CO₂ Emissions Determined by HadGEM2-ES to be Compatible with the Representative Concentration Pathway Scenarios and Their Extensions

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ABSTRACT
This paper presents the fossil fuel–derived CO₂ emissions simulated by the Hadley Centre Global Environmental Model, version 2, Earth System (HadGEM2-ES) to be compatible with four representative concentration pathways (RCPs) from 2006 to 2100. For three of the four RCPs, the analysis is extended to 2300. The compatible emissions compare well with those generated by integrated assessment models from which the RCPs were constructed. Historical compatible emissions are also presented, which closely match observation-based estimates from 1860 to 2005 (cumulatively 330 and 319 GtC, respectively). Simulated land and ocean carbon uptake, which determines the compatible emissions, is examined, with an emphasis on changes in vegetation carbon. In addition, historical land and ocean carbon uptake is compared with observations. The influences of climate change and the carbon cycle on compatible emissions are investigated individually through two additional experiments in which either aspect is decoupled from the CO₂ pathway. Exposure of the biogeochemical components of the Earth system to increasing CO₂ is found to be responsible for 68% of the compatible emissions of the fully coupled simulation, while increased radiative forcing from the CO₂ pathway reduces its compatible emissions by 11%. The importance of dynamic vegetation to compatible emissions is investigated and discussed. Two different methods of determining emissions from land use and land-use change are compared; differencing the land–atmosphere CO₂ exchange of two experiments, one with fixed land use and the other variable, results in historical land-use emissions within the uncertainty range of observed estimates, while those simulated directly by the model are well below the lower limit of the observations.

1. Introduction
The extent to which the climate will change in the future because of rising concentrations of greenhouse gases (GHGs) in the atmosphere has been the subject of much research in recent decades. For the Intergovernmental Panel on Climate Change’s Fourth Assessment Report (IPCC AR4; Solomon et al. 2007), general circulation models (GCMs) were used to examine the response of the climate system to a range of business-as-usual scenarios of CO₂ and other GHG emissions. These scenarios originated several years earlier with the IPCC’s Special Report on Emissions Scenarios (Nakićenović and Swart 2000) and lacked the influence of any direct mitigation policy. By contrast, phase 5 of the Coupled Model Intercomparison Project (CMIP5), which coordinates climate projections for IPCC’s Fifth Assessment Report (AR5), makes use of four scenarios in which policy-driven emissions cuts of varying severity are assumed (Taylor et al. 2012). These scenarios are the representative concentration pathways (RCPs) (Moss et al. 2010), which consist of time series of atmospheric concentrations of many greenhouse gases and aerosols.

The RCPs are derived from emissions profiles generated by integrated assessment models (IAMs). Underlying each emissions scenario is a set of sociopolitical and technological drivers that differ in their patterns of energy use, agriculture, population change, and other variables. The RCPs were selected from the literature to span a range of feasible futures, from a business-as-usual high-emissions scenario to one of aggressive mitigation with early and considerable cuts in emissions.

The use of concentration pathways, rather than emissions scenarios, represents a departure from CMIP phase
3 (CMIP3) and other notable projects such as the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP; Friedlingstein et al. 2006). One advantage of this approach is that a spread of radiative forcing pathways is guaranteed, uncertainty in the transition from IAM-derived emissions to GCM-simulated concentrations having been avoided. However, when a GCM is forced with a concentration pathway, the CO₂ emissions compatible with it can be diagnosed by analyzing the carbon balance of the model (section 2c; Jones et al. 2006; Matthews 2006). Most of the Earth System GCMs (ES-GCMs) participating in AR5 now diagnose land-use emissions from one or more of a range of land-use processes (Jones et al. 2013), allowing fossil fuel emissions to be diagnosed separately for the first time.

For a given CO₂ concentration scenario, the magnitude of the compatible emissions depends on the net uptake by land and oceans. Feedbacks between the climate and carbon cycle dictate how land and ocean uptake will change in the future (Cox et al. 2000). Different climate–carbon cycle models exhibit very different feedback strengths (Friedlingstein et al. 2006) and would therefore be expected to lead to a range of compatible emissions for a given CO₂ scenario. Comparison of the compatible emissions with those generated by the IAM underlying the RCP therefore illustrates the degree of consistency between the two models. It also provides a measure of the strength of the link between the range of assumptions underlying the RCP, the resulting climate change, and consequent impacts.

The range of compatible fossil fuel emissions diagnosed from CMIP5-participating models under historical and RCP forcing are presented in Jones et al. (2013). Here, we present the emissions determined by the Hadley Centre Global Environmental Model, version 2, Earth System (HadGEM2-ES) to be compatible with the historical and RCP forcing, as well as under three of the four extended concentration pathways (ECPs) that continue the RCP forcing until 2300 (Meinshausen et al. 2011b). We describe in detail how the emissions evolve through changes in the terrestrial and ocean carbon stores (section 3). In particular, we describe the changes in the vegetation distribution and discuss the role played by the dynamic vegetation scheme in shaping the emissions (section 4d). We compare the compatible fossil fuel emissions with those generated by the IAMs underlying the RCPs and ECPs and with observation-based estimates of historical emissions. We also compare carbon uptake by the oceans and land with observations from the twentieth century.

The influence on compatible emissions of changes in climate and atmospheric CO₂ can be investigated individually by decoupling either aspect within an Earth system model. Included in the CMIP5 experimental suite are two uncoupled variants of the standard historical and RCP4.5 simulations, labeled “RAD” and “BGC” (Gregory et al. 2009), in addition to the fully coupled equivalent (labeled “COU”). In the RAD experiment, the radiation scheme is exposed to the rising CO₂ concentration pathway, while the land and ocean biogeochemistry experience CO₂ fixed at the preindustrial level. In the BGC experiment, the reverse is true; the rising atmospheric CO₂ fertilizes vegetation growth (Cramer et al. 2001) and drives ocean uptake, while the climate remains comparable to that of the preindustrial throughout. The RAD experiment exhibits climate change analogous to that seen in the fully coupled experiment but with none of the additional land or ocean carbon uptake associated with elevated atmospheric CO₂. We present the compatible fossil fuel emissions from the RAD and BGC experiments and compare them with those from the fully coupled RCP4.5 (section 3c). We use these results to assess the impact on emissions of the carbon concentration and climate concentration feedbacks separately (section 4c).

