


Fig. 2. Well mixed GHG concentrations used for concentration driven simulations: **(a)** CO_2 , **(b)** CH_4 , **(c)** N_2O , **(d)** halocarbons. Plotted are historical observed concentrations (black lines), and the four RCPs as well as their extensions beyond 2100 (RCP8.5: red; RCP6: green; RCP4.5: blue; RCP3-PD: purple). See Meinshausen et al. (2011) for further details. Note that the x-axis beyond 2100 is compressed.

**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**

C. D. Jones et al.

[Title Page](#)
[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)
⏪ ⏩
⏴ ⏵
[Back](#) [Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

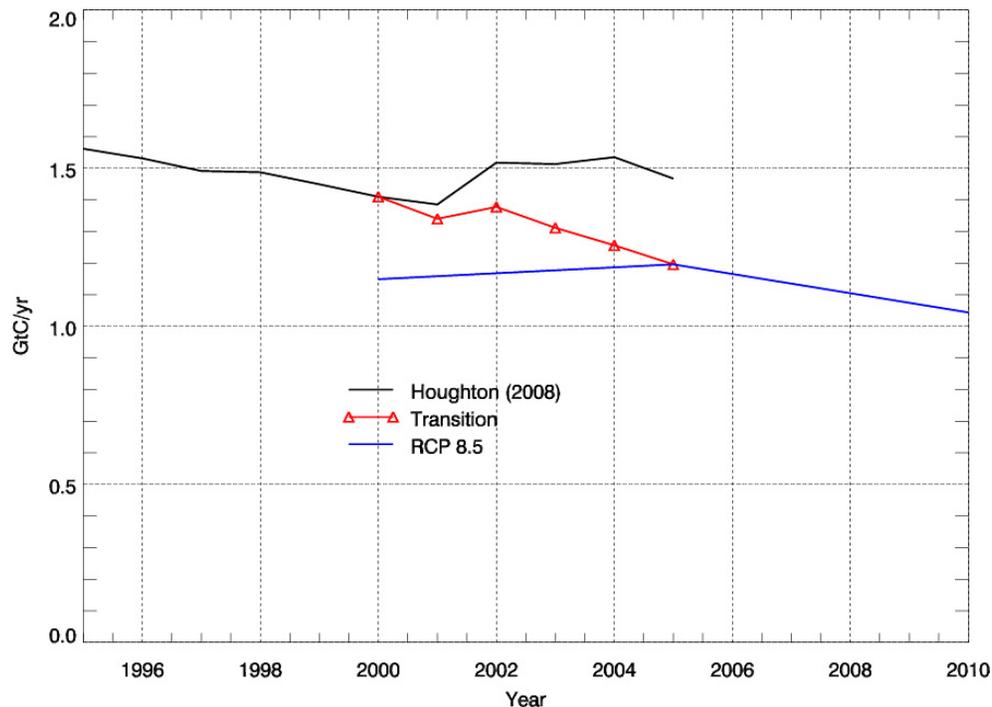


Fig. 3. Global land use emissions data during the transition from the historical simulation to the RCP8.5 simulation. The Houghton (2008) land use emissions data (black line) were scaled to meet the RCP data (blue line), resulting in the red line with triangles, which replaced the black line during 2000–2005.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**

C. D. Jones et al.

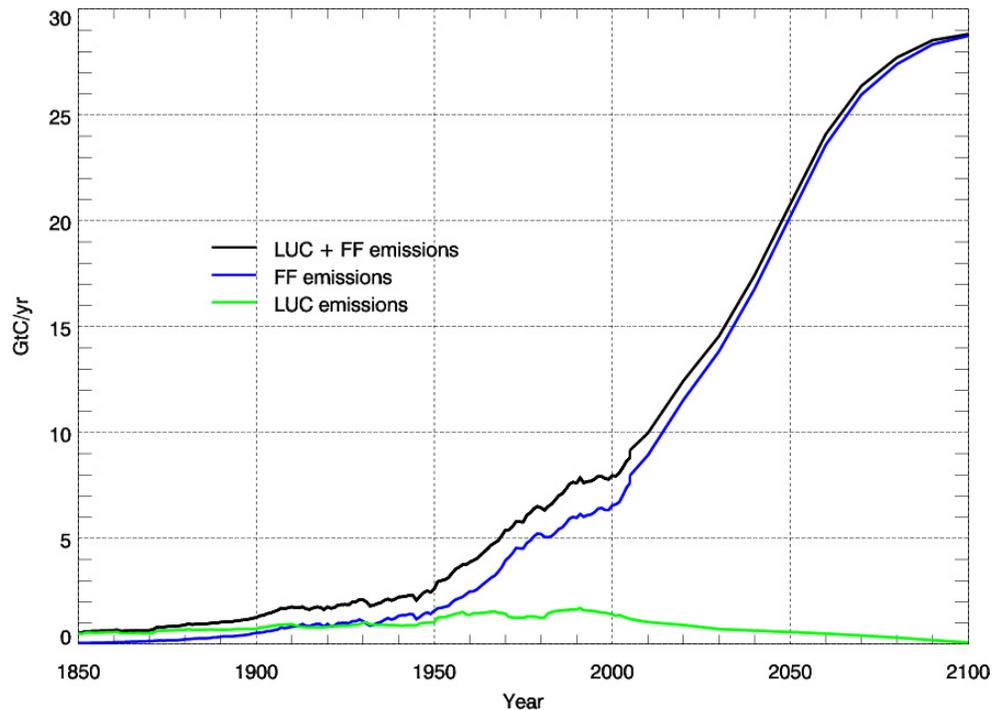


Fig. 4. Total CO₂ emissions used to force HadGEM2-ES for the emissions-driven historical and future RCP8.5 simulation. Total CO₂ emissions (black) and the individual components of fossil fuel emissions (blue) and LUC emissions (green).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

