Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-237, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 5 October 2016

Geoscientific Model Development Discussions

The Fire Modeling Intercomparison Project (FireMIP), phase 1: Experimental and analytical protocols

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Abstract. The important role of fire in regulating vegetation community composition and contributions to emissions of greenhouse gases and aerosols make it a critical component of dynamic global vegetation models and Earth system models. Over two decades of development, a wide variety of model structures and mechanisms have been designed and incorporated into global

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-237, 2016
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Published: 5 October 2016

fire models, which have been linked to different vegetation models. However, there has not yet been a systematic examination of how these different strategies contribute to model performance. Here we describe the structure of the first phase of the Fire Model Intercomparison Project (FireMIP), which for the first time seeks to systematically compare a number of models. By combining a standardized set of input data and model experiments with a rigorous comparison of model outputs to each other and to observations, we will improve the understanding of what drives vegetation fire, how it can best be simulated, and what new or improved observational data could allow better constraints on model behavior. Here we introduce the fire models used in the first phase of FireMIP, the simulation protocols applied, and the benchmarking system used to evaluate the models.

1 Introduction

Several studies have suggested that recent increases in the incidence of wildfire reflect changes in climate (Running, 2006; Westerling et al., 2006). There is considerable concern about how future changes in climate will affect fire regimes (Pechony and Shindell, 2010; Carvalho et al., 2010; Moritz et al., 2012) because of the direct social and economic impacts (Doerr and Santín, 2013; Gauthier et al., 2015), the deleterious effects on human health (Johnston et al., 2012; Marlier et al., 2012), potential changes in ecosystem functioning and ecosystem services (Sitch et al., 2007; Adams, 2013), and impacts through carbon-cycle and atmospheric-chemistry feedbacks on climate (Randerson et al., 2012; Ward et al., 2012; Ciais et al., 2013). Mitigating the most harmful consequences of changing fire regimes could require new strategies for managing ecosystems (Moritz et al., 2014). At the time of the IPCC Fifth Assessment Report, agreement about the direction of regional changes in future fire regimes was considered low – partially as a result of varying projections of future climate (Settele et al., 2014). However, that analysis relied on one statistical model of fire that was forced with a number of different climate projections; the effects of increased atmospheric carbon dioxide, changes in vegetation productivity and structure, and fire-vegetation-climate feedbacks were not considered.

The fact that fire affects so many aspects of the Earth system has provided a motivation for developing process-based representations of fire in Dynamic Global Vegetation Models (DGVMs) and Earth System Models (ESMs). Global fire models have grown in complexity in the two decades since first developed (Hantson et al., 2016). The processes represented – and the forms these processes take – vary widely between global fire models. Although these models generally capture the first-order patterns of burned area and emissions under modern conditions, biases exist in the simulations of seasonality and interannual variability. Non-negligible differences can be seen between models in the regional patterns and historical trends of fire. Evaluating and understanding these differences is a necessary step to quantify the level of confidence inherent in model projections of future fire regimes.

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Although it is common practice to compare individual fire models to observations, no study has directly compared global model performance when driven by the same climate forcing outside the context of model development (i.e., comparing a newly-developed fire module to the one it is designed to replace). One study has performed such a comparison on a regional basis, for Europe (Wu et al., 2015). Less formal comparisons (e.g., Baudena et al., 2015) are difficult to interpret because published simulations differ in terms of the techniques used to initiate the simulations, the climate inputs used, the time interval considered, and the treatment of land use. Diagnosis of the influence of structural differences between models on simulated fire regimes can only be achieved through a comparison of model performance when forced by identical inputs (e.g., Taylor et al., 2012). The Fire Model Intercomparison Project (FireMIP, http://www.imk-ifu.kit.edu/firemip.php; Hantson et al., 2016) seeks to improve our understanding of fire processes and their representation in global models through a structured analysis of simulations using identical forcings and the evaluation of these simulations against observations.

FireMIP will be a multi-stage process. The first stage, described here, will document and investigate the causes of differences between models in simulating fire regimes during the historical era (1901 to 2013). Direct observations on fire occurrence have only been available at a global scale since the 1990s, with the advent of satellite-borne sensors that detect active fires, fire radiative power, and burned area, along with algorithms that automatically process the raw data and output products available to the general public (Mouillot et al., 2014). There are regional compilations of data from other sources, of varying quality, that extend back to the mid-20th century (Kasischke et al., 2002; Stocks et al., 2003). Both types of observational records will be used to evaluate model performance, but the first half of the twentieth century is quite data-poor. This first phase of FireMIP will thus serve to produce a sort of ensemble estimate of global fire activity during that time, for which only a few estimates have been produced. Sensitivity experiments will be used to diagnose potential causes of mismatches between simulations and observations. However, fire models can be evaluated only in conjunction with their associated vegetation models: A model that reproduces burned area perfectly but simulates wildly incorrect patterns of aboveground biomass, for example, would be less than ideal. Likewise, it is possible for biases in a model to cancel each other out, resulting in the "right output" for the "wrong reasons." A number of important vegetation-related variables have observational data available, and FireMIP will assess model simulations of these in addition to fire-related variables so as to holistically evaluate model performance.

A major goal of FireMIP is to provide well-founded estimates of future changes in fire regimes. In the second phase of FireMIP, we will evaluate how different fire models respond to large changes in climate forcing by running a coordinated paleoclimate experiment. Past climate states provide the possibility to test the models under environmental conditions against which they were not calibrated (Harrison et al., 2015). In this paper, however, we describe the protocol for the first stage of FireMIP: the baseline simulation for the period 1900–2013 and associated sensitivity experiments.

2 Experimental protocol

2.1 Baseline and sensitivity experiments

The baseline simulation in FireMIP is a fully transient simulation from 1701–2013 (SF1; Table 1). This simulation involves specification of the full set of driving variables and will allow individual model performance to be evaluated against a number

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of available benchmarking datasets (Sect. 4.1). A series of sensitivity experiments (SF2) will allow the reasons for inter-model agreements and/or discrepancies to be diagnosed by analyzing the impact of each of the main drivers of fire activity separately (Table 1). These experiments use the same input and setup as the SF1 run, but keep key variables constant:

1. "World without fire" (SF2_WWF): Fire is turned off to evaluate the impact of fire on ecosystem processes and biogeography.

2. "Pre-industrial CO_2" (SF2_CO2): Atmospheric CO_2 concentration is fixed to pre-industrial levels (277.33 ppm) to analyze the impact of historical CO_2 increases on photosynthesis and consequent impacts on fire and other ecosystem processes.

3. "Fixed lightning" (SF2_FLI): Historically-varying lightning data are replaced with repeated cycles of lightning from 1901–1920 to explore the impact of changes in this potentially important source of ignitions.

4. "Fixed population density" (SF2_FPO): Human population density is fixed at its value from 1700, humans being another important source of ignitions whose distribution and number has changed over the last three centuries.

5. "Fixed land use" (SF2_FLA): Distributions of cropland and pasture are fixed at 1700 values to assess the impacts of historical land use changes and inter-model differences in implementation.

Limitations related to model structure and other constraints mean that not all participating models will be able to perform every SF2 experiment.

