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Controls on fire activity over the Holocene

S. Kloster, T. Brücher, V. Brovkin, and S. Wilkenskjeld

Land in the Earth System, Max Planck Institute for Meteorology, Hamburg, Germany

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Correspondence to: S. Kloster (silvia.kloster@mpimet.mpg.de)

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Abstract

Changes in fire activity over the last 8000 years are simulated with a global fire model driven by changes in climate and vegetation cover. The changes were separated into those caused through variations in fuel availability, fuel moisture or wind speed which react differently to changes in climate. Disentangling these controlling factors helps to understand the overall climate control on fire activity over the Holocene.

Globally the burned area is simulated to increase by 2.5 % between 8000 and 200 cal yr BP with larger regional changes compensating on a global scale. Despite the absence of anthropogenic fire ignitions, the simulated trends in fire activity agree reasonably well with continental scale reconstructions from charcoal records, with the exception of Europe. For some regions the change in fire activity is predominantly controlled through changes in fuel availability (Australia-Monsoon, American Tropics/Subtropics). For other regions changes in fuel moisture are more important for the overall trend in fire activity (North America, Sub-Saharan Africa, Europe, Asia-Monsoon). In Sub-Saharan Africa, for example, changes in fuel moisture alone lead to an increase in fire activity between 8000 and 200 cal yr BP, while changes in fuel availability lead to a decrease. Overall, the fuel moisture control is dominating the simulated fire activity for Sub-Saharan Africa.

The simulations clearly demonstrate that both changes in fuel availability and changes in fuel moisture are important drivers for the fire activity over the Holocene. Fuel availability and fuel moisture do, however, have different climate controls. As such observed changes in fire activity can not be related to single climate parameters such as precipitation or temperature alone. Fire models, as applied in this study, in combination with observational records can help to understand the climate control on fire activity, which is essential to project future fire activity.

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1 Introduction

Fires appeared on Earth soon after the onset of terrestrial plants and are an integral part of the Earth system (Bowman et al., 2009). Fires form an important natural disturbance process affecting vegetation distribution and structure (Scheiter and Higgins, 2009). Presently an area between 301 and 377 Mha burns annually (Giglio et al., 2013). Fires impact the climate through various processes, such as changes in surface properties and emissions of trace gases and aerosols into the atmosphere (Randerson et al., 2006; Ward et al., 2012; Keywood et al., 2013). At the same time fires are controlled by climate (Westerling, 2006; Harrison et al., 2010). Ongoing anthropogenic climate change is likely to alter fire activity (Scholze et al., 2006; Pechony and Shindell, 2010; Kloster et al., 2012). An analysis of paleorecords on fire activity can improve our understanding of the climate control on fire activity, which will be essential to project future fire activity and climate change.

Microscopic charcoal pieces in sediments have been related to fire history for different parts of the world going back in time for thousands of years (Patterson et al., 1987; Whitlock and Millspaugh, 1996; Scott, 2002). The Global Charcoal Database (Power et al., 2010) has collected over 400 radiocarbon-dated charcoal records covering the Late Quaternary. This database and associated updates have been used in various studies to improve our understanding of fire history (Power et al., 2007; Marlon et al., 2008, 2009).

The charcoal database provides information about changes in past fire activity. To relate those to changes in climate is often not straightforward. Fire activity is affected by changes in climate by directly altering lightning ignition sources (Price and Rind, 1994) and fuel moisture (Dwyer et al., 2000; Westerling et al., 2003) and indirectly through changes in fuel availability and vegetation distribution (Westerling et al., 2003; Martin Calvo et al., 2014). The importance of these controlling factors for fire activity varies across climate regimes. In dry regions fire activity is typically limited by fuel availability, but fuel moisture is sufficiently low to lead to successful fire ignitions. Under

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moist climate conditions fuel availability is sufficiently guaranteed but fuel moisture is often too high to allow for fires to spread (van der Werf et al., 2010). Consequently, climate change will impact fire activity differently in different climate zones and fire regimes.

Here, we investigate the climate control on fire activity over the Holocene by disentangling the controls via fuel availability, fuel moisture and wind speed within a fire model (Arora and Boer, 2005; Kloster et al., 2010) embedded in a global land vegetation model (JSBACH, Raddatz et al., 2007; Brovkin et al., 2009; Reick et al., 2013). We simulate fire activity for the period 8000 cal yr BP until 200 cal yr BP with the land vegetation model coupled to a climate model of intermediate complexity (CLIMBER-2, Petoukhov et al., 2000; Ganopolski and Rahmstorf, 2001). Fire activity has been observed to change over this period as a result of climate change (Carcaillet et al., 2002; Marlon et al., 2013). With the help of a global model we want to understand the reason for those changes.