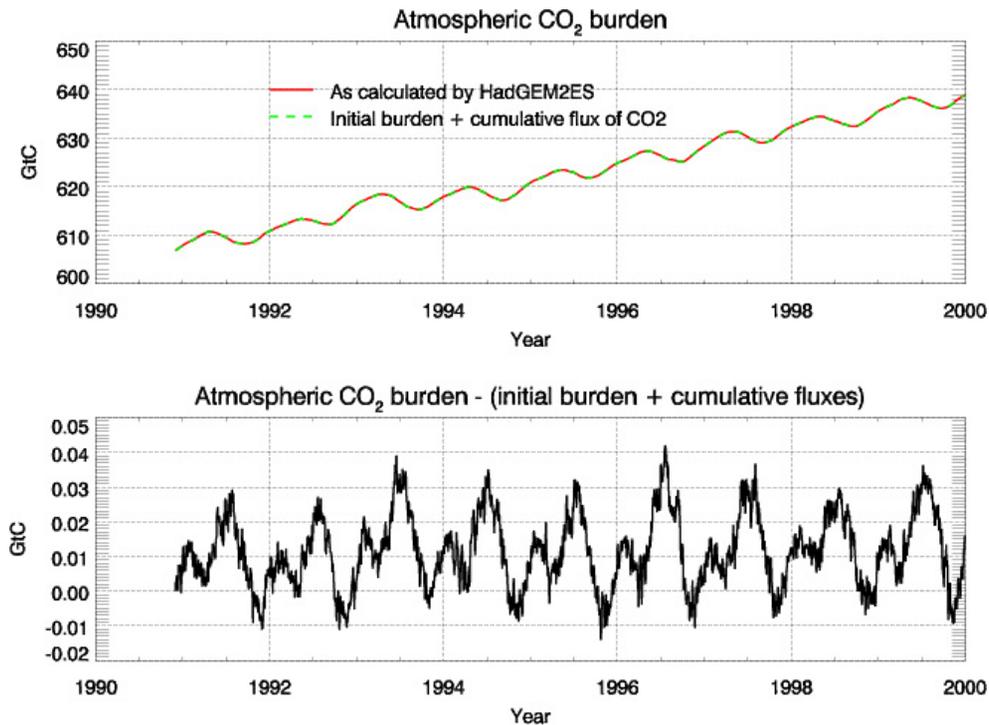


Fig. 5. The evolution of atmospheric CO₂ in HadGEM2-ES. Daily atmospheric CO₂ amount (top panel) simulated by HadGEM2-ES (red line), overlaid with the initial atmospheric burden plus the cumulative sum of CO₂ into the atmosphere (dashed green line). The lower panel shows the difference between the two.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

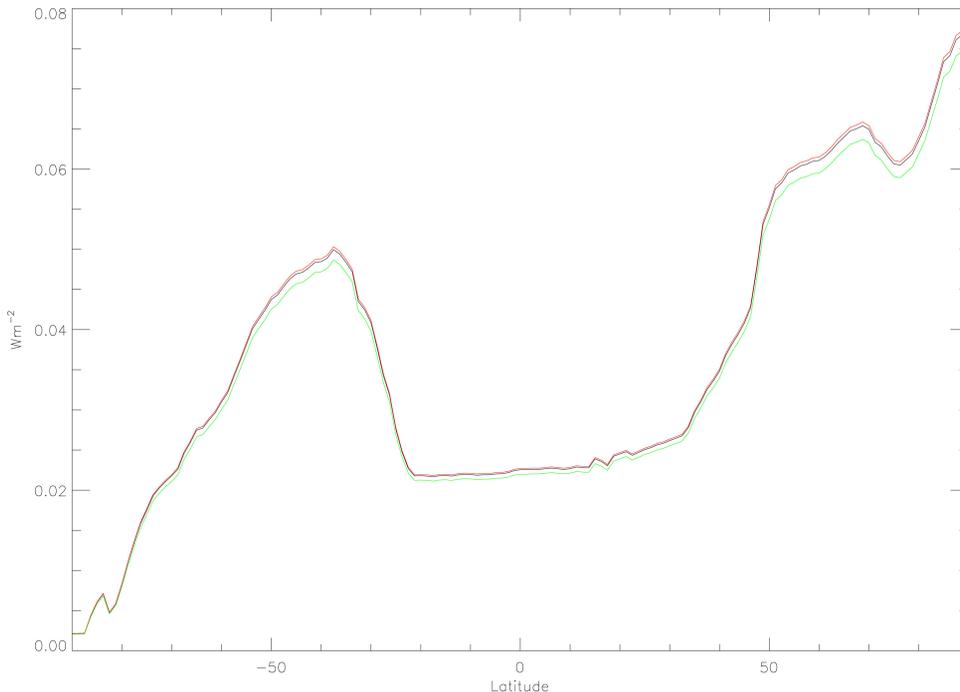


Fig. 6. Zonal-mean net tropopause forcing in which halocarbons controlled under the Montreal and Kyoto Protocol are represented as one equivalent species each, CFC-12 and HFC-134a, respectively (black line). The sensitivity tests with Montreal gases split into individual species (red line) and Kyoto gases split into individual species (green line) show a close agreement.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#) [Introduction](#)

[Conclusions](#) [References](#)

[Tables](#) [Figures](#)

[⏪](#) [⏩](#)

[◀](#) [▶](#)