2.2 Input datasets

The FireMIP baseline experiment is driven by a set of standardized inputs, which include climate, population, land use and lightning. The climate forcing is based on a merged product of Climate Research Unit (CRU) observed monthly 0.5° climatology (1901–2013; Harris et al., 2014) and the high temporal resolution NCEP reanalysis. The merged CRU-NCEP v5 product has a spatial resolution of 0.5° and a 6-hourly temporal resolution (Wei et al., 2014). Global atmospheric CO_2 concentration was derived from ice core and NOAA monitoring station data (Le Quéré et al., 2014) and is provided at annual resolution over the period 1750–2013.

Many of the participating models were developed using different climate forcing data. Figure 1 illustrates how serious of an impact this can be, using the JSBACH-SPITFIRE fire model (Lasslop et al., 2014). This model configuration was originally parameterized using the CRU-NCEP forcing data. When the CRU-NCEP wind forcing is substituted with that from the WATCH data (Weedon et al., 2011), modeled burned area decreases by ca. 27% with important spatial changes in regional patterns. Because the use of different input data – in this case wind speed – can produce such major differences in outputs, participating groups were allowed to reparameterize their fire models to adjust for the idiosyncrasies of the FireMIP-standardized input data.

Annual data from 1700–2013 at 0.5° resolution on the fractional distribution of cropland, pasture, and wood harvest – as well as transitions among land use types – were taken from the data set developed by Hurtt et al. (2011). This data set is based on gridded maps of cropland and pasture from version 3.1 of the History Database of the Global Environment (HYDE; Klein Goldewijk et al., 2010), which are generated based on country-level FAO statistics of agricultural area in combination with algorithms to estimate population, land use, and settlement patterns into the past. HYDE also provides gridded maps of historical population density, which participating FireMIP groups used if needed.

A global, time-varying data set of monthly cloud-to-ground lightning was developed for this study at 0.5° and monthly resolution (J. Kaplan, personal communication), comprising global lightning strike rate (strikes $\mathrm{km}^{-2}\ \mathrm{day}^{-1}$), for the period 1871–2010. This dataset incorporates interannual variability in lightning activity using the method described by Pfeiffer et al. (2013) by scaling a mean monthly climatology of lightning activity (covering 2005–2014; Virts et al., 2013) using convective available potential energy (CAPE) anomalies (Compo et al., 2011).

The participating models (Table 2) have different spatial and temporal resolutions; groups were thus allowed to interpolate inputs from their original resolution to that appropriate for their model. This was done so as to preserve totals as close as possible to the canonical data. Some models required additional input datasets – for example, nitrogen deposition rates or soil properties. These were not standardized.

2.3 Model runs

The models were spun-up using population density and land use specified as in 1701, CO_2 set to its year 1750 CE value of 277.33, and re-cycling the climate and lightning data from 1901–1920. The spin-up was continued until carbon values in the slowest soil carbon pool varied by less than 1% between consecutive 50-year periods for every grid cell.

The historic simulations were run from 1701 through 2013. Population and land use were changed annually from the beginning of this simulation, and CO_2 values were changed annually from 1751 onwards. However, the 1901–1920 climate and lightning inputs were recycled for the first 200 years of the simulation. Time-varying values of all variables were used from 1901 to 2010. The lightning dataset did not include 2011–2013, so the 2010 values were used for the final three years of the experiment.

Although agriculture (cropland and pasture) were specified inputs, each model calculated natural vegetation on other grid cells according to its standard set-up and no attempt was made to standardize this. The biogeography of natural vegetation, represented by plant functional types, was either prescribed by modeling groups or simulated dynamically.

2.4 Output variables

A basic set of gridded outputs (Table 3) covering the period 1950–2013 was required for model comparison and evaluation. An additional set of output variables (Table A1) was provided for diagnostic purposes. All gridded outputs are provided in NetCDF format at at least 0.5° resolution or on the native grid of the model if run at a coarser resolution. In addition to the gridded outputs, global total fire emissions per year from the period 1700–2013 were provided in ASCII format.

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3 Participating models

Nine models have run the phase 1 FireMIP simulations (Table 2). All simulate fire in "natural" ecosystems, with some also simulating cropland, pasture, deforestation, and peat fire (Table S3). Figures 2–4 use the metaphor of a flowchart to illustrate the differences among the fire models in terms of structural organization and process inclusion. Whereas GlobFIRM and BLAZE use relatively simple empirical models to estimate gridcell burned area directly, the other models use a process-based structure to separately simulate fire occurrence (Fig. 2) and burned area per fire (Fig. 3). Even within the process-based models, however, a wide range of complexity is evident. For example, the calculation of burned area per fire (Fig. 3) can be as simple as the PFT-specific constants used in INFERNO, or can be so complex as to consider factors such as human population density and economic status, fuel moisture and loading, and wind speed. Translating from burned area to fire emissions shows a similar variation in model strategy, although models tend to fall into two groups (Fig. 4). Some models define constant combustion and mortality factors to calculate the fraction of vegetation burned or killed in a fire, whereas the rest – JSBACH-SPITFIRE, LPJ-GUESS-BLAZE, LPJ-GUESS-SPITFIRE, MC-Fire, and ORCHIDEE-SPITFIRE – vary fractional mortality and combustion based on estimated fire intensity.

A more detailed and mathematical description of the fire models can be found in Tables S1–S24. In these, to the extent possible, we have included all the equations used by each model to calculate burned area and fire effects. Based on model descriptions available in the literature, combined with unpublished descriptions, model code, and extensive conversations with developers, these tables represent the most complete description yet of the inner workings of several fire models. Units have been standardized, variable names have been harmonized, and analogous processes have been grouped together. The tables enable the straightforward comparison of models whose published descriptions often do not adhere to the same conventions, and will be important tools in interpreting inter-model variation in the results of the experiments described in this paper. They will also prove useful for other researchers interested in how global fire models work and how they differ from each other. It should be noted, however, that most of these models are still under continuous development. Readers should thus not assume that the descriptions given here are applicable to anything except the model versions used for this phase of FireMIP.

In this section, we briefly describe each participating model, including details of how the model versions used for FireMIP differ from any published versions.

3.1 CLM fire module

The fire model described by Li et al. (2012, 2013, 2014), with adjusted fuel moisture parameters, was used in the NCAR CLM4.5-BGC land model (Oleson et al., 2013) to provide outputs for FireMIP. This model includes empirical and statistical schemes for modeling burned area of and emissions from crop fires, peat fires, and deforestation and degradation fires in tropical closed forests. A process-based fire model of intermediate complexity simulates non-peat fires outside croplands and tropical closed forests. CLM4.5-BGC doesn't output fire counts and fire size because the two variables are not used in the schemes for crop fires, peat fires, and deforestation and degradation fires in tropical closed forests. Note that this fire model does not simulate fireline intensity. In addition, CLM4.5-BGC doesn't distinguish above-ground and below-ground litter (Koven et al., 2013). For simplicity, this model may be referred to as CLM-Li, or CLM-Li* when only referring to the model for non-peat fires outside croplands and tropical closed forests.