In section 3, we also compare land-use emissions calculated directly by HadGEM2-ES with those inferred by comparing the net land uptake of the RCP4.5 experiment with a second simulation in which the land use is held constant at the initial (1860) level. We end with a discussion of our results (section 4) and conclusions (section 5).

2. Method
a. The RCPs

The four representative concentration pathways are known as RCP2.6 (van Vuuren et al. 2007), RCP4.5 (Clarke et al. 2007), RCP6.0 (Hijioka et al. 2008), and RCP8.5 (Riahi et al. 2007), the label indicating the approximate radiative forcing in watts per square meter exerted by the GHG and aerosol burden in 2100. The four scenarios were generated by four different IAMs: RCP2.6 by IMAGE (Integrated Model to Assess the Global Environment), RCP4.5 by MiniCAM (Mini-Climate Assessment Model), RCP6.0 by AIM (Asia-Pacific Integrated Model), and RCP8.5 by MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact). The emissions scenarios from each were converted into concentration pathways externally (Meinshausen et al. 2011a) by the reduced-complexity carbon cycle–climate Model for the Assessment of Greenhouse Gas Induced Climate Change, version 6 (MAGICC) (Wigley and Raper 2001). This approach was considered preferable to each IAM.
performing the emissions-to-concentrations step itself, since the four IAMs contain different versions of MAGICC.

The RCP2.6 scenario includes the most severe mitigation measures of the RCPs. Energy use is the least intensive of all RCPs, as is the reliance on fossil fuels; much of the energy demand is met by biofuels, which drives the greatest increase in global cropland fraction of all four RCPs. Carbon capture and storage technology helps to reduce emissions. Atmospheric CO₂ concentration peaks in 2050 at 443 ppm (Fig. 1a), before gradually declining to 421 ppm in 2100 and 361 ppm in 2300. The radiative forcing peaks at 3.0 W m⁻² around 2050, before declining to 2.6 W m⁻² at the end of the century, so this scenario is also known as RCP3 “Peak and Decline” (RCP3PD).

FIG. 1. (a) Atmospheric CO₂ concentration (ppm). (b) Global-mean temperature anomaly (K) relative to the 1861–90 average: data are from ensemble means until 2100, single simulations thereafter. (c) Fraction of global land surface devoted to agriculture. Historical period (1860–2005) is in black and RCP colors are as indicated.
Intermediate scenarios are represented by RCP4.5 and RCP6.0. Both are slightly more energy intensive than RCP2.6, but RCP4.5 relies less on fossil fuels, featuring cleaner energy sources and some use of carbon capture and storage, whereas fossil fuel use is prevalent under RCP6.0. The fraction of global vegetation dedicated to crops and pastures decreases in both RCP4.5 and RCP6.0. By 2100, the atmospheric CO₂ concentration reaches 538 ppm in RCP4.5 and 670 ppm in RCP6.0. In 2120, RCP4.5 stabilizes at 543 ppm, with RCP6.0 continuing to rise until around 2150, stabilizing at 752 ppm thereafter, though the extension of RCP6.0 until 2300 is not included in the CMIP5 core experiments and has not been performed with HadGEM2-ES.

The RCP8.5 is a business-as-usual scenario lacking any mitigation action before 2100. It assumes high population growth and a low rate of technological development. It is therefore the most energy intensive of the RCPs with the highest emissions of CO₂, with fossil fuels being the primary energy source. The total amount of land devoted to crop and pasture increases at a higher rate in RCP8.5 than the others to provide food for the rapidly expanding population. Total CO₂ emissions level out by 2100, and from 2150 to 2250 they reduce rapidly, as delayed mitigation action takes effect, causing radiative forcing to stabilize at 12 W m⁻² from 2200 onward. Atmospheric CO₂ reaches 1962 ppm in 2250 and remains at that level until the end of the century.

b. HadGEM2-ES

State-of-the-art coupled climate–carbon cycle model HadGEM2-ES contains many new Earth system processes absent from earlier Hadley Centre models. The model is described in detail in Collins et al. (2011) and Martin et al. (2011). A full description of the way in which HadGEM2-ES has been configured to perform the full range of CMIP5 experiments can be found in Jones et al. (2011).

The atmosphere model is composed of 38 levels, with a vertical extent of 39 km, and horizontal resolution of 1.875° (east–west) × 1.25° (north–south). The Met Office Surface Exchange Scheme, version 2 (MOSESII; Essery et al. 2001) calculates fluxes of heat, moisture, and momentum between the atmosphere and the land surface. The net primary productivity of vegetation covering the land surface is determined by MOSESII as a function of atmospheric CO₂, light, and soil moisture. The net accumulated carbon uptake is passed every 10 days to the dynamic vegetation model, Top-Down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) (Cox 2001). TRIFFID apportions this accumulated carbon among five plant functional types (PFTs): broadleaf tree, needleleaf tree, C3 grass, C4 grass, and shrub. The five PFTs compete for resources through Lotka–Volterra competition, and the areal coverage of each is updated accordingly every 10 days.

The HadGEM2-ES physical ocean model is based on that of HadGEM1 (Johns et al. 2006). The ocean is resolved into 40 vertical levels, with fixed longitudinal spacing of 1°. Between 30°N and 30°S latitudinal resolution rises gradually from 1° to 0.33° and is 1° elsewhere. The diatom version of the Hadley Centre Ocean Carbon Cycle model (Diat-HadOCC) provides the ocean carbon cycle component. Diat-HadOCC contains two types of phytoplankton: a diatom and other (nondiatom) phytoplankton pool and a zooplankton pool. The model contains three types of nutrients: nitrate and iron (on which both types of plankton depend for growth), and silicate (which is required only by diatoms). As well as the air–sea flux of CO₂, Diat-HadOCC computes the production of dimethyl sulfide (DMS) from phytoplankton.