[Back](#) [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



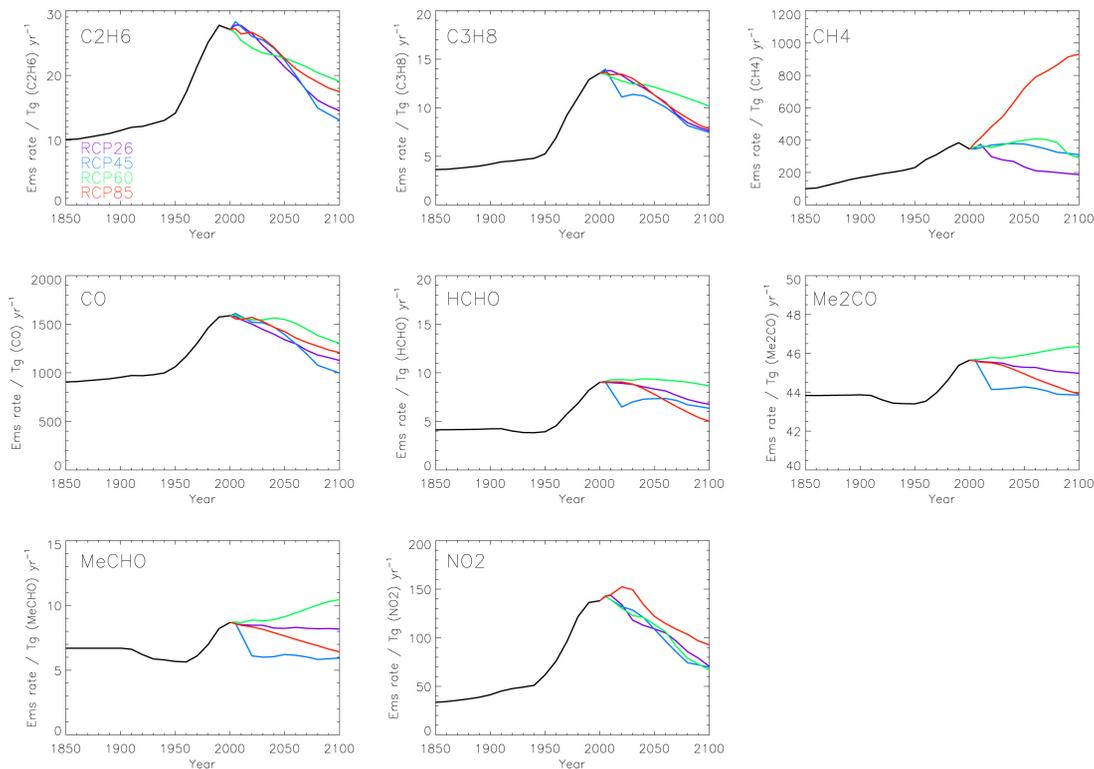


Fig. 7. Tropospheric ozone precursor surface emissions over the historical period (1850–2005) and over the future period (2005–2100) from the 4 RCPs: RCP3PD (purple), RCP4.5 (blue), RCP6 (green), and RCP8.5 (red). The methane (CH_4) emissions shown do not include a contribution from wetlands.

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

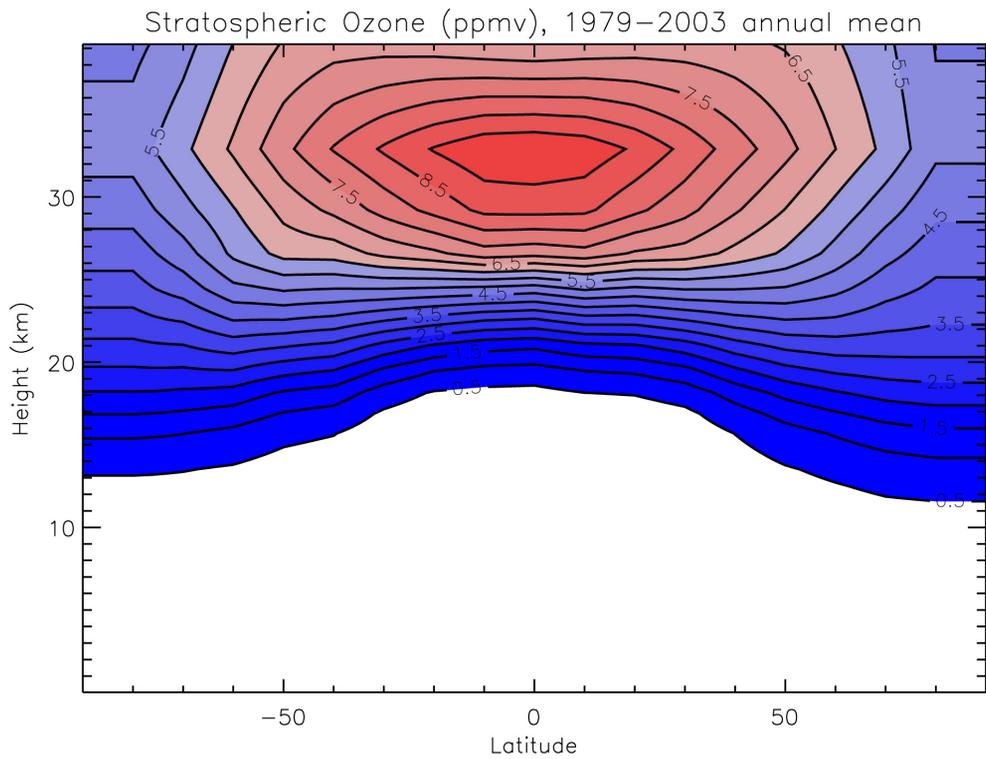


Fig. 8. Annual mean climatology of ozone volume mixing ration (ppmv) for 1979–2003.

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
⏪	⏩
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**

