



1 **INFERNO: a fire and emissions scheme for the Met**
2 **Office’s Unified Model**

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10 **Abstract.** Warm and dry climatological conditions favour the occurrence of forest fires. These fires then
11 become a significant emission source to the atmosphere. Despite this global importance, fires are a local
12 phenomenon and are difficult to represent in a large-scale Earth System Model (ESM). To address this,
13 the Interactive Fire and Emission algoRithm for Natural enviroNments (INFERNO) was developed.
14 INFERNO follows a reduced complexity approach and is intended for decadal to centennial scale climate
15 simulations and assessment models for policy making. Fuel flammability is simulated using temperature,
16 relative humidity, fuel density as well as precipitation and soil moisture. Combining flammability with
17 ignitions and vegetation, burnt area is diagnosed. Emissions of carbon and key species are estimated
18 using the carbon scheme in the JULES land surface model. JULES also possesses fire index diagnostics
19 which we document and compare with our fire scheme. Two meteorology datasets and three ignition
20 modes are used to validate the model. INFERNO is shown to effectively diagnose global fire occurrence
21 ($R=0.66$) and emissions ($R=0.59$) through an approach appropriate to the complexity of an ESM,
22 although regional biases remain.

23



24 **1 Introduction**

25 Fire is a key interaction between the atmosphere and the land surface (Bowman et al., 2009). Its impacts
26 are wide-ranging: it influences forest succession (Bond and Keeley, 2005), is a tool for deforestation
27 (van der Werf et al., 2009) and is an important natural carbon source (Bowman et al., 2013), while it also
28 provides a major natural hazard to humans through property and infrastructure destruction and air quality
29 degradation (Johnston et al., 2012; Marlier et al., 2013). Not only are biomass burning emissions
30 substantial in magnitude (Lamarque et al., 2010), they also drive the variability of atmospheric
31 composition (Spracklen et al., 2007; Voulgarakis et al., 2010, 2015) and impact short-term climate
32 forcing (Tosca et al., 2013).

33 There are feedbacks between fire and climate: low-humidity conditions cause droughts, which enhance
34 fire activity (Field et al., 2009), which, in turn, emits aerosols and trace gases (Akagi et al., 2011),
35 influencing the abundances of radiatively active atmospheric constituents, cloud formation and lifetime,
36 and in turn precipitation, and surface albedo (Voulgarakis and Field, 2015). Bistinas et al. (2014) showed
37 global fire frequency is correlated with land-use, vegetation type and meteorological factors (dry days,
38 soil moisture and maximum temperature) and human presence tends to noticeably reduce fire activity
39 (land-management, landscape fragmentation and urbanization). Examining and quantifying such impacts
40 and feedbacks is paramount to Earth System Models (ESMs), yet to integrate vegetation fires presents
41 many challenges as it intricately links multiple disciplines from ecology to atmospheric chemistry and
42 physics and climate science.

43 Integration of fires into Dynamic Global Vegetation Models (DGVMs) was the first step towards fire
44 within ESMs (e.g. (Arora and Boer, 2005; Fosberg et al., 1999; Li et al., 2012; Pfeiffer et al., 2013; Sitch
45 et al., 2003; Thonicke et al., 2001, 2010; Venevsky et al., 2002; Yue et al., 2014). Vegetation fires have
46 been implemented into only a few ESMs, e.g. ECHAM (Lasslop et al., 2014) and the Community ESM
47 (Li et al., 2013, 2014, p.2).

48 Here, we present and evaluate the INteractive Fire and Emission algoRithm for Natural enviroNments
49 (INFERNO) and its implementation. INFERNO is a necessarily simple parameterization that focuses on
50 the large-scale occurrence of fires and is suitable for ESM application. The model uses a few key driving
51 variables while retaining a broadly accurate parameterization for fire emissions. INFERNO's
52 performance against observations and well established and operationally relevant fire indices is
53 presented.

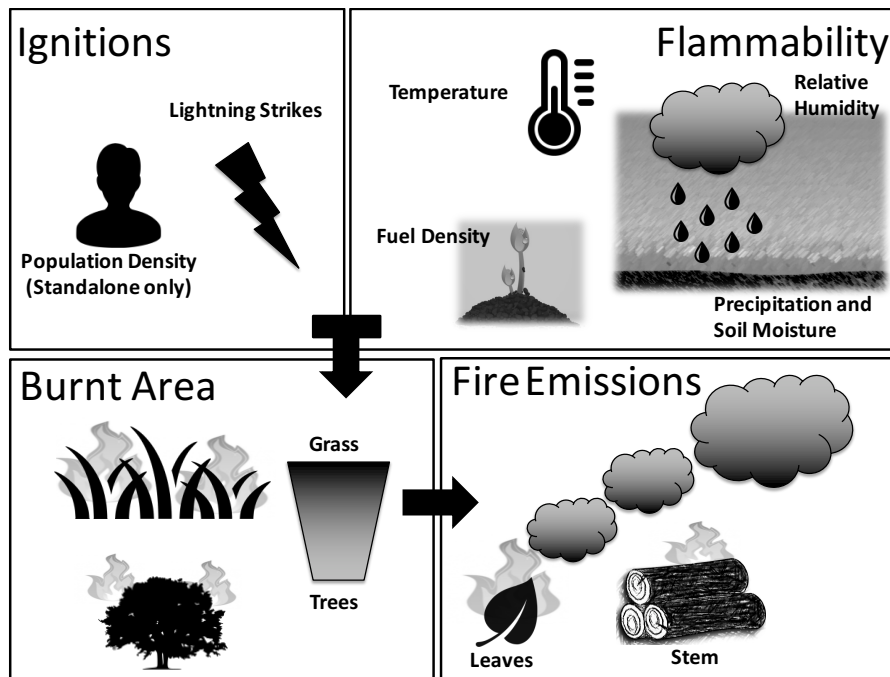
54 **2 Model description**

55 **2.1 INFERNO**

56 INFERNO was constructed upon the simplified parameterization for fire counts proposed and evaluated
57 for the present-day by (Pechony and Shindell, 2009), which was subsequently shown to provide a good
58 estimate for large-scale fire variability over climatological timescales (Pechony and Shindell, 2010). In
59 short, that parameterization used monthly mean temperature, relative humidity and precipitation to
60 simulate fuel flammability. It also used human population density and lightning to represent ignitions.
61 To incorporate this parameterization within the Joint UK Land Environment Simulator (JULES, Best et