Land-use in HadGEM2-ES is prescribed; onto each grid cell of the land surface is imposed a time-varying “disturbance” fraction in which C3 and C4 grasses only are permitted to grow. This is analogous to deforestation followed by the planting of grass-like crops and biofuels. Where the disturbed fraction increases, wood from displaced trees and shrubs enters three wood-product pools, where it is broken down at turnover rates of 1, 10, and 100 yr [see Table 3 of Jones et al. (2011) for the proportions of each PFT entering each pool]. Where the disturbed fraction decreases, the formerly managed land reverts to bare soil. Vegetation that can respond on short time scales (i.e., grasses) tends initially to dominate, although trees and shrubs may repopulate these regions as the local climate and competition dynamics permit.

The managed fraction imposed on the land surface in each experiment is derived from the land-use scenario underlying each RCP. When configured to run with a fully interactive carbon cycle, where atmospheric CO₂ is transported as a 3D tracer, the emissions from land use can be returned to the atmosphere, but since atmospheric CO₂ is prescribed in these experiments the land-use emissions are purely diagnostic.

An ensemble of four historical simulations was performed, with each separated from the next by 50 yr of preindustrial control (Jones et al. 2011). From each historical simulation all four RCPs were initialized, yielding four-member ensembles of each. One integration of each RCP was allowed to continue until 2300 under the appropriate ECP forcing, with the exception of RCP6.0.

c. Compatible fossil fuel emissions

When an Earth system model is forced with a prescribed atmospheric CO₂ concentration scenario, the
associated emissions can be diagnosed from the carbon balance of the model; the more CO₂ absorbed by the land and oceans, the greater the amount that can be emitted through anthropogenic activity while adhering to the concentration pathway. The total mass of CO₂ in the atmosphere C_A is known, and so is its rate of change dC_A/dt. The latter is related to the simulated carbon fluxes between the atmosphere and the land surface F_AL and between the atmosphere and the oceans F_AO and the total mass of carbon emitted through anthropogenic activity E_TOT by

\[ \frac{dC_A}{dt} = E_{TOT} - F_{AL} - F_{AO}. \]  

(1)

The total compatible emissions term E_TOT represents the sum of fossil fuel emissions E_FF and land-use change (LUC) emissions E_LUC. Equation (1) can be expanded and rearranged to give

\[ E_{TOT} = E_{FF} + E_{LUC} = \frac{dC_A}{dt} + F_{AL} + F_{AO}. \]  

(2)

Here, F_AL is the net ecosystem productivity (NEP); the net biosphere production (NBP); the net land carbon uptake after taking into account carbon lost through land-use emissions) is therefore (F_AL – E_LUC). From Eq. (2), the fossil fuel emissions term (i.e., E_FF) is determined as the sum of the net biosphere production [i.e., (F_AL – E_LUC)], the ocean uptake (i.e., F_AO), and the change in atmospheric CO₂ (i.e., dC_A/dt).

In HadGEM2-ES, the diagnosed land-use change emission flux (i.e., E_LUC) contains solely the carbon flux from deforested wood, with no account taken of any reuptake caused by new growth in deforested regions or regrowth in regions no longer under management. A more comprehensive way of determining the LUC flux is to compare the net land–atmosphere CO₂ flux of two parallel simulations, one with the time-varying LUC scenario and the other with the land-use distribution fixed at the initial state of the first (Arora and Boer 2010, hereafter AB10). For one of the four historical simulations with HadGEM2-ES, the complementary fixed land-use experiment was also performed; this pair of simulations has been used to compare the two methods of determining LUC emissions in section 3d. However, the compatible fossil fuel emissions (i.e., E_FF) have been calculated with the diagnosed CO₂ flux from deforested wood providing the E_LUC term, since the fixed land-use experiments do not come under the CMIP5 remit.

In a given period, if the net land and ocean carbon uptake is negative [(F_AL – E_LUC) + F_AO < 0], and greater in magnitude than the increase in the atmospheric carbon burden through changes in CO₂ concentration [(F_AL – E_LUC) + F_AO > dC_A/dt], then the compatible fossil fuel emissions will be negative (E_FF < 0), implying the need for carbon sequestration to remain on the CO₂ concentration pathway. The same is true if the atmospheric CO₂ concentration is reducing at a greater rate than the oceans and land surface can absorb that which leaves the atmosphere \{dC_A/dt < 0 and \|dC_A/dt\| > [(F_AL – E_LUC) + F_AO]\}.

3. Results

a. Temperature

The physical response of HadGEM2-ES to the historical and RCP forcing is described in detail in Caesar et al. (2013). However, since the change in global-mean temperature is one of the primary drivers of changes in global carbon stores and fluxes, along with atmospheric CO₂ and land-use change, all three are shown in Fig. 1. The ensemble-mean globally averaged warming (Fig. 1b) at the end of the historical period is 0.71 K (2001–05 average relative to the 1860–99 average). This compares well with the IPCC estimate of 0.76 ± 0.19 K warming in the same period, relative to the 1850–99 mean (Solomon et al. 2007).