2 Method

This study applies the coupled climate-carbon cycle model CLIMBA (Brücher et al., 2014). CLIMBA consists of the earth system model of intermediate complexity CLIMBER-2 (Petoukhov et al., 2000; Ganopolski and Rahmstorf, 2001) and JSBACH (Raddatz et al., 2007; Brovkin et al., 2009; Reick et al., 2013), which is the land surface and vegetation model of the MPI Earth System Model (MPI-ESM, Giorgetta et al., 2013). CLIMBA is applied with a resolution of 51° (longitude) by 10° (latitude) to simulate atmosphere and land processes, while JSBACH runs on a higher resolution (3.75° × 3.75°) including a daily cycle. JSBACH and CLIMBER-2 are coupled following Kleinen et al. (2010).

The simulations are setup similar to Brücher et al. (2014). The base climate is represented by a MPI-ESM CMIP5 simulation of the early industrial period (1850–1899). JSBACH is driven by climate anomalies as simulated in CLIMBER-2 added to the

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50 year spanning base climate. This approach is required as CLIMBER-2 does not simulate year-to-year climate variability, which is however critical to simulate land and vegetation dynamics in JSBACH. Unlike in Brücher et al. (2014) we choose not a year randomly out of the 50 year base climate, but applied a constant base climate throughout the simulation. As a result the data presented here are smoothed when averaged over 50 years.

The default JSBACH model was extended by a process based fire model (Arora and Boer, 2005; Kloster et al., 2010; Krause et al., 2014) with updates according to Li et al. (2012). The fire model calculates the total fire occurrence probability as the product of three probability functions representing the availability of biomass, fuel moisture and ignition potential. The fire then spreads as a function of wind speed and soil moisture. Fuel availability is simulated as a function of aboveground biomass. Soil moisture is used as a surrogate for fuel moisture. Lightning ignitions are prescribed from a satellite based climatology (Cecil et al., 2012) extended by a latitudinal dependency of the cloud to ground vs. intra cloud lighting fraction (Price and Rind, 1994). Human ignitions are not accounted for. With poorly constrained data on human fire interaction over the Holocene, we do not see any means to include those in the present study. However, fire models that do not explicitly account for human ignition can still reproduce the main features of the fire regime even in areas in which many fires are set by humans as has been shown by Prentice et al. (2011). Humans often set fire in regions that are fire prone, as such human ignitions tend to preempt, rather than augment, the natural fire regime (Prentice et al., 2011).

Soil moisture, aboveground biomass, and wind speed control the burned area in the fire model. A high soil moisture lowers the fire occurrence probability and the overall fire spread. A high aboveground biomass assures a high fire occurrence probability constrained by biomass abundance and a high wind speed increases the fire spread. For this study we performed several experiments to disentangle the control of these single forcings on the simulated fire activity over the Holocene (Table 1). In experiment M only the soil moisture is varying with time; fuel availability and wind speed are kept

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constant over time. In experiment F only the fuel availability if varying with time; soil moisture and wind speed are kept constant. In experiment W only the wind speed is varying with time, soil moisture and fuel availability are kept constant. Finally, in experiment FMW all parameters controlling fire activity in the model are varying with time, i.e. the full set of forcing is applied and simulated burned area represents fire activity over the Holocene. As constant conditions a 50 year cycle inline with the CLIMBER-2 base climate for 8000 to 7051 cal yr BP is applied continuously over the simulation period for the parameter of interest.

3 Results

In 200 cal yr BP on average 528 Mha burn annually (see also Brücher et al., 2014), which is on the higher end of present day satellite based observed estimates (Giglio et al., 2013). The simulation presented does, however, not account for the human-fire impact and uses dynamically simulated natural vegetation cover not including agricultural areas. As such the simulations are not directly comparable to present-day satellite based observations. Overall, the model does capture the major burning regions in sub-Saharan Africa, Southeastern Asia, Northern Australia and parts of North and South America (Fig. 1a).

Globally the change in burned area is small over the Holocene with a slight increase in fire activity simulated between 8000 and 200 cal yr BP (+14 Mha (+2.5 %)). Regionally, however, the simulation shows areas with pronounced increases (e.g. central Africa, parts of Australia and southern Europe) as well as decreases (e.g. in northern North America and in South America), which nearly compensate on a global scale (Fig. 1b). Brücher et al. (2014) has shown that the simulated climate over the Holocene is characterised for the northern tropics by an intensified and northward shifted monsoon system, which leads to a widespread greening between 8000 and 4000 cal yr BP inline with previous findings (Claussen, 1997; Brovkin et al., 2002; Prentice et al., 1992). Between 20–30° S drier conditions are simulated when zonally averaged during the time period 8000 to 6000 cal yr BP. This is a result of drier conditions in South Africa (caused by the northward shifted monsoon system), drier conditions in Amazonia and a small increase in precipitation in Australia. These changes in climate alter fire activity over the Holocene as shown by Brücher et al. (2014). Here we disentangle further what caused these changes in fire activity.