62 al., 2011; Clark et al., 2011), several changes were applied. Upper layer soil moisture is used to represent
 63 precipitation memory while precipitation acts as a rapid fire deterrent. Vegetation Density was replaced
 64 by Fuel Density, an index dependent on leaf carbon and Decomposable Plant Material (DPM), i.e. litter.
 65 Such a relationship with fine fuel and moisture was used in Thonicke et al. (2001). Furthermore, we
 66 developed a parameterization to obtain burnt area (BA), emitted carbon (EC) and fire emissions of
 67 different species (E_x) and our fire diagnostics are made for each of the nine Plant Functional Types
 68 (PFTs) in the current version of JULES (Harper et al., submitted).
 69 Figure 1 summarizes the mechanisms of INFERNO, and Fig. A1 illustrates the dependence of INFERNO
 70 on individual driving variables.



71
 72 **Fig. 1. Schematic summarizing the INteractive Fire and Emission algoRithm for Natural enviroNments**
 73 **(INFERNO) and its key components and behaviour. Ignitions can be accounted for in a variety of ways (see**
 74 **Sect. 2.1.1), meteorology influences flammability (see Sect. 2.1.2), while plant coverage influences burnt area**
 75 **(see Sect. 2.1.3), finally emissions are calculated according to leaf and stem carbon for each PFT (see Sect.**
 76 **2.1.4).**

77 **2.1.1 Ignitions (I)**

78 INFERNO calculates ignitions in either one of three modes:
 79 First, we can assume constant or ubiquitous ignitions, currently calibrated to a global average of $I_T =$
 80 $1.67 \text{ ignitions km}^{-2} \text{ month}^{-1}$. This corresponds to $1.5 \text{ ignitions km}^{-2} \text{ month}^{-1}$ due to humans (I_A),
 81 heuristically determined, and $0.17 \text{ ignitions km}^{-2} \text{ month}^{-1}$ natural ignitions due to lightning (I_N), derived
 82 from the multi-year annual mean of $2.7 \text{ strikes km}^{-2} \text{ year}^{-1}$ (Huntrieser et al., 2007) assuming 75% of
 83 strikes being cloud-to-ground (Prentice and Mackerras, 1977). This mode inherently suppresses the
 84 variability in fires due to any anthropogenic or natural ignition changes (Pechony and Shindell, 2009,
 85 2010).



86 Second, human ignitions and suppressions can be assumed to remain constant at the global mean value
 87 mentioned above ($I_A = 1.5$ ignitions km^{-2} month^{-1}), however cloud-to-ground lightning strikes may vary,
 88 and in addition each strike is assumed to start a fire. This mode accounts for natural variability in fire
 89 ignitions, which can be simulated within an ESM, or prescribed from observations.

90 Third, varying human ignitions and suppressions and varying natural ignitions (cloud-to-ground
 91 lightning strikes, as in mode 2). This was the original ignition approach in Pechony and Shindell (2009),
 92 which was left unchanged and is detailed below. In this ignition mode, anthropogenic ignition and
 93 suppression depends on population density (PD), as proposed by Venevsky et al. (2002).

$$94 \quad I_A = k(PD) PD \alpha \quad (1)$$

95 PD is in units of people km^{-2} , and $k(PD) = 6.8 \times PD^{-0.6}$ is a function that represents the varying
 96 anthropogenic influence on ignitions in rural versus urban environments. The parameter $\alpha = 0.03$
 97 represents the number of potential ignition sources per person per month per km^2 . Both natural and
 98 anthropogenic ignitions have the potential to be suppressed by humans, such that the fraction of fires not
 99 suppressed is:

$$100 \quad f_{NS} = 7.7 (0.05 + 0.9 \times e^{-0.05 PD}) \quad (2)$$

101 Equation 2 includes a scaling factor (Pechony and Shindell, 2009) originally introduced to calibrate the
 102 number of fires to MODIS observations. Assuming no suppression for the first two ignition modes
 103 ($f_{NS} = 1$), total ignitions (I_T , in units, ignitions $\text{m}^{-2} \text{s}^{-1}$) can be represented as (Eq. 3):

$$104 \quad I_T = (I_N + I_A) f_{NS} / (8.64 \times 10^{10}) \quad (3)$$

105 Dividing by 8.64×10^{10} converts ignitions $\text{km}^{-2} \text{month}^{-1}$ to ignitions $\text{m}^{-2} \text{s}^{-1}$.

106 2.1.2 Flammability (F)

107 We adapt the (Pechony and Shindell, 2009) scheme for flammability to function interactively within an
 108 ESM (see Eq. 6). Starting from the saturation vapour pressure (e^* , Eq. 4; Goff and Gratch, 1946) and
 109 its temperature dependence, we introduce a Fuel Density index (FD_{PFT} , Eq. 5) as well as Relative
 110 Humidity (RH), precipitation and soil moisture in order to obtain Flammability (Eq. 6). The land surface
 111 model (JULES) determines soil moisture content (θ) and fuel density (FD).

$$112 \quad \log_{10}(e^*) = a \left(\frac{T_s}{T} - 1 \right) + b \log_{10} \left(\frac{T_s}{T} \right) + c \left(10^{d \left(1 - \frac{T_s}{T} \right)} - 1 \right) + f \left(10^{h \left(\frac{T_s}{T} - 1 \right)} - 1 \right) \quad (4)$$

113 As illustrated in Eq. 4, INFERNO utilizes temperature (T in K, at 1.5 m height). The Goff-Gratch (Eq.
 114 4) uses the constants: $a = -7.90298$; $b = 5.02808$; $c = -1.3816 \times 10^{-7}$; $d = 11.344$; $f = 8.1328 \times$
 115 10^{-3} ; $h = -3.49149$ and the water boiling point temperature $T_s = 373.16$ K.