C. D. Jones et al.

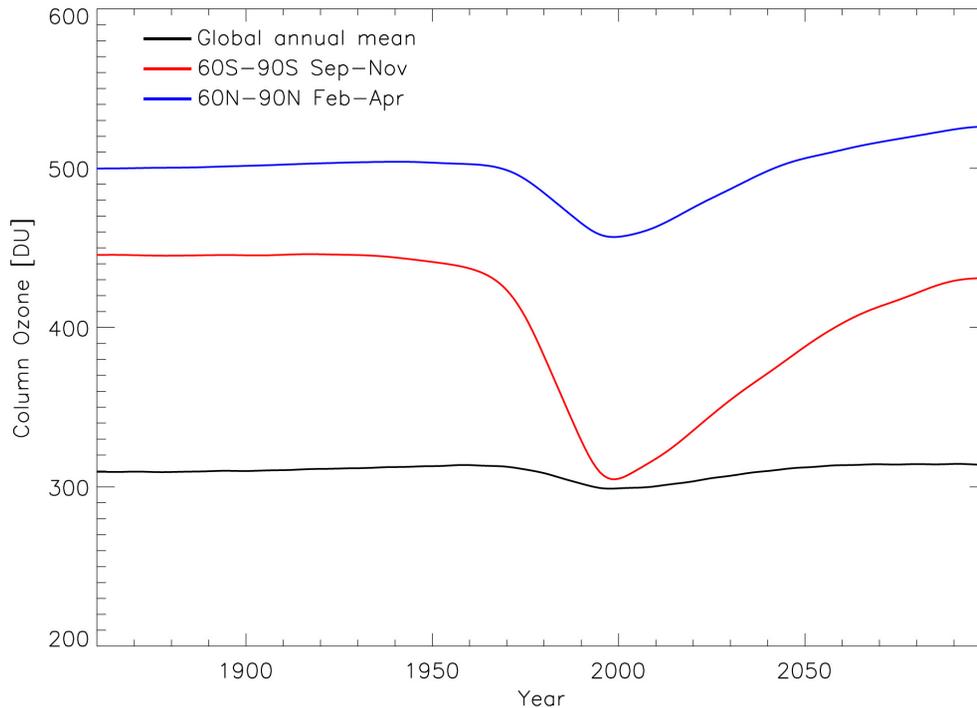


Fig. 9. Timeseries of column ozone (in Dobson Units, DU) for global annual mean (black line), 60° S–90° S September–November mean (red line) and 60° N–90° N February–April mean (blue line).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

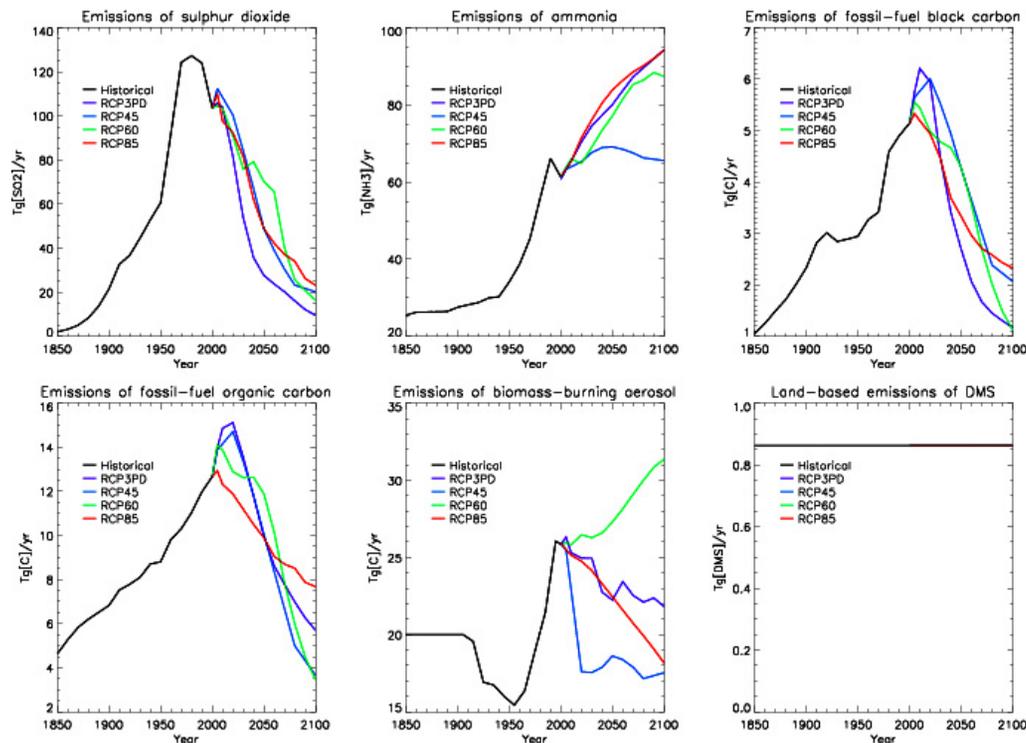


Fig. 10. Tropospheric aerosol precursors and aerosol primary emissions over the historical period (1860–2005), and future period (2005–2100) for 4 RCPs: RCP3PD (purple), RCP4.5 (blue), RCP6.0 (green), RCP8.5 (red).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

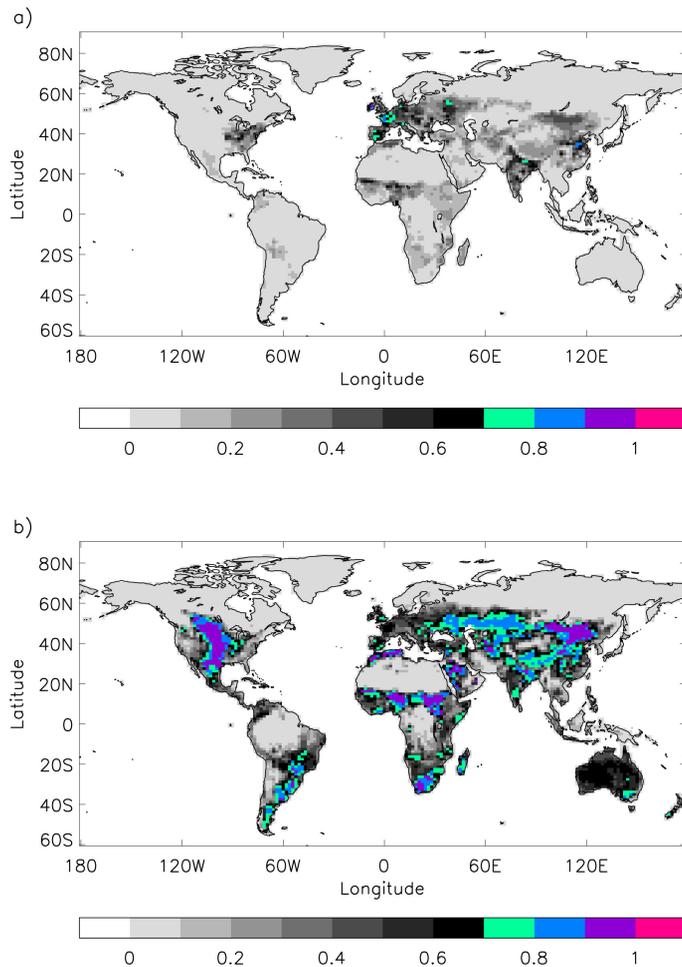


Fig. 11. Historical land use presented as fractional anthropogenic disturbance at **(a)** 1860 and **(b)** 2005.