Similar to Brücher et al. (2014) we analyse the transient evolution of the burned area between 8000 and 200 cal yr BP averaged over continental scale regions. Figure 2 and Table 2 depict the changes in burned area for the control simulation in which the fire submodel is driven with varying fuel availability, moisture and wind speed (experiment FMW), i.e. all parameters impacting fire activity are varying and the simulation is identical to the one presented in Brücher et al. (2014). The single factor experiments, in which only one parameter impacting fire activity is varying over time, are shown as well in Fig. 2 and are summarised in Table 2. The regions are chosen as analogs to Marlon et al. (2013) to facilitate comparison with changes in fire activity reported in the charcoal database. The fire activity is reported in z-scores in the charcoal database. Z-scores are a standardized measure frequently used by the palaeofire community to compare aggregated values of past fire activity. They are, however, no quantitative measure and therefor cannot be related to absolute changes (Power et al., 2010).

All regions have in common that changes in wind speed between 8000 and 200 cal yr BP do not significantly impact the fire activity. Therefore, the wind speed control on fire activity will not be further discussed for this study.

For the Asian Monsoon region (Fig. 2a) the simulated burned area increases between 8000 and 200 cal yr BP by around 11 %. For the same time period, the charcoal data reports an increase in fire activity as well. The increase in simulated burned area is primarily driven by reduced moisture in response to decreases in precipitation (15 %). Changes in fuel availability alone have only a minor impact on fire activity for this region (2 %).

For North America (Fig. 2b) the burned area increases between 8000 and 200 cal yr BP (+4 %), which agrees with the increase reported in the charcoal database.

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Changes in fuel availability alone lead to a small increasing trend (+1 %), while changes in moisture dominate the overall increase in fire activity (+5 %). Noticeable is a lower fire activity between 6000 and 4000 cal yr BP, which is in accordance with a simulated drop in temperature within that period.

For Sub-Saharan Africa (Fig. 2c) the simulated burned area decreases between 8000 to 3000 cal yr BP (−2 %) and remains constant afterwards. In contrast, the charcoal data indicates lower fire activity during the time period 8000 to 2000 cal yr BP compared to the time period 2000 to 200 cal yr BP. The decrease in simulated burned area is dominated by the biomass control on fire activity, which leads to a decrease in burned area between 8000 and 200 cal yr BP (−4 %). This trend fits to with an increase in desert extent between 8000 and 200 cal yr BP.

For the American Tropics (Fig. 2d) the burned area shows an increase between 8000 and 200 cal yr BP (+4 %). Similar findings are reported in the charcoal data, with somewhat lower levels between 4000 and 200 cal yr BP compared to the period 6000 to 4000 cal yr BP. Overall the trend in fire activity is dominated by a fuel availability control (+4 %), which is linearly with an increase in available biomass. Changes in fire activity due to moisture are smaller (+1 %) and in line with the simulated decrease in precipitation.

For Europe (Fig. 2e) the burned area decreases over the Holocene. In 200 cal yr BP the burned area is approximately 23 % lower compared to 8000 cal yr BP. For the same time period the charcoal data show an increase in fire activity. The simulated changes in burned area for Europe can be largely explained by the moisture control on fire activity, while changes in fuel availability alone result in a smaller decrease (−25 % compared to −10 %, respectively). Biomass decreases when averaged over Europe between 8000 and 200 cal yr BP which is inline with the fuel availability driven trend in fire activity. Precipitation is increasing averaged over Europe in accordance with a decrease in fire activity driven by changes in moisture.

For the Australia Monsoon region (Fig. 2f) the burned area increases between 8000 and 200 cal yr BP (+8 %). The charcoal data show a drop in fire activity between 8000

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and 7000 cal yr BP, an increase up to 5000 cal yr BP and constant fire activity thereafter. For this region the overall trend in burned area is to a large extent explained by changes in fuel availability (+9 %), whereas changes in moisture have no impact on fire activity averaged over the region.

Moisture, fuel availability and wind speed do not control the fire activity independently but interact with each other. As such the system is non-linear, i.e. changes in burned area caused by changes in fuel availability, moisture and wind speed alone do not add to the changes in burned area which are simulated when fuel availability, moisture and wind speed are changed simultaneously. This is also reflected in the model simulations. For all regions we find negative synergies, i.e. the changes in burned area are smaller when driving factors are changed simultaneously (control simulation, experiment FMW) compared to adding the response of the individual experiments, in which only one forcing factor at a time is changed (adding the experiments F, M and W).