$$116 \quad FD_{PFT} = \begin{cases} 1 & \text{for } Fuel_{high} < (DPM_C + Leaf_{C,PFT}) \\ \frac{(DPM_C + Leaf_{C,PFT})}{Fuel_{high} - Fuel_{low}} & \text{for } Fuel_{low} < (DPM_C + Leaf_{C,PFT}) < Fuel_{high} \\ 0 & \text{for } Fuel_{low} > (DPM_C + Leaf_{C,PFT}) \end{cases} \quad (5)$$

117 Equation 5 shows FD is taken as the PFT-specific leaf carbon ($Leaf_{C,PFT}$) plus the carbon within
 118 decomposable plant material (DPM_C). DPM is a soil carbon pool of which we assume 70% is available
 119 to fires i.e. near-surface (DPM is shared across all PFTs). FD scales linearly between 0 (at a threshold
 120 of $Fuel_{low} = 0.02$ kgC m^{-2}) and 1 (at a threshold of $Fuel_{high} = 0.2$ kgC m^{-2}). Similar approaches to



121 represent fuel availability within fire parameterizations have commonly been adopted (Arora and Boer,
 122 2005; Li et al., 2012; Thonicke et al., 2010).

$$123 F_{PFT} = e^* (RH_{up} - RH) / (RH_{up} - RH_{low}) e^{-2R} FD_{PFT} (1 - \theta) \quad (6)$$

124 RH is the relative humidity (%) and R is the precipitation rate (mm day^{-1}). The influence of relative
 125 humidity (RH) scales between (and is bound by): 0 (at a threshold of $RH_{low} = 10\%$) and 1 (at a threshold
 126 of $RH_{up} = 90\%$). We then adapt the formula by replacing a vegetation index dependent on leaf area
 127 index with the Fuel Density index (FD). Finally, Flammability (F_{PFT}) is dependent on upper-level (down
 128 to 0.1 m) soil moisture: θ is the unfrozen soil moisture as a fraction of saturation. The individual
 129 importance of these variables to our model is illustrated in Fig. A1.

130 2.1.3 Burnt Area (BA)

131 Our approach is to associate an average burnt area per fire to each PFT, effectively decoupling the fire-
 132 spread stage from local meteorology and topography, which is typically not resolved in the relatively
 133 coarse grid of an ESM. An average burnt area ($\overline{BA_{PFT}}$) was heuristically determined for each PFT: 0.6,
 134 1.4 and 1.2 km^2 for trees, grass and shrubs, respectively, such that grass and shrubs will fuel larger fires
 135 than trees. Observational evidence supports that the land cover type is an efficient way to characterize
 136 fires, which tend to be larger in grasslands than in forests (Chuvieco et al., 2008; Giglio et al., 2013).
 137 The BA is then calculated following Eq. 7:

$$138 BA_{PFT} = I_T F_{PFT} \overline{BA_{PFT}} \quad (7)$$

139 Here BA_{PFT} is the burnt area (fraction of PFT cover burnt per second) for each PFT; meanwhile the
 140 number of ignitions times the flammability ($I_T F_{PFT}$) represents the number of fires.

141 Inferring burnt area from number of fires in this manner stands out from other fire models which utilize
 142 wind speed (Arora and Boer, 2005; Thonicke et al., 2010; Li et al., 2012), effectively modelling the fire
 143 rate of spread. Wind is key to the modelling of individual fires; yet implementing wind effectively within
 144 fire models designed for the relatively coarse grid of ESMs was found to be problematic (Lasslop et al.,
 145 2014, 2015). Conversely, Hantson et al. (2014) found global fire size was mostly influenced by
 146 precipitation, aridity and human activity (population density and croplands).

147 2.1.4 Emitted Carbon (EC)

148 To account for the wetness of fuel in INFERNO, combustion completeness (the fraction of biomass
 149 exposed to a fire that was volatilized) scales linearly with soil moisture (as a fraction of saturation) with
 150 different upper and lower boundaries for leaf and stem carbon.

$$151 EC_{PFT} = BA_{PFT} \sum_{leaf,stem}^i (CC_{min,i} + (CC_{max,i} - CC_{min,i})(1 - \theta)) C_i \quad (8)$$

152 Equation 8 shows how the PFT-specific emitted carbon (EC , in $\text{kgC m}^{-2} \text{s}^{-1}$) is computed. BA is the burnt
 153 area (fraction s^{-1}), CC_{min} and CC_{max} are the minimum and maximum combustion completeness for both
 154 leaves ($CC_{min} = 0.8$ and $CC_{max} = 1.0$) and stems ($CC_{min} = 0.8$ and $CC_{max} = 1.0$), C_i is the carbon
 155 stored in each PFT's leaves or stems (kgC m^{-2}). The parameters used for combustion completeness
 156 (CC_{min} and CC_{max}) are similar to the Global Fire Emission Database (GFED (van der Werf et al., 2010),
 157 albeit with lower minimum combustion of stems (0.0 as opposed to 0.2). This change is justifiable by



158 the difference in the moisture used. Indeed GFED uses a more complex representation of moisture across
 159 multiple fuel types, while our scheme only relies on soil moisture.

160 2.1.5 Emitted Species (E_X)

161 There has been a significant amount of work on estimating emission factors (EFs) across fire biomes
 162 (such as savannahs, boreal forest etc.). This was synthesized in Akagi et al. (2011) as well as Andreae
 163 and Merlet (2001) and its updates. To convert these biome-specific EFs to PFT specific EFs, each PFT
 164 was linked to a fire biome (see Table A1). INFERNO uses these to estimate emissions (Eq. 9).

$$165 E_{X,PFT} = EC_{PFT} EF_{X,PFT} / [C] \quad (9)$$

166 Here E_X is the amount of species X emitted by fires (in $\text{kg m}^{-2} \text{s}^{-1}$), EC is the emitted carbon (in kgC m^{-2}
 167 s^{-1}) and EF_X is the PFT-specific emission factor (see Table 1) (in kg of species emitted per kg of biomass
 168 burnt), and $[C]$ is the dry biomass carbon content, express as a percentage (Lamloom and Savidge, 2003).
 169 INFERNO currently provides emissions for basic trace gases: CO_2 , CO, CH_4 , NO_x , SO_2 and aerosols:
 170 organic carbon (OC) and black carbon (BC).