The aggressive mitigation of the RCP2.6 scenario just fails to limit warming to 2 K; by the middle of the twenty-first century the ensemble-mean global-mean temperature anomaly reaches 2.04 K, declining slowly thereafter to about 1.4 K during the decade 2290–99. Under the RCP4.5 scenario, the global-mean temperature continues to rise after stabilization of the CO₂ concentration, reaching 3.6 K by 2300; the weaker emissions cuts of the RCP6.0 scenario result in the same amount of warming (i.e., 3.6 K) by 2100. The business-as-usual approach of RCP8.5 results in steady warming throughout the twenty-first and twenty-second centuries, approaching stabilization in 2300 at around 11.4 K above preindustrial temperatures, several decades after CO₂ stabilizes at approximately 1960 ppm in 2240.

b. Compatible fossil fuel emissions and biogeochemical fluxes

The diagnosed fossil fuel emissions (i.e., E_FF) are shown in Fig. 2a. Observation-based estimates of historically emitted CO₂ and the IAM-generated fossil fuel emissions of the RCPs and ECPs are overlaid for comparison. The cumulative equivalents are shown in Fig. 2c, with accumulated totals shown in Table 1.

Variability in E_FF is an artificial consequence of the way in which it is diagnosed and is caused mostly by interannual variability in net land carbon uptake as F_AO and C_A change relatively smoothly over time. A 10-yr
smoothed version of Fig. 2a is included (Fig. 2b) to clarify long-term trends and provide greater confidence of when negative emissions become necessary. The emissions $E_{FF}$ and the component fluxes $F_{AO}$, ($F_{AL} - E_{LUC}$), and $dC_A/dt$ from which they are calculated are shown together in Fig. 3, to help to explain how the emissions evolve over time.

1) HISTORICAL PERIOD: 1860–2005

The $E_{FF}$ compares well with observed historical fossil fuel emissions (Figs. 2a,b). From 1860 to 2005, the cumulative total of $E_{FF}$ (330 GtC) matches very closely the observed estimates (Boden et al. 2011) over the same period (319 GtC).

The ocean carbon uptake $F_{AO}$ is shown in Fig. 2d. From 1850 to 1950, $C_A$ generally rises very gradually (Fig. 1a), with a long-term rising trend in $F_{AO}$ as a result. After 1950, $C_A$ increases much more rapidly, driving stronger ocean uptake for the remainder of the century. The ensemble-mean ocean uptake from 1860 to 2005 is 117.3 GtC, which is within the uncertainty range of the observation-based estimate of 141 ± 27 GtC (Arora et al. 2011; based on Sabine and Feely 2007). From 1980 to 1999, observed ocean uptake was 37 ± 8 GtC (Sabine et al. 2004); the ensemble-mean ocean uptake for the same period in HadGEM2-ES is extremely close, at 36.6 GtC.

Historical net carbon uptake on land is slightly lower than that by the oceans. Observation-based estimates of net land uptake are highly uncertain (Denman et al. 2007) at 211 ± 27 GtC from 1850 to 2005, but the HadGEM2-ES cumulative (1860–2005) total of 15.5 GtC

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<th>TABLE 1. Cumulative diagnosed $E_{FF}$ (GtC) during the periods 1860–2005, 2006–2100, and 2101–2299. The IAM-derived equivalent emissions are in italics beneath the HadGEM2-ES entry.</th>
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<td>HISTORICAL</td>
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is within this uncertainty range. Processes absent from HadGEM2-ES that would affect the net ecosystem productivity include interactions between the carbon and nitrogen cycles and carbon loss through fire. Land management practices are not explicitly included other than through the prescribed disturbance fraction as described in section 2b.

2) RCP (ECP) 2.6

The severe mitigation measures assumed by RCP2.6 result in a strong reduction in $E_{FF}$ over the course of the twenty-first century. The smoothed $E_{FF}$ plot (Fig. 2b) does not indicate the need for negative emissions until very close to 2100, though variability in the unsmoothed version (Fig. 2a) results in occasional years of negative emissions during the last two decades of the twenty-first century. However, from 2100 onward negative emissions are required for much of the time (Fig. 2b), at an average rate of $-0.45$ GtC yr$^{-1}$ from 2150 to 2300. This is caused by a combination of declining atmospheric CO$_2$ concentration causing net land uptake to become negative for much of the final century (Fig. 2c) and ocean uptake declining from around 1 GtC yr$^{-1}$ in 2100 to 0.2 GtC yr$^{-1}$ by 2300 (Fig. 2d). The net land uptake reduces gradually as the fractional coverage of shrubs and broadleaf and needleleaf trees reduce as they begin to be replaced by grasses (Fig. 4a), due in part to the expansion of the fraction of land devoted to agriculture (Fig. 5a, discussed in greater detail below), though this is partly offset by the northward expansion of trees and shrubs onto previously bare soil at high latitudes. So for much of the latter half of the extended RCP2.6 the land becomes a net source of carbon as $C_A$ is reduced with the phasing out of fossil fuel use, rather than as a result of climate–carbon cycle feedbacks, which caused the sink to source transition of Cox et al. (2000).

The cumulative total of $E_{FF}$ from 2006 to 2100 is 383 GtC, compared with 321 GtC from the IAM. Over the next two centuries, HadGEM2-ES requires the sequestration of considerably less carbon (75 GtC) to maintain the RCP than the IAM (185 GtC), although the rate of sequestration required in HadGEM2-ES is only slightly less than that of the IAM; integrated over 200 yr, this results in a difference of 110 GtC.

3) RCP (ECP) 4.5

Under the RCP4.5 scenario, $E_{FF}$ peaks at around 13 GtC yr$^{-1}$ in 2040 and then declines fairly rapidly, stabilizing at about 2 GtC yr$^{-1}$ from 2150 onward.
Ocean carbon uptake $F_{AO}$ (Fig. 2d) peaks at about 2050 and then gradually declines to stabilize at about 1 GtC yr$^{-1}$ from 2250 onward as $C_A$ begins to reduce. Land uptake (Figs. 2e, 3b) also decreases, falling to below 1 GtC yr$^{-1}$ in 2300, following a peak of 4.5 GtC yr$^{-1}$ at 2050. By the late twenty-first century, shrubs have expanded northward to inhabit regions that were previously bare soil, and over the next 100 yr needleleaf trees start to follow. Over the twenty-second century, shrubs start decline from around 45° to 65°N, with broadleaf trees growing to replace them as the climate becomes suitable. Shrubs and needleleaf trees are partially replaced in temperate regions, as are broadleaf trees in the tropics, due largely to the expansion of agriculture (Fig. 5b). These effects combine to increase vegetation carbon throughout, although the rate of increase decreases over time, contributing to the reduction in land uptake. Soil carbon outgrows until about 2250, when it plateaus (Fig. 2f), also limiting $F_{AL}$. The cumulative total of $E_{FF}$ from 2006 to 2100 is 873 GtC, compared with the IAM equivalent of 785 GtC. From 2101 to 2299, $E_{FF}$ totals 459 GtC, greater than IAM equivalent (272 GtC), as the rate of increase of $E_{FF}$ slightly exceeds that of the IAM emissions throughout the period.