3.2 CTEM fire module

The Canadian Terrestrial Ecosystem Model (CTEM v. 2.0; Melton and Arora, 2015) represents disturbance as both natural and human-influenced fires. The original fire parameterization is described in Arora and Boer (2005), with Melton and Arora (2015) describing recent changes and its implementation in CTEM v. 2.0. The only changes between the version of the model used here and that described by Melton and Arora (2015) were made to accommodate the FireMIP lightning dataset, which differed significantly from that generally used by CTEM. The lower and upper thresholds of cloud-to-ground lightning strikes (Melton and Arora, 2015, Table S1) were reduced from 0.25 and 10.0 to 0.025 and 1.0, respectively, and the representative area was reduced from 500 km^2 to 300 km^2 (Melton and Arora, 2015, Table S1).

3.3 INFERNO

The INteractive Fire and Emission algoRithm for Natural envirOnments (INFERNO Mangeon et al., 2016) was developed for the UK Met Office's Unified Model (UM) and has been integrated within the Joint UK Land Environment Simulator (JULES; Best et al., 2011; Clark et al., 2011). INFERNO focuses on offering a simple, stable parameterization to diagnose fire occurrence, burnt area, and biomass burning emissions in the context of an Earth system model. It builds upon the fire parameterization proposed by Pechony and Shindell (2009). It is an empirical scheme that uses vapor pressure deficit (Goff and Gratch, 1946), precipitation, and soil moisture to diagnose burnt area and subsequent emissions. Within INFERNO, humans only explicitly impact biomass burning through the number of fires. The algorithm foregoes physical calculations for the rate of spread, instead assigning a vegetation-dependent average burned area: 0.6, 1.4, and 1.2 km^2 for fires in trees, grasses, and shrubs, respectively. Because of this specificity, no outputs for fire counts and fireline intensity are provided. Furthermore, fire-induced tree mortality and vegetation carbon removal have not been included. The FireMIP simulations were run on a relatively coarse N96 grid (192 cells longitude by 145 cells latitude).

3.4 JSBACH-SPITFIRE

The SPITFIRE model (Thonicke et al., 2010) was implemented in the JSBACH land surface component of the MPI Earth System Model (MPI-ESM; Giorgetta et al., 2013) to account for the effect of fire on vegetation, the carbon cycle, and the emissions of trace gases and aerosols into the atmosphere. The resulting JSBACH-SPITFIRE model (Lasslop et al., 2014) runs on a daily time step and can be applied in a coupled MPI-ESM model setup as well as an offline model forced with meteorological input data. Differences between JSBACH-SPITFIRE and the original SPITFIRE model described by Thonicke et al. (2010) include a modification of the effect of wind speed on fire spread rate, changes to parameters related to human ignitions and fuel drying, and a dependence of fire duration on population density (Lasslop et al., 2014). There have been several as-yet-unpublished changes to JSBACH. The conversion factor from biomass to carbon was changed from 0.45 to 0.5

to ensure consistency with emission factors. The definition of the green pool was revised to include only 1-hour fuel, while previously it also included sapwood. Finally, combustion completeness has been changed to match to that used by ORCHIDEE-SPITFIRE (Yue et al., 2014), which are based on a recent collection of field measurements (van Leeuwen et al., 2014).

3.5 LPJ-GUESS-BLAZE

The new BLAZe-induced land-atmosphere flux Estimator (BLAZE; Nieradzik et al., in prep.) was recently implemented into the latest version of LPJ-GUESS (Lindeskog et al., 2013; Smith et al., 2014). Burned area is generated once per year by the empirical fire model SIMFIRE (Knorr et al., 2014, 2016) based on fire weather, fuel continuity, and human population density. This annual burned area is distributed to each month of the next year based on observed fire seasonality. Fuel consumption and tree mortality are then estimated using the BLAZE module, which computes fire-line intensities from existing fuel load and fire weather parameters which are translated into height-dependent survival probabilities as described in the Population-Order-Physiology (POP) tree demography model (Haverd et al., 2014). Mortality functions for different biomes are derived from the literature (Hickler et al., 2004; van Nieuwstadt and Sheil, 2005; Kobziar et al., 2006; Bond, 2008; Dalziel and Perera, 2009). The fluxes between live and litter pools and the atmosphere are then computed accordingly.

3.6 LPJ-GUESS-GlobFIRM

The Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) dynamic global vegetation model includes the Glob-FIRM fire model (Thonicke et al., 2001) to estimate global fire disturbance. Glob-FIRM simulates fire once per year if enough fuel is available, with annual fire probability based on the daily water status of the upper soil layer over the previous year. Fuel consumption and vegetation mortality then depend on fire probability and a PFT-specific fire resistance parameter. (Note that because LPJ-GUESS-GlobFIRM estimates burned area directly, no outputs having to do with number of fires or fire size will be generated.) While LPJ-GUESS shares many core ecophysiological features with the other models in the LPJ family (Sitch et al., 2003), its distinguishing feature is that it also includes detailed representations of stand-level vegetation dynamics (Smith et al., 2001). In LPJ-GUESS, these are simulated as the emergent outcome of growth and competition for light, space, and soil resources among annual cohorts of woody plants and an herbaceous understory (Smith et al., 2001). These processes are simulated stochastically by using multiple "patches," each representing random samples of each simulated locality or grid cell and which correspond to different histories of disturbance and stand development (succession). Recently, the nitrogen cycle and N limitations on primary production were included in LPJ-GUESS (Smith et al., 2014) as well as land management for pastures and croplands (Lindeskog et al., 2013).

3.7 LPJ-GUESS-SPITFIRE

The SPITFIRE model (Thonicke et al., 2010) was originally added to the LPJ-GUESS vegetation model (Ahlström et al., 2012) by Lehsten et al. (2009, 2015). This implementation generally followed the original SPITFIRE formulation, but initial applications employed prescribed fire regimes and did not use the full set of burned area calculations in SPITFIRE. This

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Manuscript under review for journal Geosci. Model Dev.
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initial version also included modifications to account for the detailed representation of stand-level vegetation dynamics in LPJ-GUESS. For example, because many patches are smaller than many individual fires, each patch burns stochastically at each time step, with the probability of a patch burning set equal to the gridcell burned fraction in that time step. The version of LPJ-GUESS-SPITFIRE used here extends the version of Lehsten et al. (2009, 2015) by incorporating the complete burned area calculation from SPITFIRE (Thonicke et al., 2010), including lightning ignitions, burnt area, fire intensity, residence time, and trace gas emissions. However, human ignitions have been recalibrated to match global burned area data, and the effect of wind speed on rate of spread has been been modified (both adjustments follow Lasslop et al., 2014). The raingreen phenology follows Lehsten et al. (2009, 2015), but some important parameters for post-fire mortality and biomass of tropical trees have been updated since those publications. These are: tree allometry (Feldpausch et al., 2011; Dantas and Pausas, 2013), bark thickness (Mike Lawes, unpublished data), fuel bulk density (from Hoffmann et al., 2011), and maximum crown area (increased to 300 m^2 based on Seiler et al., 2014, but taking a more conservative value appropriate for a global parameterization). For details see Table S22. Furthermore, a simple land use scheme was implemented for compliance with the FireMIP protocol. A time-evolving fraction of patches was designated as pasture or cropland based on the HYDE land use data set (Klein Goldewijk et al., 2010). When natural patches were converted to cropland or pastures, 90% of the aboveground carbon was immediately respired to the atmosphere and 10% was added to a woody products carbon with a 25-year residence time (following Lindeskog et al., 2013). In cropland and pasture patches, tree establishment is forbidden, so only grass PFTs are present. Lightning ignitions occur in both cropland and pasture, but human ignitions were forbidden in croplands. One further change to the model compared to previous versions is that fuel moisture was taken as the average of the standard SPITFIRE fuel moisture (calculated per fuel class based on a fire danger index) and soil moisture. This was done to take into account the vertical moisture gradient through the fuel bed from the topmost fuel (whose moisture will equilibrate with the air moisture) and the bottommost fuel (which will be in contact with the soil and therefore will tend to equilibrate with soil moisture). This improved the timing and magnitude of simulated burnt area in development simulations.