171 **Table 1.** INFERNO's emission factors per PFT created from the emission profiles in Akagi et al. (2011), such
 172 that each PFT was attributed a fire biome (see Suppl. 2). This method of attributing emission factors to PFTs
 173 is similar to that presented in Thonicke et al. (2010), and can be extended to include all species of trace gases
 174 and aerosols compiled in Akagi et al. (2011).

Emission Factors (g / kg)	CO_2	CO	CH_4	NO_x	SO_2	OC	BC
Broadleaf Evergreen Tree (Tropical)	1643	93	5.07	2.55	0.40	4.71	0.52
Broadleaf Evergreen Tree (Temperate)	1637	89	3.92	2.51	0.40*	8.2**	0.56**
Broadleaf Deciduous Tree	1643	93	5.07	2.55	0.40	4.71	0.52
Needleleaf Evergreen Tree	1637	89	3.92	2.51	0.40*	8.2**	0.56**
Needleleaf Deciduous Tree	1489	127	5.96	0.90	0.40*	8.2**	0.56**
C3 grass	1637	89	3.92	2.51	0.40*	8.2**	0.56**
C4 grass	1686	63	1.94	3.9	0.48	2.62	0.37
Evergreen Shrub	1637	89	3.92	2.51	0.40*	8.2**	0.56**
Deciduous Shrub	1489	127	5.96	0.90	0.40*	8.2**	0.56**

175 *Profile not available in Akagi et al. (2011), therefore we mimic tropical forests; **from Andreae and Merlet (2001).

176 2.2 Implementation within JULES

177 INFERNO is currently implemented within the Joint UK Land Environment Simulator (JULES). (Best
 178 et al., 2011; Clark et al., 2011) its carbon fluxes and vegetation dynamics. The results shown here used
 179 JULES v4.3.1 and INFERNO will be included in JULES from version 4.5 onwards. INFERNO utilizes
 180 soil moisture (see Eq. 6,8) which JULES calculates as the balance between precipitation (following the



181 scheme for rainfall interception in (Johannes Dolman and Gregory, 1992)) and extraction by
182 evapotranspiration and runoff (Cox et al. 1999; Best et al. 2011). JULES has four soil layer, and
183 INFERNO uses the top layer unfrozen soil moisture (0 to 0.1 m depth). Note that in its current state,
184 JULES does not associate carbon pools with depths, hence it is not possible to access the top-most DPM
185 only for example. The vegetation dynamics and litter carbon used obey the TRIFFID DGVM (Cox,
186 2001).

187 In JULES, vegetation carbon content is determined by the balance between photosynthesis, respiration,
188 and litterfall. Within JULES, TRIFFID (the Top-down Representation of Foliage and Flora Including
189 Dynamics; Cox et al., 2001) predicts changes in biomass and the fractional coverage of nine plant
190 functional types (Table A1) based on accumulated carbon fluxes and height-based competition, where
191 the tallest trees have the first access to space (Harper et al. *In Prep*). Vegetation can grow in height, and
192 the carbon in leaves, roots, and wood is related allometrically to the “balanced LAI”, L_b (Cox et al. 2001).
193 L_b is the seasonal maximum leaf area index (LAI) and a function of plant height. Within INFERNO, leaf
194 carbon ($Leaf_c$, used for calculating FD and emissions) is:

$$195 \quad Leaf_c = \sigma_l L_b \quad (10)$$

196 Meanwhile, wood carbon ($Wood_c$, which affects emissions), is calculated as:

$$197 \quad Wood_c = a_{wl} L_b^{b_{wl}} \quad (11)$$

198 PFT dependent parameters (σ_l , the Specific Leaf Density, a_{wl} , the allometric coefficient and b_{wl} , the
199 allometric exponent) are given in Table A1.

200 When using JULES in its standalone version, INFERNO can use inputs of population density (in people
201 km^{-2}) and cloud-to-ground lightning flash rates (in flashes $\text{km}^{-2} \text{month}^{-1}$) from ancillary datasets.
202 Similarly, meteorology needs to be prescribed and is then interpolated from its native temporal resolution
203 to the model’s time-step. Although designed to be integrated within an ESM, the capability to run
204 INFERNO with JULES only is particularly useful for present-day comparison with observations, and to
205 dissociate causes of biases in results.

206 **2.3 Fire Weather Indices**

207 Three other well-established daily fire indices are also available within JULES. These indices have been
208 used for several decades to help plan operational response to wildfires on Numerical Weather Predictions
209 (NWP) timescales. Although unit-less and ill-defined risk-based quantities, comparison to INFERNO is
210 still useful for understanding the results in the context of practically established metrics.

211 The Canadian Fire Weather Index (Forestry Canada, 1992; Van Wagner and Pickett, 1985) consists of
212 six components, calculated from basic meteorological parameters. Three are fuel moisture codes
213 designed to represent the drying of different fuel types, their characteristics are displayed in Table A2.
214 Two intermediate quantities, the Initial Spread Index and the build-up index are calculated from these,
215 and are in turn used to yield the final Fire Weather Index.

216 The McArthur Forest Fire Danger Index (Noble et al., 1980; Sirakoff, 1985) was developed for use in
217 Australia. Simpler in its formulation than the Canadian index, it consists of a drought component
218 modified by the local temperature, humidity and wind speed. The calculation of the drought component



219 depends on the soil moisture deficit (the amount of water needed to restore the soil moisture content of
220 the top 800 mm of soil to 200 mm), which is related to the JULES soil moisture.
221 Finally, the Nesterov Index (Nesterov, 1949) is the simplest fire index implemented in JULES. It uses
222 only the daily mean temperature, mean daily dew point (or suitable substitute), daily total precipitation
223 and the previous day's index. The index is incremented daily, unless daily precipitation exceeds 3 mm,
224 in which case it is reset. The Nesterov index is a key component for other fire models (Venevsky et al.,
225 2002; Thonicke et al., 2010).