GMDD

4, 689–763, 2011

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

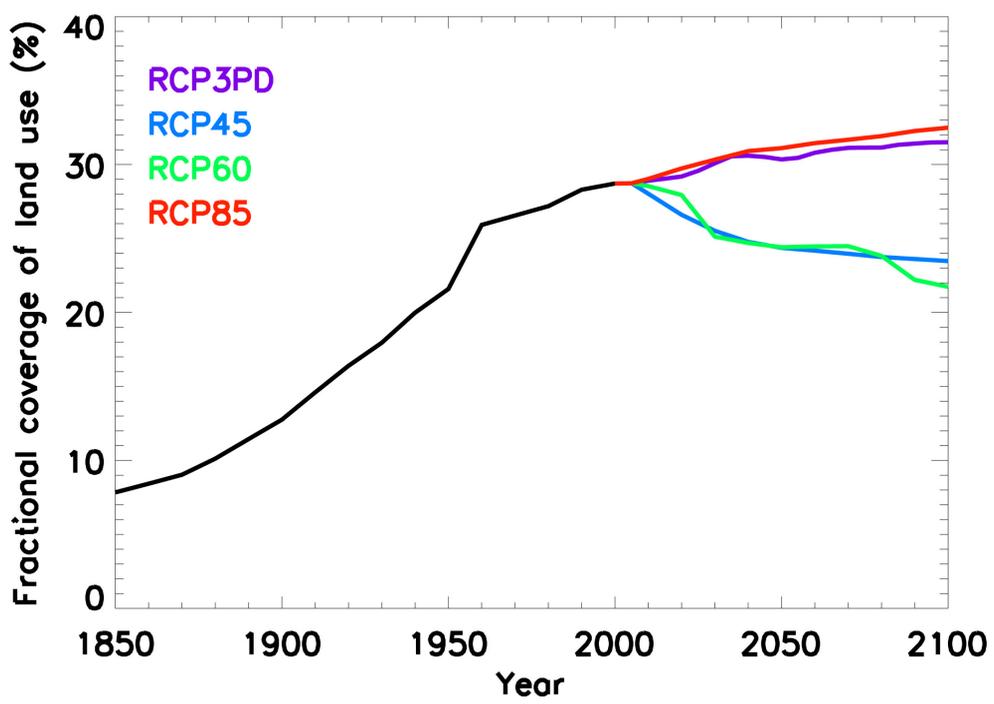


Fig. 12. Fractional coverage of anthropogenic disturbance, defined as the sum of crop and pasture, for the historical period 1860–2005, and up to 2100 following the 4 RCP scenarios, RCP3PD (purple), RCP4.5 (blue), RCP6 (green) and RCP8.5 (red).

[Title Page](#)
[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)
⏪ ⏩
◀ ▶
[Back](#) [Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



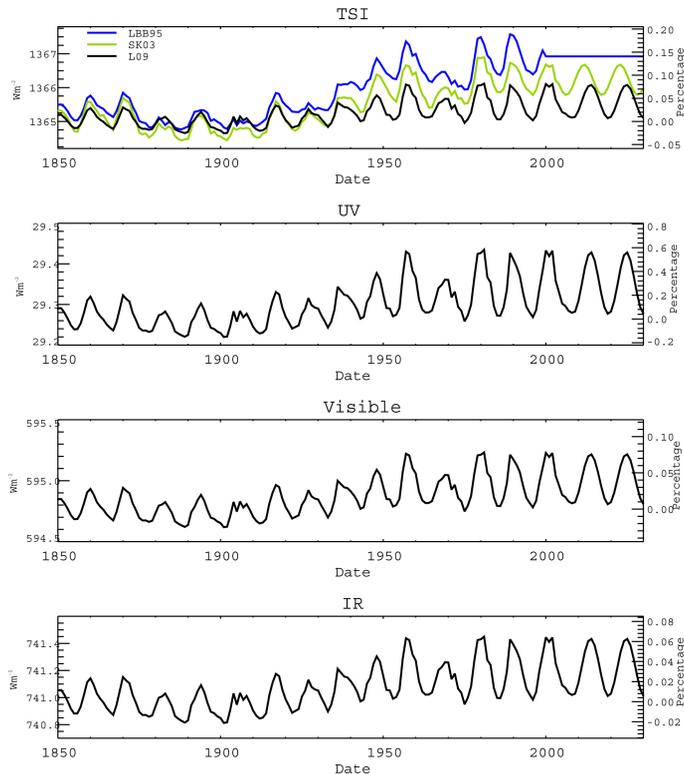


Fig. 13. Annual mean solar irradiance variations used in the historic model simulation (L09 – Lean et al., 2009). **(a)** Total solar irradiance. Also shown are the TSI used in previous model simulations, LBB95 (Lean et al., 1995b) used in HadCM3 (Stott et al., 2000) and SK03 (Solanki and Krivova, 2003) used in HadGEM1 (Stott et al., 2006). Solar irradiance averaged over **(b)** the ultraviolet band (200–320 nm), **(c)** the two visible bands (320–690 nm), and **(d)** infrared bands (690–1190, 1190–2380, and 2380–10 000 nm). Percentages are given with respect to the solar constant (1365 Wm^{-2}), and associated distribution across the shortwave spectral bands.