3.8 MC-Fire

The MC-Fire module (Conklin et al., 2015; Lenihan and Bachelet, 2015) simulates fire occurrence, area burned, and fire impacts including mortality, consumption of aboveground biomass, and nitrogen volatilization. Mortality and consumption of overstory biomass are simulated as a function of fire behavior and the canopy vertical structure. Fire occurrence is simulated as a discrete event, with an ignition source assumed to always be present and generating at most one fire per year in a grid cell. Fire return interval varies between minimum and maximum values for each vegetation type, based on fuel loading and moisture. The version of MC-Fire run here is identical to the version described by Conklin et al. (2015) and Lenihan and Bachelet (2015).

3.9 ORCHIDEE-SPITFIRE

The ORCHIDEE-SPITFIRE model was developed by incorporating the SPITFIRE model (Thonicke et al., 2010) into the land surface model ORCHIDEE. All equations as described in Thonicke et al. (2010) were implemented, except for changes

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to lightning ignitions and combustion completeness, as well as the addition of a fuel-dependent ignition efficiency term (as described in Yue et al., 2014, 2015). In version 2 (used here), an anthropogenic suppression of lightning-ignited fires was added based on Equation 10 in Li et al. (2012). Combustion completeness values were updated compared to those in Yue et al. (2014, 2015), based on data published in van Leeuwen et al. (2014). Scaling factors were also introduced, to adjust simulated burned area for each of the 14 GFED regions to agree with burned area reported by GFED3 (Giglio et al., 2010). Finally, the standard FireMIP lightning dataset was adjusted to account for the fact that the original model (Yue et al., 2014, 2015) was calibrated using the LIS/OTD lightning flash rate climatology (Cecil et al., 2012). Specifically, the cloud-to-ground numbers provided were reinterpreted as flashes and scaled so that the mean annual global lightning flash rate during 1997–2009 was the same as that given in the LIS/OTD data.

4 Model evaluation

4.1 Benchmarking protocol

Model run outputs will be compared to observations using the metrics and methods devised by Kelley et al. (2013) to quantify model performance for individual processes. For most variables, this system uses normalized mean error (NME) and normalized mean squared error (NMSE) to evaluate geographic patterns of total values, annual averages, and interannual variability. Spatial performance of variables measuring relative abundance (i.e., cases where the sum of items in each cell must be equal to one, as in the case of vegetation cover) are evaluated using the Manhattan Metric (MM) or squared chord distance (SCD). Kelley et al. (2013) also developed metrics to assess temporal performance – for example, comparing the timing and length of the simulated fire season with observations.

Importantly, Kelley et al. (2013) also introduced the idea of creating a kind of experimental control for putting these metric scores into context. The “mean model” consists of a dataset of the same size as the observations, where every element is replaced with the observational mean. Similarly, the “random model” is produced by bootstrap resampling of the observations. These datasets allow the performance of the actual models to be compared against an external standard in addition to each other.

This benchmarking system can be used to evaluate model performance with regard to aspects of land and vegetation other than fire; the complete set of observational datasets to be used in this phase of FireMIP can be found in Table 4, and a description of the criteria for choosing datasets is given in Section 4.3 below.

4.2 Comparison to empirical relationships

Benchmarking will establish the degree to which a model is able to reproduce key temporal and spatial patterns in fire regimes and drivers of fire regimes (Pyne et al., 1996), including vegetation and hydrology. However, it is important to establish that the model reproduces these patterns for the right reasons rather than because it is highly tuned. Analyses involving process evaluation focus on assessing the realism of model behavior rather than simply model response, a necessary step in establishing

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confidence in the ability of a model to perform well under substantially different conditions from present. The basis of such analyses is the identification of causal relationships between key processes and potential drivers, based on analyses of observations using appropriate tools to isolate causal from purely statistical relationships (see, e.g., Bistinas et al., 2014). Model outputs are then interrogated to determine whether the model reproduces these relationships (e.g., Lasslop et al., 2014; Li et al., 2014). The analysis of the FireMIP results will rely on this sort of evaluation in addition to the structured, direct comparison to observations described in Section 4.1.

4.3 Observational data

The observational database assembled for FireMIP consists of a collection of datasets selected to allow systematic evaluation of a range of model processes. The system is an updated and extended version of that presented by Kelley et al. (2013). As in Kelley et al. (2013), the site-based and remotely-sensed observational data sets were chosen to fulfill a number of criteria. They are all global in coverage or provide an adequate sample of different vegetation types on each continent. The datasets are also all independent, in that they do not require the calculation of vegetation properties from the same driving variables as the fire-enabled DGVMs. This excludes, e.g., net primary productivity or evapotranspiration products that are based on the interpretation of remotely-sensed data using a vegetation model. For variables that display significant seasonal or interannual variability, the data must be available for multiple years and seasonal cycles. And finally, the data must be publicly accessible, so that other modeling groups can use the benchmarks subsequently.

The selected datasets provide information for vegetation properties, fire properties, hydrology, and fire emissions (Table 4). All remotely sensed data were re-gridded to a 0.5° grid and masked to a land mask common to all the models. There are multiple data sets available for some variables; we retained all of these products in order to be able to take account of observational uncertainties in the benchmarking procedure. It should be noted that many of the individual data sets do not provide measures of uncertainty.

5 Data availability

To facilitate the use and extension of the FireMIP data, in addition to publishing the results in the literature, we will make the output files publicly accessible. We will also make available the input data used for modeling and analysis of results.

6 Discussion and Conclusions

The goal of FireMIP is to compare the performance of a number of different global fire models in a systematic and uniform manner, evaluating model performance against standard benchmarks. Each model has been developed for different purposes, and thus we cannot expect that they will be equally good at simulating every aspect of the fire regime. Thus, our goal is not to identify a single best model, but rather to assess the strengths and weaknesses of individual models, and to identify how individual models could be improved.