226 3 Model configuration

227 Monthly lightning data was obtained from LIS-OTD (Lightning Imaging Sensor-Optical Transient
228 Detector) observations for 2013 (Christian et al., 2003) and was recycled for every year in the simulation.
229 These detections were converted to cloud-to-ground strikes using the relationship presented in (Prentice
230 and Mackerras, 1977). Land use and population density were obtained from the HYDE dataset (Hurt et
231 al., 2011) and then linearly interpolated to create inter-annually varying data. Finally annual CO₂
232 concentrations, which affect vegetation dynamics, were prescribed as a global average following the
233 dataset prepared for the global carbon budget (Le Quéré et al., 2015).

234 To test the sensitivity to the meteorological input, JULES simulations were driven by meteorology from
235 both CRU-NCEP (Climate Research Unit and -National Center for Environmental Prediction) v5
236 (<http://dods.extra.cea.fr/data/p529viov/cruncep/>), and WFDEI (Weedon et al., 2014) with precipitation
237 from the GPCC (Schneider et al., 2013). Both datasets were used on a 6-hourly basis.

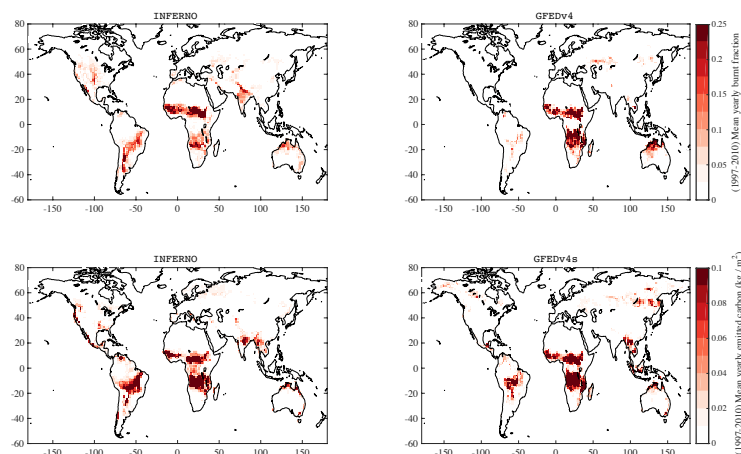
238 Outside of these driving variables, JULES was configured according to the TRENDY project (Sitch et
239 al., 2015)(Peng et al., 2015)(Peng et al., 2015). 100 year spin-up was performed repeating the 1990-2000
240 conditions tenfold. Four configurations were used to create simulations covering 1990-2013, although to
241 validate INFERNO only the 1997-2010 period was analysed. The first three use CRU-NCEP
242 meteorology with each of our three ignitions modes (see Sect. 2.1.1); constant ignitions (mode 1),
243 prescribed lightning and constant anthropogenic ignitions (mode 2), and both natural and anthropogenic
244 ignitions varying with prescribed lightning and population density (mode 3). The fourth simulation
245 assumes mode 1 (constant ignitions), while meteorology is prescribed from WFDEI and precipitation
246 from GPCC.

247 4 Results

248 Maps of the burnt area and emitted carbon are displayed in Fig. 2, their resolution is 192 longitudes by
249 145 latitudes grid-cells (1.875°x1.24°). The results from INFERNO used a configuration with CRUNCEP
250 meteorology and the third ignition mode: interactive lightning and anthropogenic ignitions. We compare
251 our results with downscaled means from GFED. Note GFEDv4s' burnt area (<http://globalfiredata.org>,
252 manuscript in preparation) differs from GFEDv4's (Giglio et al., 2013) as it includes small fires
253 (Randerson et al., 2012). Over the total study period, INFERNO diagnoses accurate global fire
254 occurrence and emissions (with R=0.66 for burnt area and R=0.59 for emitted carbon). In addition,
255 regional mean yearly budgets are compared with GFED in Table B1. We notice burnt area is higher in

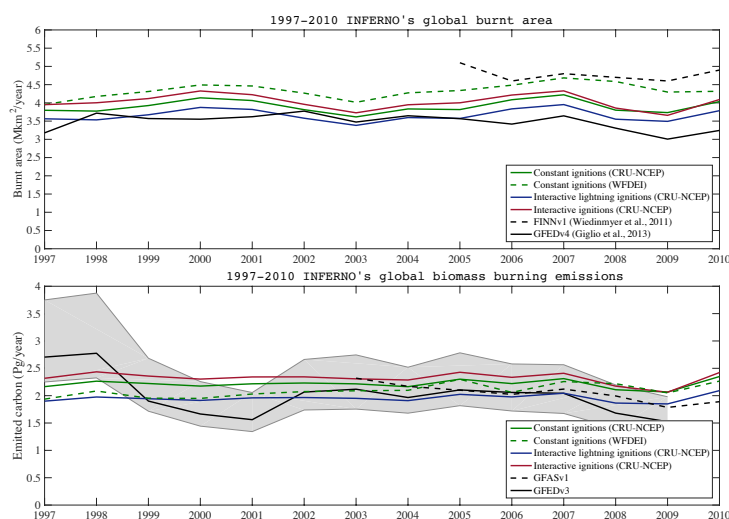


256 all regions other than Australia and New Zealand, and southern hemisphere Africa. Meanwhile emitted
257 carbon is underestimated in boreal regions and equatorial Asia, but overestimated in most other regions
258 (significantly in southern hemisphere America). GFEDv4 observes the grid-box with maximum burnt
259 area within the Central African Republic (87% of grid fraction burnt per year), while INFERNO finds a
260 maximum burnt area of 57%, slightly to the North (south-east of lake Tchad). The discrepancy is much
261 larger for emissions, with a maximum emitted carbon of 1.47 kg per m² in Indonesia predicted by
262 GFEDv4s, against 0.4 kg per m² for INFERNO, in Angola. These results could be expected, as
263 INFERNO focuses on capturing global biomass burning, it will not represent such extremes of burning,
264 furthermore the immense emitted carbon observed in Indonesia follows from undiagnosed peat fires.