4) RCP6.0

Under RCP6.0, $E_{FF}$ rises steadily until the 2070s, after which it begins a downward trend until 2100. Land uptake increases steadily throughout the century (Figs. 2f, 3c) because of extensive growth of shrubs on bare soil north of 70°N and a slight increase in broadleaf trees in the tropics (Fig. 2f), despite fairly widespread replacement of trees and shrubs with grasses. Ocean uptake peaks at about 2080 (Fig. 3c) and reduces slightly thereafter. The main driver in the reduction in $E_{FF}$, however, is the slowdown in the rate of increase of $C_A$; Fig. 3c shows that $dC_A/dt$ starts to reduce at around 2080 and, since this is not compensated for by $(F_{AL} - E_{LUC})$ and $F_{AO}$, $E_{FF}$ must reduce. Cumulative fossil fuel emissions from 2006 to 2099 sum to 1223 GtC showing very good agreement with the IAM total of 1206 GtC.

5) RCP (ECP) 8.5

Consistent with the delayed mitigation approach of RCP8.5, $E_{FF}$ rises rapidly throughout the twenty-first century to reach 30 GtC yr$^{-1}$, before leveling off as late but stringent mitigation measures take effect. Then, $E_{FF}$ reduces rapidly from 2150 to 2250 (Figs. 2a, 3d), reducing to around 2 GtC yr$^{-1}$ from 2250 onward as $C_A$ stabilizes. The initial increase in $E_{FF}$ is caused by the rise in $C_A$, (Fig. 3d) as well as by the strong uptake on land and by the oceans that this drives. By the 2070s, absorption by the ocean levels off for a few decades before slowly reducing as the net result of a reduction in the atmosphere–ocean gradient of CO$_2$ partial pressure, circulation changes, and reduced solubility through rising sea surface temperature. Land carbon uptake peaks in 2070, then reduces rapidly (Fig. 3d), becoming negative in the late twenty-second century and remaining negative for most of the twenty third. The land ecosystem undergoes significant change over time, with the expansion of broadleaf trees to populate most of land surface between 50° and 70°N (Fig. 4d). This gain in vegetation carbon is offset by loss of soil carbon through heterotrophic respiration in excess of 150 GtC yr$^{-1}$, much of which occurs in southern Asia, South America, and central Africa, from the 2150s onward.

The net result of the land and ocean uptake is the requirement for very low emissions following the stabilization of atmospheric CO$_2$ concentration in 2240. The cumulative total of $E_{FF}$ under the RCP8.5 scenario from 2006 to 2100 is 1873 GtC compared with 1918 GtC from the IAM. From 2100 to 2299, $E_{FF}$ totals a further 2964 GtC, while the IAM total is 3050 GtC.

c. Uncoupled variants of the historical and RCP4.5 experiments

Figure 6 shows $E_{FF}$ for the BGC, RAD, and fully coupled experiments from 1860 to 2100, smoothed with a 10-yr running mean; $dC_A/dt$ is included for comparison (red curve). The emissions are summarized in Table 2. Comparison of $E_{FF}$ from the RAD and COU experiments reveals the extent to which the emissions in the latter are caused by the effects of CO$_2$ on the biogeochemistry. From 1860 to 2100, exposure of the biogeochemistry to elevated CO$_2$ is responsible for 68% of the compatible emissions. The remainder is caused by the net rise in the total atmospheric burden; 535 GtC of emitted CO$_2$ remains in the atmosphere.

Comparison of the BGC and COU experiments shows that the CO$_2$-induced climate change in the coupled experiment only reduces the compatible emissions from 1457 to 1306 GtC over the period 1860–2100; the BGC emissions are reduced by around 11% when the climate is allowed to change. This is discussed further in section 4c.

d. Offline versus online land-use emissions

In parallel with the standard historical experiment with time-varying land-use cover, an additional experiment has been performed with HadGEM2-ES in which the land-use cover is fixed at the preindustrial (1860) level. In the standard experiment, the land-use emissions are diagnosed as the carbon flux caused by deforestation (see section 2b); the carbon contained in trees...
that are cleared to make way for agriculture constitutes the online land-use change flux (i.e., $E_{LUC}$). This flux is not adjusted to take into account the carbon taken up by crops populating the deforested regions or differences in soil carbon as a result of changing land cover. In the fixed land-use experiment $E_{LUC} = 0$, by definition. Comparison of the net land uptake in the two experiments gives a more accurate estimate of the emissions associated with the land-use change scenario employed (see, e.g., AB10), since the effects of crop growth on deforested areas, regrowth of trees and shrubs on areas abandoned by agriculture, and associated soil carbon changes are now included implicitly. This can be thought of as the offline land-use change flux, since it is not diagnosable during any individual experiment.

Figure 7 compares the online land-use change flux (dotted line) with the offline equivalent (dashed line smoothed with a 10-yr running mean). The offline is generally higher than the online flux throughout. They increase at similar rates for around a century, after which the online flux levels out while the offline flux continues to increase slightly for another two decades before reducing at the end of the century. Cumulatively from 1860 to 2005 the offline flux (128 GtC) is within the Houghton (2010) range of 108–188 GtC for emissions from land use and land-use change (1850–2000), whereas the online flux (44 GtC) is much too low. Use of the online flux in the calculation of the compatible fossil fuel emissions is discussed in section 4b. Figure 7 also includes the historical land-use emissions (red curve) from Houghton (2008), with a cumulative total from 1860 to 2005 of 150.6 GtC. The two different methods of determining land-use emissions are discussed further in section 4b.