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The FireMIP protocol uses standardized inputs for climate, lightning, land use, and population density. These inputs represent major drivers of fire regimes, and standardization should therefore minimize a major cause of differences between model simulations and help to isolate the impact of structural differences between the models on the simulation of fire regimes. However, there are secondary sources of inter-model differences that are more difficult to standardize and are not dealt with in this protocol. For example, each of the models prescribes or simulates natural vegetation outside of agricultural and/or urban areas. Differences in the prescribed or simulated natural vegetation at a regional scale could lead to differences in the simulated fire regimes. However, prescribing vegetation distributions in coupled fire-vegetation models means neglecting the critical two-way interaction between vegetation type and fire regime, and real-world interactions between climate and the coupled fire-vegetation system conflict with the idea of prescribing vegetation in Earth system models. The outputs from each model about leaf area and the fractional cover of different plant functional types (Table 3) for each grid cell will, at least, make it possible to examine whether differences in the simulated regional fire regimes reflect significant differences in vegetation. Similarly, the protocol has not standardized soil inputs – which will affect the water-balance calculations and hence control vegetation distribution – because this would likely require major re-calibrating of the models. However, differences in the soil inputs used by individual models could lead to differences in fire regimes at a regional scale. We anticipate that this is a second-order effect, and will rely on process-based diagnoses to identify the degree to which it explains inter-model differences. Finally, the exact implementation of land use and land cover change can cause important differences in model outputs, even given the same land use driver dataset (Brovkin et al., 2013).

The participating models vary in spatial resolution: Most are run on a 0.5° grid but some are run at coarser resolution (Table 2) and provide outputs at the native resolution of the model. Model parameterizations are specific to model resolution, and thus differences caused by differences in resolution are an inherent part of the structural uncertainty. However, resolution has an impact on the benchmarking metrics, with goodness-of-fit being inflated as resolution becomes coarser. Thus, the interpretation of the benchmarking metrics will need to take this into account by calculating appropriate null models for the different resolutions.

Model benchmarking will examine several different aspects of the fire regime, but will also consider how well each model captures vegetation properties and hydrology (Table 4). There are multiple data sets available for some of these properties, including e.g. burned area. Padilla et al. (2015) have shown that currently-available burned area products differ considerably both in terms of global total and at a regional scale. Differences between different data sets effectively define the current range of uncertainty in observations, and this level of uncertainty needs to be taken into account when evaluating model performance.

Nine modeling groups are performing the baseline FireMIP simulations, meaning that there are a number of fire models that are not included in this preliminary exercise. However, we hope that publishing this experimental and benchmarking protocol will encourage other fire modeling groups to participate in FireMIP.

We provide a standardized modeling and benchmarking protocol for a wide variety of global fire-enabled ecosystem models. The wide variety of approaches taken by the participating models lead us to expect notable inter-model variation in results. Some models, for example, estimate energy release for calculations of fire behavior and effects, while others use simplifications – an important structural difference. Process treatment (and, indeed, inclusion) should also cause variation in results;

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human ignitions and suppression, for example, are treated very differently by the different models, with some ignoring them entirely. By systematically comparing models developed with such a wide array of approaches, that this effort will advance our understanding of fire dynamics and its effects on ecosystem and Earth system functioning. The analyses will reveal important model shortcomings, which are crucial for assessing model uncertainties in future projections, and should, in the longer term, contribute to the development of better and more reliable fire models and projections.

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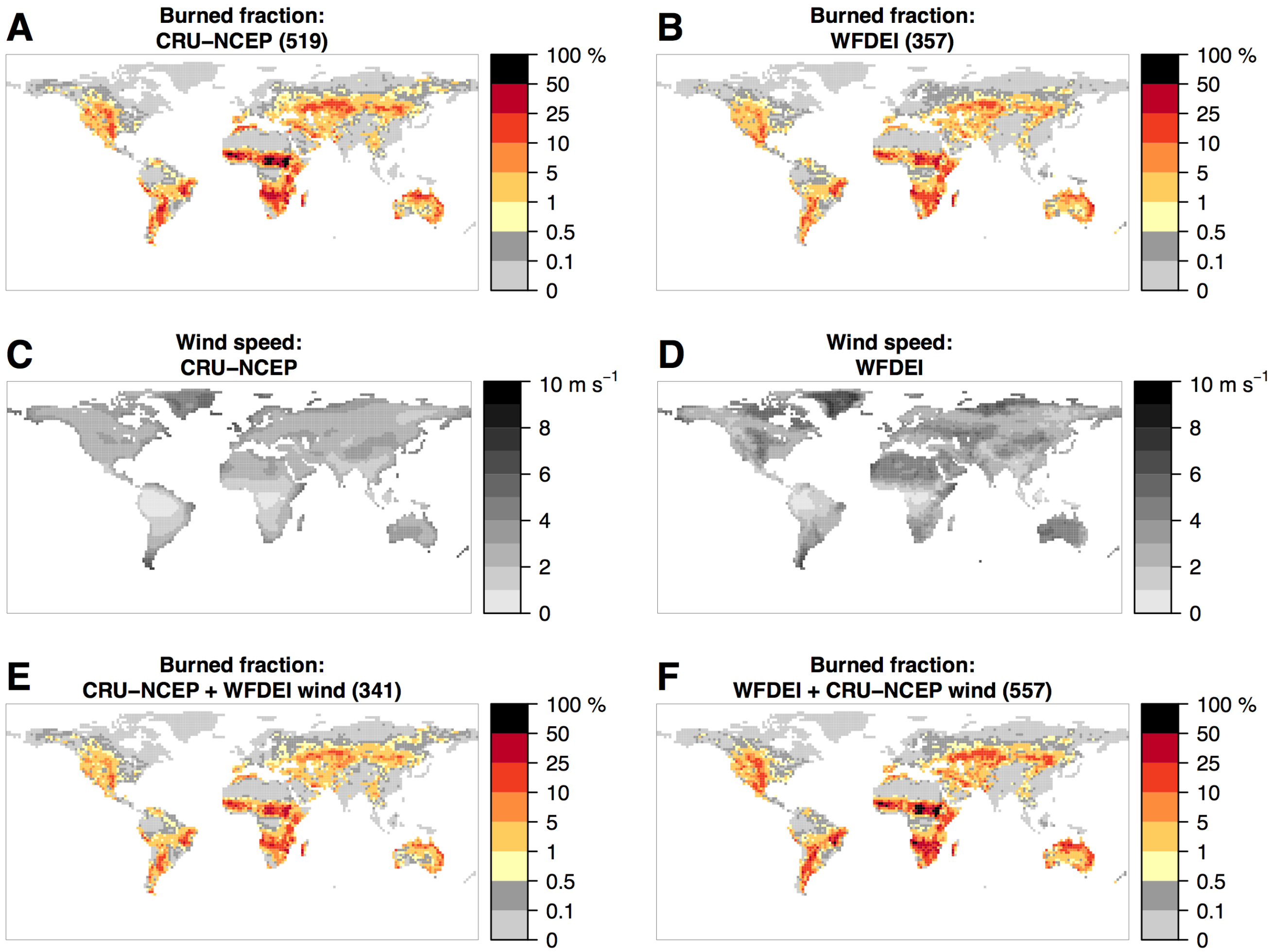

Figure 1. Comparing the effect of different wind forcing data on burned area simulated by JSBACH-SPITFIRE (Lasslop et al., 2014) over the years 1997–2005. (**a–b**) Annual burned fraction (%) modeled by JSBACH-SPITFIRE using (**a**) the CRU-NCEP forcing data (Wei et al., 2014) and (**b**) the WATCH (WFDEI) forcing data (Weedon et al., 2011). (**c–d**) Mean wind speed over the simulated period from (**c**) the CRU-NCEP and (**d**) WFDEI datasets. (**e–f**) Annual burned fraction (%) modeled by JSBACH-SPITFIRE with switched wind forcing: (**e**) CRU-NCEP except with WFDEI wind, (**f**) WFDEI except with CRU-NCEP wind. Numbers in sub-figure titles give mean annual global burned area (Mha) for each run.