265
266 **Fig. 2. 1997-2010 mean yearly burnt fraction (above) and emitted carbon (below, in kg m⁻²).** Shown for
267 **INFERNO on the left (with CRUNCEP meteorology and interactive ignitions: mode 3) and for GFED on the**
268 **right.**

269 Figure 3 shows the modelled global annual average biomass burning emissions and burnt area from 1997
270 to 2010. The three ignition methods are evaluated: fully interactive ignitions (red) predict the highest
271 carbon emissions while interactive lightning with constant human ignitions (blue) the lowest. WFDEI
272 was observed to lead to more biomass burning emissions in tropical forest areas (and in particular the
273 borders of rainforests), while CRU-NCEP favoured burning in near-desert areas (the Sahel, India and
274 south American grasslands). We expect this result to be significantly influenced by differences in
275 precipitation (GPCC for WFDEI runs and CRU for CRU-NCEP; (Schneider et al., 2013).



276
 277 **Fig. 3. 1997-2010 biomass burning emissions and burnt area predicted by INFERNO. Two driving datasets**
 278 **were used, CRU-NCEP (solid lines) and WFDEI (green dotted line). Observations are shown in black**
 279 **(MODIS-based estimates).**

280 Comparisons with GFASv1 (and GFEDv3 for emissions (the grey shading represents one standard
 281 deviation within GFEDv3's estimates), to FINNV1 and GFEDv4 for burnt area, were restricted to their
 282 budgets published in (Kaiser et al., 2012; van der Werf et al., 2010; Wiedinmyer et al., 2011; Giglio et
 283 al., 2013) respectively. We also calculated global emissions from GFEDv4s (<http://globalfiredata.org>,
 284 manuscript in preparation), which adds a small fire contribution (Randerson et al., 2012) to GFEDv4's
 285 burnt area.

286 Biomass burning emissions and burnt area simulated by the model follow similar trends to GFEDv3,
 287 although with a smaller inter-annual variability in the model. Carbon emissions from all simulations fall
 288 within one standard deviation of GFEDv3, apart from three years: 1997, 1998 and 2001. Note that for
 289 these years, emissions in GFED were obtained from the lower resolution AVHRR rather than MODIS.
 290 1997 and 1998 were strong El-Niño years during which droughts in equatorial Asia led to extreme
 291 emissions from land-clearing fires, a recurrent problem in the region (Field et al., 2009). Indeed in 1997,
 292 in the region contained between 20S-20N and 90E-160E (or equatorial Asia), GFEDv3 estimate
 293 emissions of 1.07 PgC, while INFERNO (with CRU-NCEP and fully interactive ignitions) estimates
 294 0.15 PgC. Unfortunately, peat is not modelled in JULES and thus neither is peat present in our fire
 295 scheme. It was estimated tropical peat fires alone produced an average of 0.1 PgC per year for 1997-
 296 2009, and 0.7 PgC in 1997 in particular (van der Werf et al., 2010). Peat-lands can be significant in
 297 equatorial Asia but also boreal regions where their combustion leads to the release of long-stored carbon
 298 (Turetsky et al., 2015). In 1998 and 2001, the difference in emissions could not be attributed to a
 299 particular location. While fire emissions from Equatorial Asia were underestimated, GFEDv3 observed
 300 lower emissions over Africa compared to INFERNO, which seems to be the key driver of our
 301 discrepancies.

302 **Table 2. Mean yearly emission budgets in Peta-grams of emitted carbon and mean yearly burnt area budgets**
 303 **in Mkm² for the 1997-2010 period. Latitudes were bound to: beyond 50° (high latitudes), 35° to 50° (mid-**



304 latitudes), 15° to 35° (low latitudes) and below 15° (equatorial). Four configurations of INFERNO are
 305 presented, with CRU-NCEP and WFDEI driving meteorology coupled with three ignition modes: mode 1
 306 indicates constant anthropogenic and lightning ignitions, mode 2 is for constant anthropogenic with
 307 interactive lightning ignitions, and mode 3 for interactive lightning and anthropogenic ignitions.

Emitted carbon (PgC/year)	mode 1 CRU-NCEP	mode 1 WFDEI	mode 2 CRU-NCEP	mode 3 CRU-NCEP
High latitudes	0.087	0.096	0.082	0.091
Mid-latitudes	0.185	0.193	0.170	0.191
Low latitudes	0.716	0.624	0.627	0.591
Equatorial	1.157	1.130	1.021	1.385

308

Burnt area (Mkm ² / year)	mode 1 CRU-NCEP	mode 1 WFDEI	mode 2 CRU-NCEP	mode 3 CRU-NCEP
High latitudes	0.176	0.196	0.162	0.179
Mid-latitudes	0.485	0.557	0.445	0.531
Low latitudes	1.648	1.884	1.558	1.531
Equatorial	1.524	1.580	1.423	1.693

309

310 Table 2 shows the budgets for four latitudinal bands across the various simulations performed. The
 311 second ignition mode (constant anthropogenic and interactive lightning ignitions at any time and place)
 312 appears to consistently predict lower emissions and burnt area (with the exception of low latitudes).
 313 Furthermore, the main impact of using an ignition model that varies with both natural and anthropogenic
 314 ignitions is a reduction of fires at low (tropical and sub-tropical) latitudes, and an increase in equatorial
 315 regions. Indeed, when compared to constant ignitions (mode 1), interactive ignitions (mode 3) predict
 316 more emissions in forest encroachment regions (noticeably surrounding the Congo and Amazon
 317 rainforests), and less in heavily-populated areas (Nigeria, India). Meanwhile, we observed interactive
 318 lightning ignitions (mode 2) significantly reduced burning in grassland-savannah environments. We link
 319 this to the predominance of cloud-to-ground lightning strikes in wet environment within the LIS-OTD
 320 dataset (e.g. the Congo rainforest, (Christian et al., 2003) and fewer strikes (and ignitions) in the more
 321 flammable grasslands and savannahs. These issues are visible in Fig. B1, which shows difference maps
 322 of the four model configurations, for 1997-2010 mean yearly totals. Equatorial and boreal regions include
 323 peat that leads to large fuel consumption, which is unaccounted for in JULES, suggesting that our model
 324 will inherently underestimate emissions from these regions.