4. Discussion

a. Agreement of $E_{FF}$ with IAM-derived emissions

The CMIP5-participating models represent a wide range of dynamical, physical, and biogeochemical processes of the Earth system and treat land use and associated emissions in a variety of ways (Jones et al. 2013). These differences mean that the fossil fuel emissions diagnosed by the CMIP5 models will inevitably match the IAM fossil fuel emissions to varying degrees.

Reasonable agreement between the IAMs and ESGCMs is desirable, as it demonstrates consistency of behavior across the intermediate-complexity IAMs and the fully process-based ESGCMs. This validates the CMIP5 approach of employing concentration-driven rather than emissions-driven climate projections as in earlier projects (AR4 and C4MIP).

Version 6 of the MAGICC model, which was used to convert the GHG emissions generated by the individual IAMs into the RCP concentration pathways, was tuned to give a climate response resembling the median of 19 CMIP3 AO-GCMs and carbon cycle behavior representative of the midrange of the C4MIP models (Meinshausen et al. 2011a). A good match between compatible fossil fuel emissions of an ES-GCM and those of the IAMs is also therefore suggestive of similarity in behavior between the ES-GCM and the range of CMIP3 and C4MIP models to which MAGICC was tuned. Furthermore, similarity between ES-GCM and IAM emissions also provides confidence that the outcomes of impacts and vulnerability studies carried out with the climate data generated by the ES-GCMs are realistic consequences of the range of societal, technological, and population change scenarios upon which the IAM emissions and concentration scenarios are based.

b. Use of online LUC emissions in determining $E_{FF}$

Section 3d demonstrates that the LUC emissions determined by the offline method (128 GtC from 1860 to 2005) are much closer to the observation-based estimate of Houghton (2008) (~150 GtC) than those diagnosed online (44 GtC). Since the offline emissions can only be calculated where the fixed land-use equivalent of the standard LUC simulation has been performed, the less-accurate online emissions have been used in the calculation of $E_{FF}$ historically and in the projections to 2300. This does not, however, compromise the integrity of our estimate of the associated fossil fuel emissions, as will now be discussed.

The inclusion of a land-use change scenario in an Earth system model has far-reaching consequences because of biophysical and biogeochemical feedbacks between the various components of the Earth system (see, e.g., AB10). Replacing forest with crops or pasture changes the albedo and roughness of the land surface, modifying the fluxes of heat and momentum between it and the atmosphere. Similarly, changes to vegetation will affect evapotranspiration and runoff and therefore the local climate. As the vegetation changes, so too will the nature of the litter inputs to soil and therefore the soil carbon content and heterotrophic respiration. Where managed land is abandoned, carbon uptake by regrowth of natural vegetation offsets some of the CO$_2$ released through earlier deforestation.

The land-use flux diagnosed online by HadGEM2-ES represents solely the release of CO$_2$ through the breakdown of deforested wood. Yet the biophysical and biogeochemical changes described above are all accounted for in the model and modify the fluxes of CO$_2$ between the land and the atmosphere accordingly.
Fig. 4. Six latitude–time plots of change in fractional coverage of broadleaf tree, needleleaf tree, C3 grass, C4 grass, shrub, and bare soil, relative to 1860, for (a) RCP2.6, (b) RCP4.5, (c) RCP6.0, and (d) RCP8.5. White regions are within ±5% of the 1860 value. Data are from ensemble means until 2100, individual simulations thereafter.
The offline method of determining land-use emissions by comparing the land–atmosphere CO$_2$ exchange in LUC and no-LUC experiments allows us to quantify more accurately the net effect of the presence of LUC on this exchange (effectively, to partition the total land–atmosphere flux more accurately between LUC emissions and natural fluxes). By using the online rather than offline emissions, we are effectively overestimating the fraction...
of the land–atmosphere CO2 exchange that occurs naturally and therefore underestimating the anthropogenic component; the wider influence of LUC on this exchange is not being neglected, however, so this approach does not compromise our inferred fossil fuel emissions.

Our approach to evaluating the fossil fuel emissions contrasts with Jones et al. (2013), who consider changes to carbon stores rather than fluxes between them for 14 CMIP5 models, including HadGEM2-ES, from 1860 to 2100. Jones et al. (2013) therefore make no estimate of the emissions from LUC, making use instead only of the deforested biomass resulting from the LUC scenario employed; yet their cumulative fossil fuel emissions for HadGEM2-ES (328 GtC from 1860 to 2005) are very similar to the 330 GtC from the present study. Our approach takes into account the rate of conversion of deforested biomass into CO2, a process not included in the analysis of Jones et al. (2013), so the two estimates of $E_{FF}$ are very similar but not identical.

AB10 compare the different approaches of determining LUC emissions. Online LUC emissions in HadGEM2-ES are diagnosed in the manner AB10 refer to as the bookkeeping approach taken by Houghton (2003). Our calculation of the offline LUC emissions follows that of AB10 and is similar to McGuire et al. (2001), though our experimental setup is slightly different from both. In McGuire et al. (2001), a land surface model is driven with prescribed atmospheric CO2 (i.e., $C_A$) and climate. In AB10, a fully coupled GCM is used, with prognostic $C_A$ driven by prescribed fossil fuel emissions and interactive land-use emissions. The offline approach presented here uses a full ES-GCM, permitting biophysical feedbacks between the land surface and the atmosphere but prescribed $C_A$. As AB10 state, a portion of the prescribed historical atmospheric CO2 trajectory used to drive both the LUC and no-LUC simulations can be attributed to CO2 released through land-use change. This leads to artificially high uptake in the no-LUC case, and therefore an overestimation of the offline emissions presented here. It is partly for this reason that our cumulative historical LUC emissions from 1860 to 2005 (128 GtC) exceed that from AB10 (40–77 GtC from 1850 to 2000), who used prognostic atmospheric CO2 and a variety of different LUC scenarios.
Simulation of emissions associated with land use and land-use change is a significant challenge facing Earth system modelers, and is the focus of forthcoming research such as the Land Use and Climate, Identification of Robust Impacts (LUCID) extension to CMIP5 (http://www.mpimet.mpg.de/en/science/the-land-in-the-earth-system/climate-biogeosphere-interaction/lucid-cmip5.html). A more sophisticated representation of land-use processes is being prepared for the next generation of the Hadley Centre ES-GCM.