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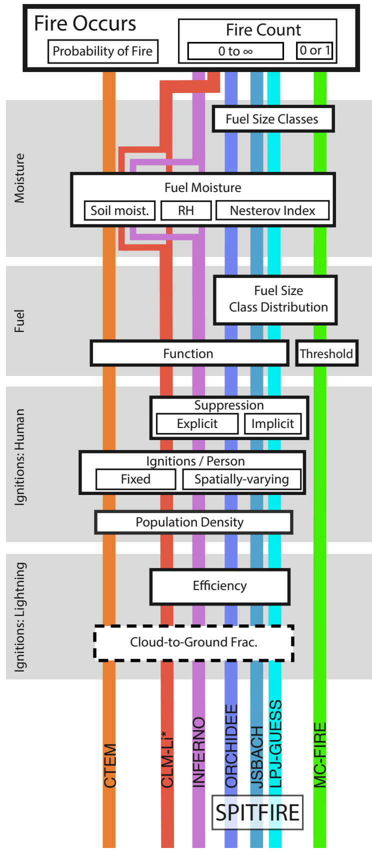

Figure 2. Modeled processes leading to fire starts for the participating models. Beginning at the bottom, models explicitly simulate processes that their colored line passes through, with the end result being the calculation of fire count (which in most models can be any nonnegative number, but in MC-FIRE can only be zero or one) or probability of fire. (LPJ-GUESS-BLAZE and -GlobFIRM are not included here because they do not calculate fire count or probability.) Fire occurrence depends on three factors: Ignitions, fuel availability, and fuel moisture. Lightning ignitions are a function of the flash rate multiplied in some models by the "Cloud-to-Ground Fraction" (which the input data for FireMIP already includes and is thus not calculated here; dashed box) and/or by an "Efficiency" term describing what fraction of cloud-to-ground strikes actually serve as potential ignitions. Human ignitions are influenced by an "ignitions per person" parameter, which can either be one "fixed" constant or "spatially-varying." Population density can also contribute to "Suppression," which can be either "Explicit" (i.e., calculated by a separate function) or "Implicit" (i.e., included in the initial calculation of ignitions). Fuel load affects fire occurrence either as a simple "threshold" or by the use of some more complex "function" such as a logistic curve. Some models use several "fuel size classes," which can be important for both fuel loading and moisture terms.

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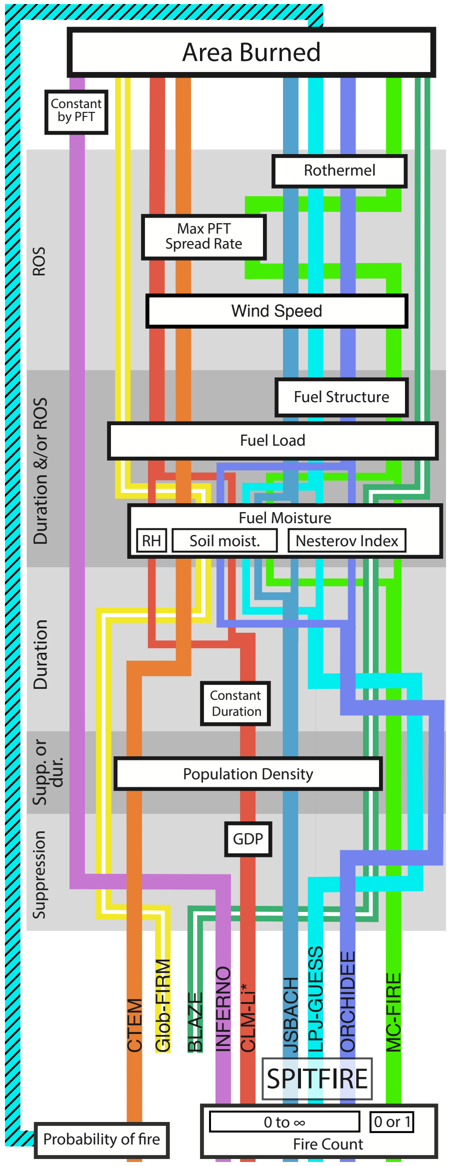

Figure 3. Modeled processes leading from fire starts (bottom; Fig. 2) to the calculation of burned area (top). The main processes include suppression, duration, and rate of spread (ROS). (Some variables involved can contribute to more than one of these processes, as indicated by the areas of overlap in dark gray.) "Suppression," which *per se* only occurs in CLM-Li, refers to the reduction of burned area per fire. This can occur after the calculation of other terms (as in CLM-Li* and LPJ-GUESS-BLAZE) or it can affect fire duration (as in CTEM and JSBACH-SPITFIRE). "Fuel structure" refers to the distribution of fuel among different size classes. The "Rothermel" equations (Rothermel, 1972) are used by some models to determine rate of spread based on fire intensity and other factors. The additional striped line for LPJ-GUESS-SPITFIRE leading from "Area Burned" to "Probability of Fire" represents the approach of burning individual patches stochastically (see main text). LPJ-GUESS-BLAZE and -GlobFIRM are denoted with white stripes through their lines to indicate that they are actually not simulating fire spread, instead using purely empirical formulas to calculate gridcell-level burned area.