**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**

C. D. Jones et al.

[Title Page](#)
[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)
⏪ ⏩
◀ ▶
[Back](#) [Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)



The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

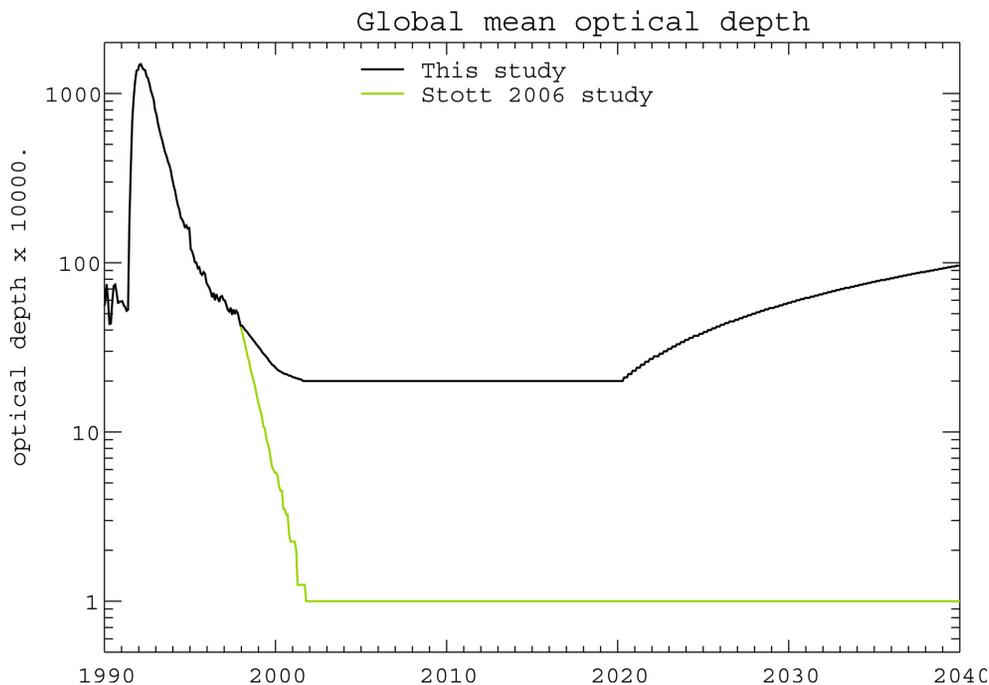


Fig. 14. Monthly global mean stratospheric optical depth as used in this study and what was included in the HadGEM1 simulations (Stott, 2006), for the period 1990–2040.

[Title Page](#)
[Abstract](#) [Introduction](#)
[Conclusions](#) [References](#)
[Tables](#) [Figures](#)
⏪ ⏩
◀ ▶
[Back](#) [Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

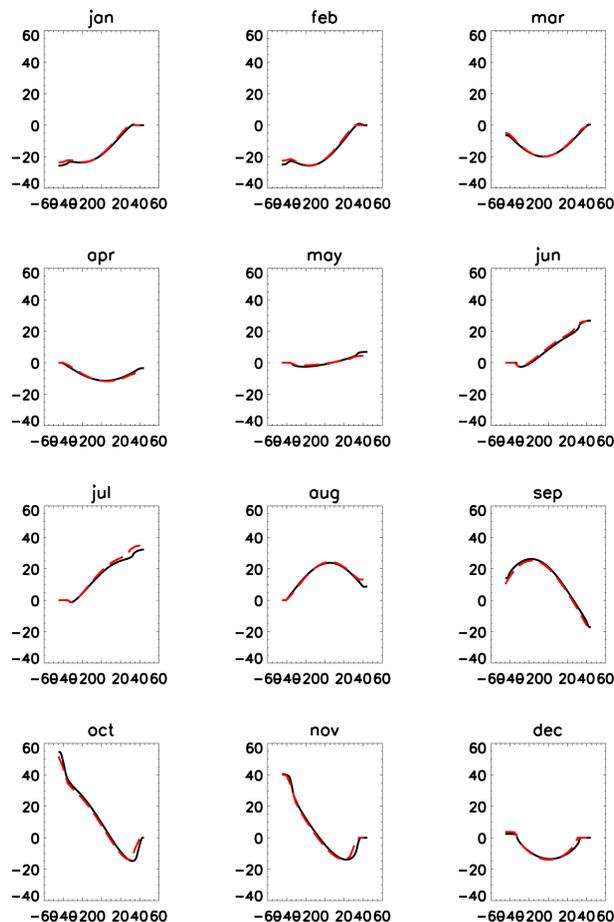


Fig. 15. Mid-Holocene changes in monthly TOA solar insolation relative to the present day, as a function of latitude as supplied by PMIP3 and calculated within HadGEM2-ES.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)

[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**C. D. Jones et al.

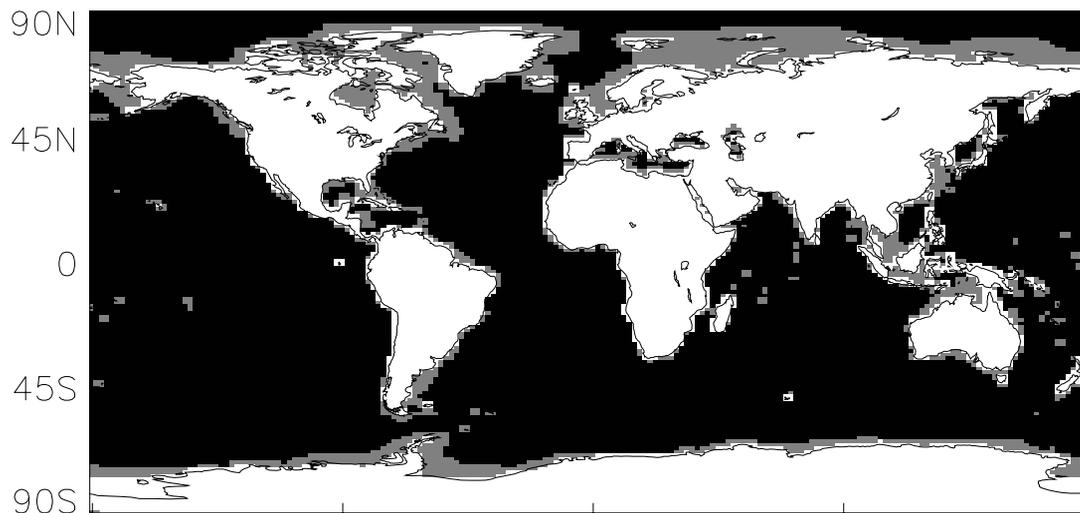


Fig. 16. Land sea masks used by HadGEM2-ES. Modern and mid-Holocene land points are denoted by white and additional LGM land points by grey. Black points denote points that are ocean in all simulations.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