325 In order to examine whether our flammability can represent fire occurrence, three other fire indices were
 326 diagnosed, namely the McArthur, Nesterov and Canadian fire indices. These indices were obtained
 327 seamlessly during the model runs, therefore utilizing the same meteorological and hydrological driving
 328 variables, and the same vegetation condition. Their predictions were regressed with GFEDv4 1997-2010



329 annual burnt area (Giglio et al., 2013). This analysis relies on the assumption that fire indices can be used
 330 as a proxy for fire occurrence and spread, and eventually burnt area. Only areas that had been observed
 331 to burn sometime between 1997 and 2010 were sampled; to avoid accounting for high fire indices in
 332 non-vegetated areas such as the Sahara.

333 Table 3 shows the result of our analysis. Ignitions followed mode 1; in this mode ignitions are constant,
 334 therefore the only variability in burnt area (and performance) is due to INFERNO's flammability scheme.
 335 The McArthur index performs poorly at high latitudes (it was made for Australia), but outperforms the
 336 other indices in low latitude regions. The Canadian and Nesterov indices correlate best with observed
 337 burnt area in high latitude regions (for which they were developed). Altogether, INFERNO's burnt area
 338 appears to follow observed burnt area better than the sole usage of a fire index.

339 **Table 3. Temporal correlation coefficients (R) of annual means (1997-2010) shown for four latitudinal bands.**
 340 **R-coefficients were obtained between either of the three simulated fire indices or INFERNO's burnt area**
 341 **(ubiquitous ignitions – ignition mode 1, using CRU-NCEP meteorology) and burnt area from GFEDv4 (Giglio**
 342 **et al., 2013). We restrict our analysis to grid-boxes in which GFEDv4 observed burning. Latitudes were bound**
 343 **to: beyond 50° (high latitudes), 35° to 50° (mid-latitudes), 15° to 35° (low latitudes) and below 15° (equatorial).**

R-coefficient (with GFEDv4 burnt area)	INFERNO Burnt area	Nesterov Index	McArthur Index	Canadian Index
Global	0.649	0.088	-0.009	0.266
High latitudes	0.476	0.522	-0.005	0.519
Mid-latitudes	0.179	-0.006	0.069	0.060
Low latitudes	0.603	0.476	0.499	0.480
Equatorial	0.689	0.239	0.354	0.392

344

345 **5 Conclusion**

346 Through a minimalistic approach we propose a parameterization for fire occurrence of appropriate
 347 complexity for application at large spatial scales within an ESM context: the INteractive Fire and
 348 Emission algoRithm for Natural enviroNments (INFERNO). It directly only varies according to
 349 precipitation (and resulting soil moisture), temperature and humidity, and indirectly it utilizes vegetation.
 350 It is also capable of explicitly simulating ignitions using lightning and anthropogenic information. While
 351 our scheme manages to represent fire occurrence on large scales (both spatial and temporal), it performs
 352 best at low latitudes. INFERNO's burnt area scheme appears superior to the use of fire indices alone
 353 (Nesterov, McArthur and basic Canadian) for capturing annual burnt area variations, and thus one form
 354 of fire impact. However, due to the nature of our analysis (fire danger and burnt area remain different
 355 quantities) this does not imply INFERNO should supersede fire weather indices for operational purposes,
 356 neither has our algorithm been built for numerical weather prediction or seasonal fire danger forecasting.
 357 Nonetheless, our current simulations suggest the variability in emissions is underestimated by
 358 INFERNO, in particular the impact of the 1997-1998 El-Niño and the subsequent La Niña, which may



359 be attributable to the lack of representation of peat in the model, critical to biomass burning in equatorial
360 Asia and boreal areas. The use of different present-day meteorological datasets, in particular
361 precipitation, has an important impact on the magnitude and variability of our diagnostics. Using
362 WFDEI-GPCC rather than CRU-NCEP led to more burnt area but lower fuel consumption and eventually
363 less emitted carbon (this follows from grasslands burning rather than forests). Vegetation zone interfaces
364 were key to this difference. Similarly, lightning appears to ignite more fires in wet environments
365 (rainforests) while flammable environments (savannah, grasslands) are sensitive to the presence of an
366 ignition source. Including a scheme to parameterise human impacts appears to significantly reduce fires
367 in heavily populated areas, while favouring their encroachment of rainforests (the vicinity of which are
368 an anthropogenic ignition ‘sweet spot’ in our parameterization). Nevertheless there is much uncertainty
369 attributed to human induced emissions and effects on fire regime (Marlon et al., 2008; Thonicke et al.,
370 2010). Accordingly, we include different modes of ignition to dampen the impact of this uncertainty in
371 INFERNO.

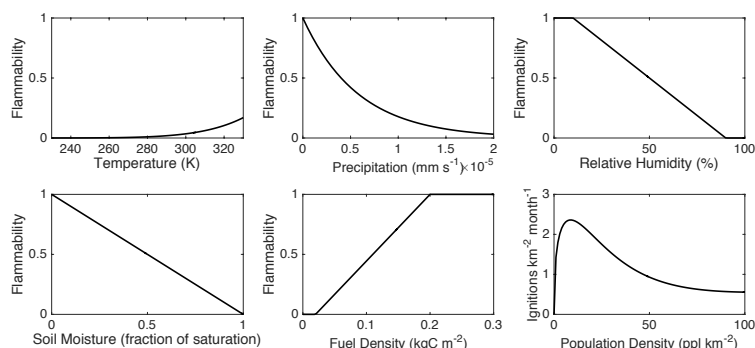
372 The implementation of INFERNO within the Met Office’s Unified Model and its significance for
373 present-day atmospheric composition and climate will be investigated in a separate paper. While a
374 strength of the model is its minimalistic approach the scheme holds potential for improvements: while
375 litter influences flammability, only live vegetation is vaporized. In reality, litter is observed to burn more
376 than live vegetation. Similarly, we predict that the inclusion of peat within JULES would improve its fire
377 diagnostics, especially for locations with large fuel consumptions (e.g. equatorial Asia and boreal
378 climates; van der Werf et al., 2010). Given the predictability of emissions from peat fires in relation with
379 precipitation (van der Werf et al., 2008), this would be a promising area of exploration. The value of this
380 model being its simplicity and linearity, any improvements to INFERNO’s meteorological and
381 hydrological assimilation need to remain minimalistic; complex parameterizations are better suited for
382 more specialized fire schemes (Lasslop et al., 2014; Li et al., 2013, p.1).