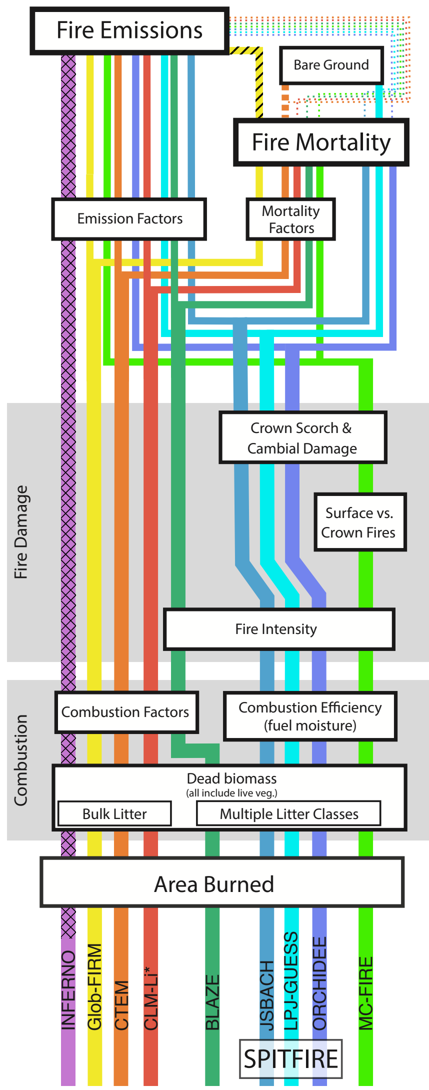

Figure 4. Modeled processes leading from burned area (bottom; Fig. 3) to fire emissions and mortality (top). The amount of biomass combusted is a function of the "vegetation biomass" and the fraction of biomass combusted, which is either a constant by vegetation type ("combustion factors") or variable with fuel moisture ("combustion efficiency"). Combusted biomass is allocated to "fire emissions" of different gas and aerosol species by the use of constant "emissions factors." In some models, mortality depends on the "fire intensity," which controls the death of vegetation by "crown scorch and cambial damage." In other models, constant "mortality factors" for each vegetation type give the fraction of non-combusted vegetation killed in burns. LPJ-GUESS-SPITFIRE and CTEM can both then simulate the creation of "bare ground" as a result of fire death, although this will be turned off for CTEM in this phase of FireMIP (dashed line). The decomposition of fire-killed biomass can be considered part of the total "fire emissions" (indicated here for most models by fine dotted lines, although FireMIP will not record these). LPJ-GUESS-GlobFIRM is different (striped line from "mortality" to "emissions"): Fire-killed vegetation is instantly transferred to the atmosphere instead of being deposited in soil or litter. Also, INFERNO (cross-hatched line) does not calculate fire mortality and only calculates fire emissions diagnostically (i.e., material is not actually transferred from vegetation to the atmosphere).

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Table 1. Experiments run in this first phase of FireMIP. All experiments used repeated 1901–1920 climate forcings from the beginning of the simulation through 1900. "Year 1" refers to the first transient (non-spinup) year of the simulation, which was 1700 for all models except for CTEM (1850).

Abbrv.	Name	Fire	CO_2	Lightning	Pop. dens.	Land use
SF1	Transient run	On	Transient	Transient	Transient	Transient
SF2_WWF	World without fire	Off	Transient	Transient	Transient	Transient
SF2_CO2	Preindustrial CO_2	On	277.33 ppm	Transient	Transient	Transient
SF2_FLI	Fixed lightning	On	Transient	Repeated 1901–1920	Transient	Transient
SF2_FPO	Fixed population density	On	Transient	Transient	Fixed: Year 1	Transient
SF2_FLA	Fixed land use	On	Transient	Transient	Transient	Fixed: Year 1

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Table 2. List of models participating in FireMIP, including contact person's email and key references. Also included is information relating to the configuration to be used in this phase of FireMIP. Note that "Resolution" refers to spatial and temporal resolution of the fire model only; the associated land/vegetation may update more frequently.

Fire model	Land/vegetation model	Dynamic vegetation			N cycle?	# PFTs	# soil layers	# litter classes	Resolution	Contact
		Physiology	LAI, biomass	Biogeography						
CLM-Li fire module (Li et al., 2012, 2013, 2014)	CLM4.5–BGC (Oleson et al., 2013)	Yes	Yes	Yes, but not in FireMIP	Yes	17	15	1	~1.9° lat. × 2.5° lon. (F19), half-hourly	Fang Li (lifang@mail.iap.ac.cn)
CTEM fire module (Arora and Boer, 2005; Melton and Arora, 2015)	CTEM (Arora and Boer, 2005; Melton and Arora, 2015)	Yes	Yes	Yes, but not in FireMIP	No	9	3	1	2.8125°, daily	Joe Melton (joe.melton@canada.ca)
INteractive Fire and Emission algoRithm for Natural envirOnments (INFERNO; Mangeon et al., 2016)	JULES (Best et al., 2011; Clark et al., 2011)	Yes	Yes	Yes	No	9	4	4	~1.2414° lat. ×1.875° lon., half-hourly	Stéphane Mangeon (stephane.mangeon12@imperial.ac.uk)
JSBACH-SPITFIRE (Lasslop et al. (2014); Hantson et al. (2015a)	JSBACH	Yes	Yes	Yes, but not in FireMIP	No	12	5	2	1.875°, daily	Gitta Lasslop (gitta.lasslop@mpimet.mpg.de)
LPJ-GUESS-BLAZE	LPJ-GUESS (Smith et al., 2001, 2014; Lindeskog et al., 2013)	Yes	Yes	Yes	Yes	19	2	3	0.5°, annual	Stijn Hantson (stijn.hantson@kit.edu)
LPJ-GUESS-GlobFIRM	LPJ-GUESS (Smith et al., 2001; Lindeskog et al., 2013; Smith et al., 2014)	Yes	Yes	Yes	Yes	20	2	2	0.5°, annual	Stijn Hantson (stijn.hantson@kit.edu)
LPJ-GUESS-SPITFIRE (Lehsten et al., 2009; Thonicke et al., 2010; Lehsten et al., 2015)	LPJ-GUESS (Smith et al., 2001; Sitch et al., 2003; Ahlström et al., 2012)	Yes	Yes	Yes	No	13	2	2	0.5°, daily	Matthew Forrest (matthew.forrest@senckenberg.de)
MC-Fire	MC2 (Bachelet et al., 2015; Sheehan et al., 2015)	Yes	Yes	Yes	Yes	39	Depends on total soil depth	5	0.5°, monthly	Dominique Bachelet (dominique@consbio.org)
ORCHIDEE-SPITFIRE (Yue et al., 2014, 2015)	ORCHIDEE	Yes	Yes	Yes, but not in FireMIP	No	13	2	2	0.5°, daily	Chao Yue (chao.yue@lsce.ipsl.fr)

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Table 3. Standard output variables. See Table A1 for additional, optional output variables. *: If calculated by model.

Category	Name	Units	Dimensions	Time period
Fire	Fire emissions: Total C	$kgC\,m^{-2}\,s^{-1}$	lon. lat. PFT month	1700–2013
	Fire emissions: CO_2-C	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1700–2013
	Fire emissions: $CO-C$	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Burned fraction of gridcell	—	lon. lat. PFT month	1700–2013
	Fireline intensity*	$kW\,m^{-1}$	lon. lat. month	1950–2013
	Fuel loading	$kgC\,m^{-2}$	lon. lat. month	1700–2013
	Fuel combustion completeness	—	lon. lat. month	1950–2013
	Fuel moisture*	—	lon. lat. month	1950–2013
	Number of fires*	count $m^{-2}\,yr^{-1}$	lon. lat. month	1950–2013
	Fire-caused frac. tree mortality	—	lon. lat. month	1950–2013
	Fire size: Mean*	m^{-2}	lon. lat. month	1950–2013
	Fire size: 95th percentile	m^{-2}	lon. lat. month	1950–2013
Physical properties	Total soil moisture content	$kg\,m^{-2}$	lon. lat. month	1950–2013
	Total runoff	$kg\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Total evapotranspiration	$kg\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
Carbon fluxes	Gross Primary Production (grid cell)	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Gross Primary Production (by PFT)	$kgC\,m^{-2}\,s^{-1}$	lon. lat. PFT month	1950–2013
	Autotrophic respiration	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Net Primary Production (grid cell)	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Net Primary Production (by PFT)	$kgC\,m^{-2}\,s^{-1}$	lon. lat. PFT month	1950–2013
	Heterotrophic respiration	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Net Biospheric Production (grid cell)	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Net Biospheric Production (by PFT)	$kgC\,m^{-2}\,s^{-1}$	lon. lat. PFT month	1950–2013
	Land-use change C flux: To atmosphere (as CO_2)	$kgC\,m^{-2}\,s^{-1}$	lon. lat. month	1950–2013
	Land-use change C flux: To products	$kgC\,m^{-2}$	lon. lat. month	1950–2013
Carbon pools	Carbon in vegetation	$kgC\,m^{-2}$	lon. lat. month	1700–2013
	Carbon in aboveground litter	$kgC\,m^{-2}$	lon. lat. month	1700–2013
	Carbon in soil (incl. belowground litter)	$kgC\,m^{-2}$	lon. lat. month	1700–2013
	Carbon in vegetation, by PFT	$kgC\,m^{-2}$	lon. lat. PFT month	1700–2013
Vegetation structure	Fractional land cover of PFT	—	lon. lat. PFT year	1700–2013
	Leaf Area Index	$m^2\,m^{-2}$	lon. lat. PFT year	1950–2013
	Tree height	m	lon. lat. PFT year	1950–2013