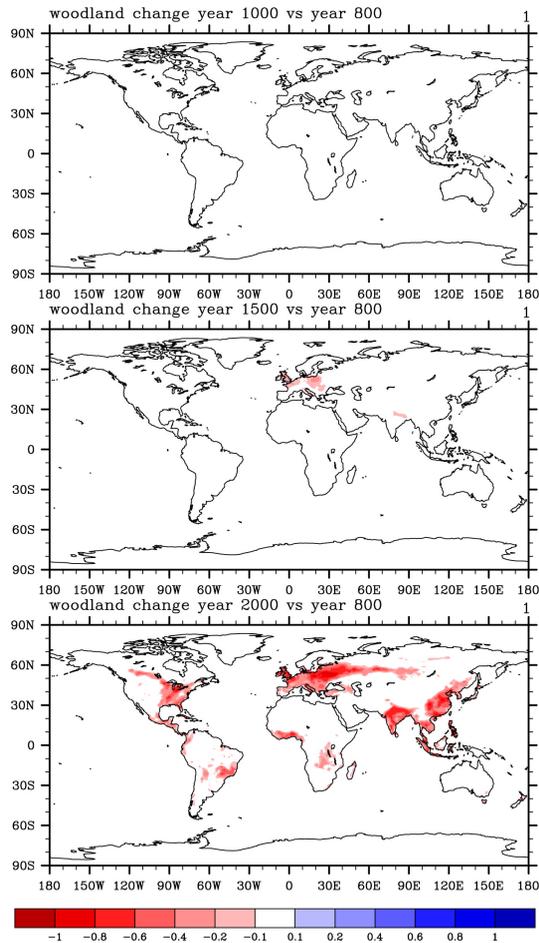


Fig. 17. Changes in fractional area coverage of woodland (broad leaf + needle leaf tree) in year 1000 AD, 1500 AD and 1990 AD with respect to the year 800 AD. Data from Pongratz et al. (2008) regridded on HadGEM2-ES grid.

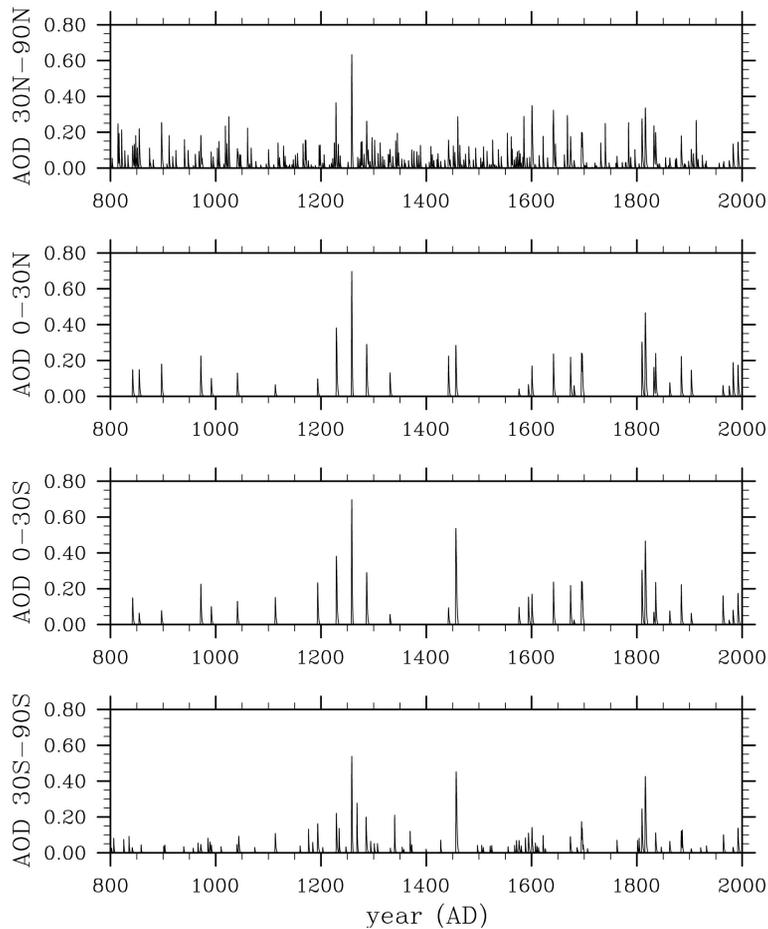


Fig. 18. Reconstructed stratospheric volcanic aerosol optical depth at 550 nm since year 800. From Crowley et al. (2008), for four different latitudinal bands.

**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**

C. D. Jones et al.

[Title Page](#)

[Abstract](#) [Introduction](#)

[Conclusions](#) [References](#)

[Tables](#) [Figures](#)

[⏪](#) [⏩](#)

[◀](#) [▶](#)