c. Isolating the contribution of the radiative and biogeochemical effects on $E_{\text{FF}}$

Figure 6 summarizes the effects of the radiative and biogeochemical properties of the Earth system on fossil fuel emissions. The red curve labeled $dC_A/dt$ shows the change in atmospheric CO$_2$ of the RCP4.5 scenario. In the absence of any natural CO$_2$ sources or sinks, this curve would represent the compatible emissions; the only way of adhering to the pathway would be to emit CO$_2$ at the rate shown by the red curve. Any deviation in emissions from the red $dC_A/dt$ curve is due therefore to the presence of the carbon cycle.

The $E_{\text{FF}}$ curve of the RAD experiment (labeled $E_{\text{FF}}$ [RAD] in Fig. 6) is similar in magnitude to $dC_A/dt$; the cumulative total of $E_{\text{FF}}$ [RAD] from 1860 to 2100 is 401 GtC, less than a third of $E_{\text{FF}}$ in the fully coupled experiment (1306 GtC), and comparable to the net increase in $C_A$, 535 GtC, over the same period (Table 2). Since the $E_{\text{FF}}$ [RAD] curve is lower than the $dC_A/dt$ curve, the net result of taking into account the radiative effects of atmospheric CO$_2$ is to reduce natural carbon storage.

Conversely, the absence of CO$_2$-induced radiative forcing from the BGC experiment allows fossil fuel CO$_2$ to be emitted at a rate more than twice that at which CO$_2$

<table>
<thead>
<tr>
<th>Year</th>
<th>Compatible $E_{\text{FF}}$ (GtC)</th>
<th>Emissions due to elevated CO$_2$ on biogeochemistry (COU – RAD)</th>
<th>Emissions reduction due to climate change (COU – BGC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COU</td>
<td>RAD</td>
<td>BGC</td>
</tr>
<tr>
<td>1860–2005</td>
<td>326</td>
<td>84</td>
<td>339</td>
</tr>
<tr>
<td>2005–2100</td>
<td>861</td>
<td>298</td>
<td>977</td>
</tr>
<tr>
<td>1860–2100</td>
<td>1187</td>
<td>382</td>
<td>1316</td>
</tr>
</tbody>
</table>
accumulates in the atmosphere (i.e., $dC_A/dt$, red curve). So the net result of including the effects of CO$_2$ on the biogeochemistry is to hugely increase carbon uptake by the natural sinks: for example, by CO$_2$ fertilization of vegetation.

The coupled simulation (black curve of Fig. 6, labeled $E_{FF}$ [Coupled]) combines the two effects isolated in the RAD and the BGC experiments; that $E_{FF}$ [Coupled] is so much closer to the BGC experiment (green curve of Fig. 6, labeled $E_{FF}$ [BGC]) than $E_{FF}$ [RAD] demonstrates the extent to which the biogeochemical CO$_2$ response dominates. In the coupled experiment $E_{FF}$ proceeds at approximately twice the rate of accumulation of CO$_2$ in the atmosphere, indicating an airborne fraction of approximately 0.5 throughout the historical and coupled RCP4.5.

**d. Impact of dynamic vegetation on $E_{FF}$**

The RAD and BGC experiments demonstrate the extent to which elevated CO$_2$ promotes uptake by vegetation and other natural carbon sinks, thereby increasing the compatible fossil fuel emissions. We now consider how the emissions are influenced by compositional changes in vegetation cover, making use of the extensions until 2300, which permit the emergence of centennial-scale changes in vegetation.

Figure 8 shows time series of total vegetation carbon simulated by HadGEM2-ES historically and under the RCP and ECP forcing (solid curves). In the dashed curves on the same figure, the time-varying PFT-specific vegetation carbon from the RCPs has been combined with the 1860 PFT distribution to illustrate how the vegetation carbon might have proceeded with a static, preindustrial vegetation distribution. Variation in the dashed curves is due therefore to changes in the carbon content of the individual PFTs as they respond to changes in climate and CO$_2$.

Land-use change is present in the solid curves of the standard RCPs but absent from the dashed curves of fixed vegetation distribution; it is predominantly the replacement of natural forest with cultivated land in the nineteenth and twentieth centuries that causes the two curves to diverge. Over the twenty-first century, the total area of land devoted to crop and pasture increases in RCPs 2.6 and 8.5, while that of RCPs 4.5 and 6.0 decreases. From 2100 onward, however, the distribution of cultivated land in the standard simulations is fixed, so subsequent changes in the vegetation distribution are natural. Although at 2100 the vegetation distributions of the solid and dashed curves are different, thereafter the differences in the rates of change of vegetation carbon are from the vegetation dynamics alone. This gives us an indication of the role played by dynamic vegetation in the compatible emissions. As the amount of CO$_2$ removed from the atmosphere and stored in vegetation increases (e.g., because of the northward migration of
plants in a warming climate), the implied fossil fuel emissions rise accordingly. It is not possible here to quantify exactly the amount by which the fossil fuel emissions change because of dynamic vegetation, as the land carbon storage will be affected by other changes such as soil carbon inputs and plant and soil respiration, but where dynamic vegetation leads to an increase in vegetation carbon it would also be expected to lead to a net increase in soil carbon through additional litter input and to a rise in $E_{\text{FF}}$.