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Table 4. Summary description of the observational datasets to be used for model evaluation. "Frequency" refers to the temporal resolution at which the analyses will be performed, which may be coarser than the native resolution of the data.

Type	Variable	Source	Time period	Frequency	References
Vegetation properties	GPP	Site-based	1950–2006	Snapshots	Luyssaert et al. (2007); Kelley et al. (2013)
	NPP	Site-based	Various	Snapshots	Olson et al. (2001); Luyssaert et al. (2007); Kelley et al. (2013); Michaletz et al. (2014)
	Frac. tree, herbaceous, bare ground	ILSLCP II vegetation continuous fields	1992–1993	Snapshot	Hansen et al. (2000)
	Canopy height	ICESat GLAS	2005	Snapshot	Simard et al. (2011)
	Forest biomass	Composite of previous work adjusted with *in situ* measurements	2000s	Snapshot	Avitabile et al. (2016)
Fire	# new fires d^{-1}, burned area per fire	MCD45	2003–2014	Monthly	Archibald et al. (2013); Hantson et al. (2015b)
	Burned area	GFED4	1994–2014	Monthly	Giglio et al. (2013)
		MCD45	2002–2014	Monthly	Roy et al. (2008)
		ESA CCI	2006–2008	Monthly	Alonso-Canas and Chuvieco (2015)
	Fuel load, combustion completeness	Site-based	Various	Snapshots	van Leeuwen et al. (2014)
Emissions	CO_2	Site-based	1998–2005	Monthly	CDIAC: cdiac.ornl.gov
	Total C	GFAS	2003–2015	Monthly	Kaiser et al. (2012)
	NO_2	OMI	2005–2015	Monthly	Krotkov (2013)
Hydrology	Runoff	Site-based	1950–2005	Ann. means	Dai et al. (2009)

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Table A1. Second-priority output variables. See Table 3 for primary model outputs. *: If calculated by model.

Category	Name	Units	Dimensions	Time period
C fluxes	Crop harvesting to atmosphere	$kgC\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Grazing to atmosphere	$kgC\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Litter to soil	$kgC\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Vegetation to litter	$kgC\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Vegetation to soil	$kgC\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
Fire	Ignitions*	$m^{-2}\,yr^{-1}$	lon. lat. month	1950–2013
Physical properties	Broadband albedo (by PFT)	—	lon. lat. PFT month	1950–2013
	Evaporation: Canopy	$kg\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Evaporation: Soil	$kg\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Evaporation: Soil (by PFT)	$W\,m^{-2}$	lon. lat. PFT month	1950–2013
	Evapotranspiration (by PFT)	$W\,m^{-2}$	lon. lat. PFT month	1950–2013
	Near-surface air temperature	K	lon. lat. year	1950–2013
	Net radiation (by PFT)	$W\,m^{-2}$	lon. lat. PFT month	1950–2013
	Irrigation (by PFT)	$kg\,m^{-2}\,s^{-1}$	lon. lat. PFT year	1950–2013
	Precipitation	$kg\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Sensible heat flux (by PFT)	$W\,m^{-2}$	lon. lat. PFT month	1950–2013
	Skin temperature (by PFT)	K	lon. lat. PFT year	1950–2013
	Snow depth or equivalent (by PFT)	$m\,m^{-2}$	lon. lat. PFT month	1950–2013
	Soil moisture (by PFT)	$kg\,m^{-2}$	lon. lat. PFT year	1950–2013
	Soil temperature	K	lon. lat. layer year	1950–2013
	Surface downwelling shortwave radiation	$W\,m^{-2}$	lon. lat. year	1950–2013
	Transpiration	$kg\,m^{-2}\,s^{-1}$	lon. lat. year	1950–2013
	Transpiration (by PFT)	$W\,m^{-2}$	lon. lat. PFT month	1950–2013
Vegetation structure	Leaf area index	$m^2\,m^{-2}$	lon. lat. year	1950–2013

Author contributions. All authors contributed to the development of the protocol, with A. Arneth and S. Hantson leading and contributing text for Section 2. S. Rabin compiled and edited text and information from other authors, and wrote the Introduction and Conclusion. S. Sitch contributed text for Section 2.2. S. Harrison contributed to the Evaluation section. J. Melton constructed Figures 2–4. G. Lasslop performed analyses for and contributed Figure 1. J. Kaplan constructed lightning dataset. V. Arora, D. Bachelet, M. Forrest, T. Hickler, S. Kloster, W. Knorr, G. Lasslop, F. Li, J. Melton, S. Mangeon, L. Nieradzik, A. Spessa, and C. Yue contributed text and information for model descriptions, tables, and flowchart figures, and contributed to model development. G. Folberth, T. Sheehan, and A. Voulgarakis contributed to model development.

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Acknowledgements. S. Rabin was supported by a National Science Foundation Graduate Research Fellowship and by the Carbon Mitigation Initiative, and along with S. Hantson and A. Arneth would like to acknowledge support by the EU FP7 projects BACCHUS (grant agreement no. 603445) and LUC4C (grant agreement no. 603542). This work was supported, in part, by the German Federal Ministry of Education and Research (BMBF), through the Helmholtz Association and its research programme ATMO, and the HGF Impulse and Networking fund. F. Li was funded by the National Natural Science Foundation of China under Grant No. 41475099 and the CAS Youth Innovation Promotion Association Fellowship. The UK Met Office contribution was funded by BEIS under the Hadley Centre Climate Programme contract (GA01101). G. A. Folberth also wishes to acknowledge funding received from the European Union's Horizon 2020 research and innovation programme under grant agreement No 641816 (CRESCENDO). J. O. Kaplan was supported by the European Research Council (COEVOLVE, 313797).

The article processing charges for this open-access publication were covered by a Research Center of the Helmholtz Association.

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Published: 5 October 2016

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