[Back](#) [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



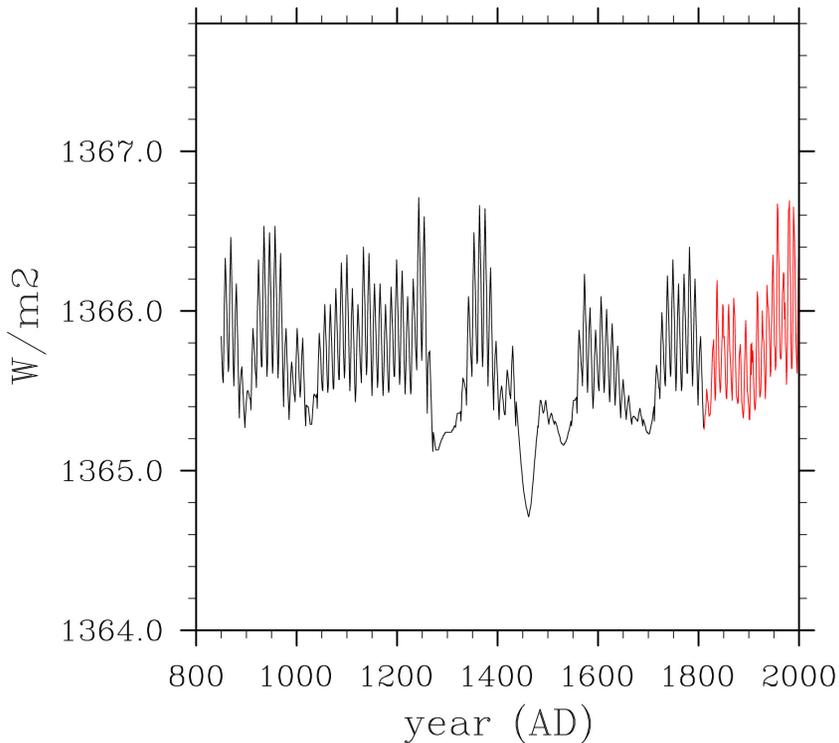


Fig. 19. Reconstruction of total solar irradiance since year 850 AD. The black line indicates data from Steinhilber et al. (2009), the red line data from Wang et al. (2005).

**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**

C. D. Jones et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**The HadGEM2-ES
implementation of
CMIP5 centennial
simulations**C. D. Jones et al.

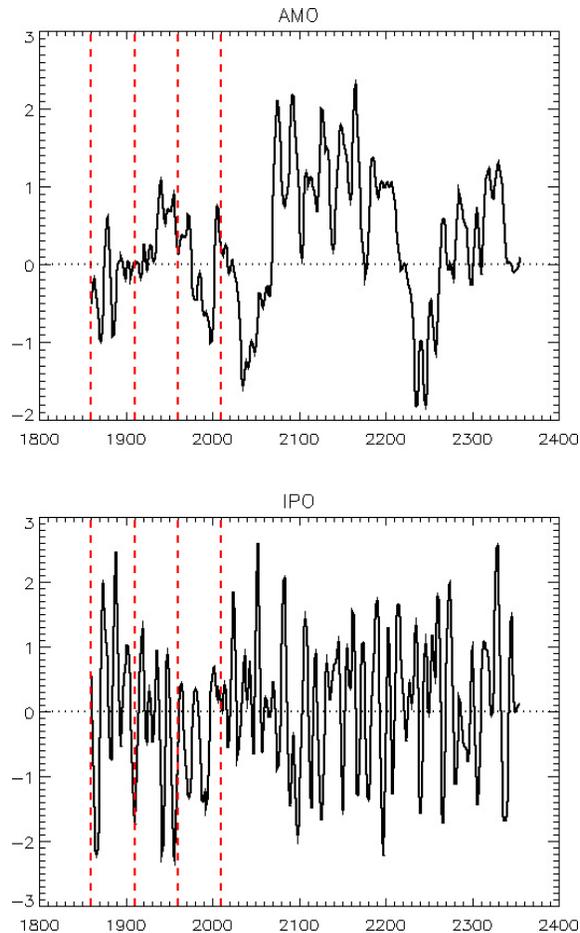


Fig. 20. Evolution of the AMO and IPO indices in the HadGEM2-ES pre-industrial control simulation. Vertical red lines show 50-yr intervals chosen as interval between ensemble member initial conditions. 4 ensemble members have been performed to date.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The HadGEM2-ES implementation of CMIP5 centennial simulations

C. D. Jones et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

◀

▶

◀

▶

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

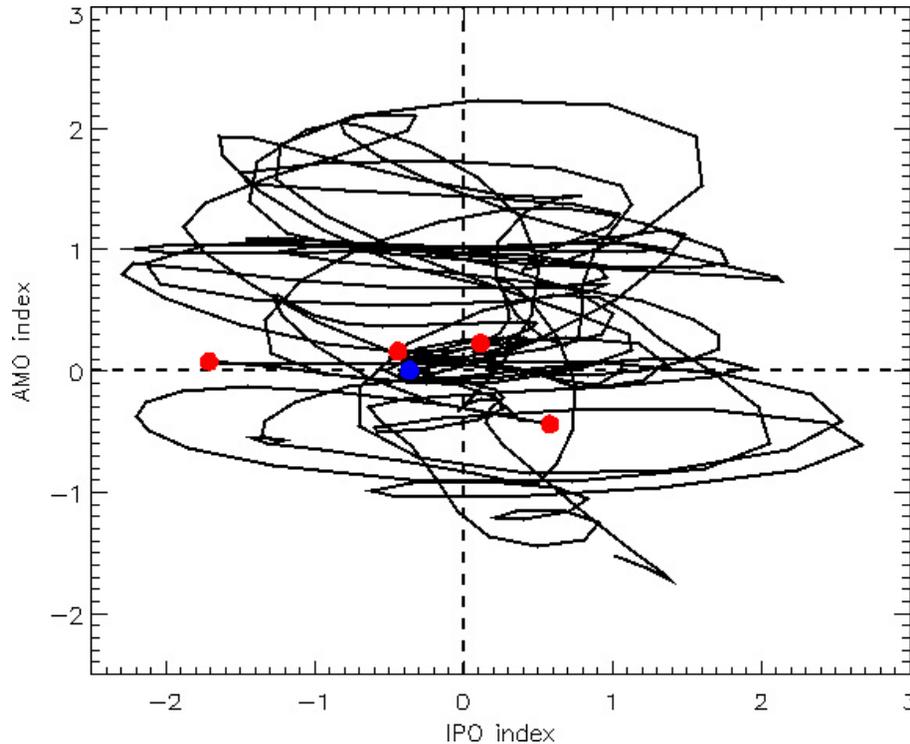


Fig. 21. HadGEM2-ES control run evolution in AMO/IPO phase space. Red dots show 50-yr intervals used for four existing HadGEM2-ES historical ensemble members. The blue dot shows the mean position of these four initial conditions.