From 2100 to 2295, vegetation carbon in the standard RCP8.5 simulation rises by 248 GtC; the reconstructed curve with fixed vegetation distribution reduces by 45 GtC over the same period, after declining from a peak in the 2150s. The dynamic vegetation scheme therefore permits a further 293 GtC (10% of the cumulative $E_{\text{FF}}$ over the same period) to be stored in vegetation, primarily through the northward expansion of broadleaf and needleleaf trees and shrubs (section 3). Toward the end of RCP8.5, as global-mean warming becomes extreme, it is likely that the additional carbon inputs to the soil from dynamic vegetation are partially offset by increasing soil respiration, thereby reducing the net gain in land carbon and $E_{\text{FF}}$, caused by the presence of dynamic vegetation.

In the standard RCP4.5 experiment, vegetation carbon gains 105 GtC from 2100 to 2295 compared with just 3 GtC when the 1860 vegetation distribution is imposed. Dynamic vegetation allows, therefore, an additional 102 GtC to be stored as vegetation, 22% of $E_{\text{FF}}$ in that period.

Under RCP2.6 forcing, vegetation carbon reduces by around 0.2 GtC yr$^{-1}$ from 2055 onward, regardless of whether the PFT distribution is fixed at the 1860 state or allowed to change dynamically. The climate in the RCP2.6 simulation changes little from 2100 to 2300 (Fig. 1; Caesar et al. 2013) and changes in the vegetation composition are quite minor (Fig. 4a), so the decline in total vegetation carbon is due primarily to reduction in the scale (canopy height and leaf area index) of the vegetation present, because of the declining $C_A$.

The inclusion of a dynamic vegetation scheme has the greatest effect on vegetation carbon storage therefore, adding 293 GtC, under RCP8.5; this business-as-usual scenario leads to extensive and rapid change in climate, allowing widespread migration of vegetation into previously uninhabitable regions or a change of composition to denser, more woody PFTs (grasses and shrubs to trees and needleleaf to broadleaf trees). However, since emissions are so high under RCP8.5, the additional carbon stored from dynamic vegetation has the greatest influence proportionally on the compatible emissions of RCP4.5, which sees more modest changes in vegetation (an increase of 102 GtC) but considerably less CO$_2$ emitted from fossil fuel burning.

5. Conclusions

The fossil fuel CO$_2$ emissions simulated by HadGEM2-ES to be compatible with the historical atmospheric CO$_2$ trajectory (330 GtC from 1860 to 2005) match observation-based estimates extremely closely (319 GtC; Boden
et al. 2011). Under the RCP forcing, HadGEM2-ES-diagnosed emissions are close to those derived by the integrated assessment models from which the RCPs were generated. This adds to the evidence that the relatively simple IAMs are able to capture the behavior of the complex, process-based ES-GCMs and lends support to the AR5 approach of driving ES-GCMs with IAM-derived concentration pathways.

HadGEM2-ES does not simulate the need for negative fossil fuel emissions by 2100 to remain on the RCP2.6 pathway. Thereafter, however, negative emissions are necessary much of the time, at an average rate of \(-0.37\, \text{GtC yr}^{-1}\) from 2100 to 2300, as the net land uptake becomes negative and ocean uptake reduces to 0.2 GtC yr\(^{-1}\). The global-mean temperature under the RCP2.6 scenario marginally exceeded the threshold of 2 K above the preindustrial, reaching 2.04 K by the 2050s. Neither the RCP4.5 nor the RCP8.5 extension requires negative emissions, but from 2200 to 2300 they decrease to 1.7 and 5.4 GtC yr\(^{-1}\) respectively, levels not seen since around 1900 (RCP4.5) and the 1980s (RCP8.5).

Comparison of the fully coupled and RAD RCP4.5 experiments shows that the response of the carbon cycle to atmospheric CO\(_2\) is the primary driver in the magnitude of compatible emissions, leading to 68% of \(E_{\text{RF}}\) from 1860 to 2100. The degree to which this is offset through the radiative effect of rising atmospheric CO\(_2\) concentration is relatively small; cumulative emissions under the fully coupled experiment were only 11% lower than those of the BGC experiment. This reduction is likely to be larger in a model with a stronger climate–carbon cycle feedback; the reduction of HadGEM2-ES is close to the mean of the nine CMIP5 models analyzed in Arora et al. (2013). Constraining this feedback further is important therefore to reduce uncertainty for policymakers when setting emissions targets to keep global-mean warming to within a proposed limit. It is clear that land-use activities that significantly impair long-term carbon uptake by vegetation, such as continued widespread deforestation, will reduce the amount of CO\(_2\) that can be emitted in other ways if warming targets are to be met.

Historical land-use emissions determined offline, by comparison of the land–atmosphere flux of LUC and no-LUC simulations, are within the observed range of historical LUC emissions. They provide a better estimate than the online diagnosed flux, because as well as emissions from deforestation they account for the impacts of LUC on the biophysical and biogeochemical land–atmosphere fluxes and therefore on carbon exchange.

Interactions between the carbon and nitrogen cycles are not included in HadGEM2-ES. Recent studies (Zaehler et al. 2010; Zaehler and Friend 2010; Thornton et al. 2009) suggest that models that include these interactions are likely to simulate reduced emissions compared with equivalent carbon-only models, as nitrogen limitation weakens the response of vegetation to elevated CO\(_2\). Nor does HadGEM2-ES take into account the loss of carbon from thawing permafrost, which is likely to be significant under a high-emissions scenario such as the RCP6.0 or RCP8.5 (Burke et al. 2012). The same is true of carbon emitted through fire. It is likely, therefore, that the compatible emissions presented here would be revised downward these effects taken into account. Carbon–nitrogen interactions are among new processes to be included in the next-generation Hadley Centre Earth System model to investigate this and other aspects of Earth system behavior.

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