383 **Code availability**

384 Information on the JULES land surface model can be found at: <http://jules-lsm.github.io/>. INFERNO is
385 included in JULES vn4.5 and is included in this documentation. The JULES source code can be accessed
386 via the Met Office’s science repository (requires registration): <https://code.metoffice.gov.uk/trac/jules>.
387 In particular, the version of the code used to produce the outputs included in this study can be accessed
388 at:
389 https://code.metoffice.gov.uk/trac/jules/browser/main/branches/dev/stephanemangeon/vn4.3.1_inferno.

390 **Appendix A**

391 This appendix contains additional information relating to the INFERNO scheme.



392

393 **Fig. A1.** The individual dependencies of INFERNO on key driving variables. Note the population density only
 394 influences the model output if ignition mode 3 is selected (interactive lightning and human ignition).

395 **Table A1.** The key JULES PFT-specific parameters for allometry and vegetation carbon used in our
 396 simulations (Clark et al., 2011).

	Specific leaf density σ_l (kg C m ⁻²)	Allometric coefficient a_{wl} (kg C m ⁻²)	Allometric exponent b_{wl}	Associated Fire Biome in Akagi et al., 2011
Broadleaf Evergreen Tree (Tropical)	0.0375	0.65	1.667	Tropical Forests
Broadleaf Evergreen Tree (Temperate)	0.0375	0.65	1.667	Temperate Forests
Broadleaf Deciduous Tree	0.0375	0.65	1.667	Tropical Forests
Needleleaf Evergreen Tree	0.1	0.65	1.667	Temperate Forests
Needleleaf Deciduous Tree	0.1	0.75	1.667	Boreal Forests
C3 grass	0.025	0.005	1.667	Temperate Forests
C4 grass	0.05	0.005	1.667	Savannah and Grasslands
Evergreen Shrub	0.05	0.10	1.667	Temperate Forests
Deciduous Shrub	0.05	0.10	1.667	Boreal Forests

397

398 **Table A2.** The characteristics of the Canadian's Fire Weather Index's three fuel moisture codes.

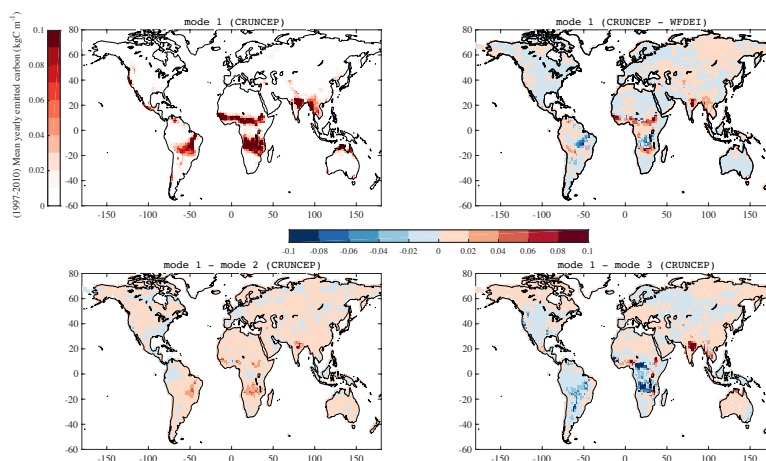
	Type of fuel	Dry weight (kg m ⁻²)	Time lag (days)	Water capacity (mm)
Fine Fuel Moisture Code	Litter and other fine fuels	0.25	2-3	0.6
Duff Moisture Code	Loosely compacted decomposing organic matter	5	12	15



Drought Code	Deep layer of compact organic matter	25	52	100
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399 **Appendix B**

400 This appendix contains additional results illustrating the dependence of INFERNO with ignitions and its
 401 performance on a regional basis.



402

403 **Fig. B1.** Emitted carbon difference maps between the four runs performed to analyse the sensitivity of
 404 INFERNO to ignitions (our three ignition modes, see Sect. 2.1.1) and meteorology (CRUNCEP and WFDEI-
 405 GPCP).

406

Table B1. Regional budgets according to the standard GFED regions (van der Werf et al., 2010).

GFED standard regions	Mean Yearly Burnt Area (in Mha)		Mean Yearly Emitted Carbon (in TgC)	
	GFED4*	INFERNO**	GFED3***	INFERNO**
Boreal North America	2.2	5.2	54	37
Temperate North America	1.8	29.9	9	106
Central America	1.8	7.9	20	45
Northern Hemisphere South America	2.6	4.0	22	51
Southern Hemisphere South America	18.7	68.3	271	483
Europe	0.7	5.0	4	29
Middle East	0.8	12.3	2	19



Northern Hemisphere Africa	117.7	120.4	481	533
Southern Hemisphere Africa	125.0	57.6	557	610
Boreal Asia	5.6	9.7	128	55
Central Asia	13.6	23.8	36	50
Southeast Asia	7.0	29.6	103	170
Equatorial Asia	1.6	0.5	191	10
Australia and New Zealand	50.2	30.2	135	96

407 * GFED4 mean yearly burnt area from Giglio et al. (2013), from 1997 to 2011. ** INFERNO mean yearly burnt area from 1997
408 to 2010, using ignition mode 3 (varying anthropogenic and natural ignitions) and CRU-NCEP driving meteorology. *** GFED3
409 mean yearly emitted carbon from van der Werf et al. (2010) from 1997 to 2009.



410 **Author contribution**

411 Apostolos Voulgarakis supervised the scientific design of INFERNO and the writing of this article. Gerd
412 Folberth also supervised these aspects, with an emphasis on technical aspects of INFERNO in relation
413 with the Met Office's Unified Model. Richard Gilham contributed to the technical design of the model
414 and its implementation and led the writing on fire indices. Anna Harper contributed to the design of
415 INFERNO in relation to the vegetation scheme's recent development, helped with the analysis of
416 vegetation biases in the study's results and led the writing on the vegetation scheme. Stephen Sitch
417 contributed throughout the writing, analysis and the scientific design of this study.

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