4 Conclusions

Globally the burned area is simulated to increase by 2.5 % between 8000 and 200 cal yr BP. Regionally, however, the change in burned area is larger with decreases and increases nearly compensating on a global scale.

While in some regions the burned area changes are predominantly controlled via changes in fuel availability (Australia-Monsoon, American Tropics/Subtropics) others are stronger impacted via changes in fuel moisture (North America, Europe, Asia-Monsoon, Sub-Saharan Africa). Fuel availability and fuel moisture do have, however, different climate controls. While for example precipitation generally allows the build up of fuel load it also increases fuel moisture; both processes having opposite effects on fire occurrence. As such the climate control on fire activity is difficult to assess from simple climate indices (such as temperature or precipitation) and paleo-fire records alone as done previously (e.g. Marlon et al., 2008, 2009). Only more complex relationships taking into account more than one explaining climate variable might be suitable to interpret the climate control of past fire activity (Daniau et al., 2012).

Fire models can help to understand the climate control on past fire activity, as shown in this study. However, fire models are limited in their ability to reproduce global fire activity as they are build on a still incomplete process understanding on vegetation fire occurrence (Pfeiffer et al., 2013; Kloster et al., 2010; Pechony and Shindell, 2010). The human control on vegetation fires through fire ignition and fire suppression are controlled by population evolution and various social-economical factors (Archibald et al., 2012), which are difficult to assess on a global scale. In this study we are, therefore, not able to account for human ignition. Lightning ignition are kept constant even though they are climate controlled (Price and Rind, 1994), but no data on lightning occurrence over the Holocene is available.

The most striking mismatch between simulated fire activity and fire activity derived from charcoal data is found for Europe, showing opposite trends in the simulation and the observations over the Holocene. While this might be a result of the model itself, it might be also caused by uncertainties in the charcoal data and an averaging over large regions that include different fire regimes with different climate controls. Combining fire models and charcoal data more closely in future studies could help to overcome the high uncertainties related with fire modeling as well as reconstructing fire activity from charcoal records.

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References

Archibald, S., Staver, A. C., and Levin, S. A.: Evolution of human-driven fire regimes in Africa, P. Natl. Acad. Sci. USA, 109, 847–852, 2012. 4266

Arora, V. K. and Boer, G. J.: Fire as an interactive component of dynamic vegetation models, J. Geophys. Res.-Biogeo., 110, G02008, doi:10.1029/2005JG000042, 2005. 4260, 4261

Bowman, D. M. J. S., Balch, J. K., Artaxo, P., Bond, W. J., Carlson, J. M., Cochrane, M. A., D'Antonio, C. M., DeFries, R. S., Doyle, J. C., Harrison, S. P., Johnston, F. H., Keeley, J. E., Krawchuk, M. A., Kull, C. A., Marston, J. B., Moritz, M. A., Prentice, I. C., Roos, C. I., Scott, A. C., Swetnam, T. W., van der Werf, G. R., and Pyne, S. J.: Fire in the Earth System, Science, 324, 481–484, 2009. 4259

Brovkin, V., Bendtsen, J., Claussen, M., Ganopolski, A., Kubatzki, C., Petoukhov, V., and Andreev, A.: Carbon cycle, vegetation, and climate dynammics in the Holocene: experiments with the CLIMBER-2 model, Global Biogeochem. Cy., 16, 4, 86-1–86-20, 2002. 4262

Brovkin, V., Raddatz, T., Reick, C. H., Claussen, M., and Gayler, V.: Global biogeophysical interactions between forest and climate, Geophys. Res. Lett., 36, L07405, doi: 10.1029/2009GL037543, 2009. 4260

Brücher, T., Brovkin, V., Kloster, S., Marlon, J. R., and Power, M. J.: Comparing modelled fire dynamics with charcoal records for the Holocene, Clim. Past, 10, 811–824, doi:10.5194/cp-10-811-2014, 2014. 4260, 4261, 4262, 4263, 4275

Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R. H. W., Carrión, J. S., Gaillard, M. J., Gajewski, K., Haas, J. N., Haberle, S. G., Hadorn, P., Müller, S. D., Richard, P. J. H., Richoz, I., Rösch, M., Sánchez Goñi, M. F., von Stedingk, H., Stevenson, A. C., Talon, B., Tardy, C., Tinner, W., Tryterud, E., Wick, L., and Willis, K. J.: Holocene biomass burning and global dynamics of the carbon cycle, Chemosphere, 49, 845–863, 2002. 4260

Cecil, D. J., Buechler, D. E., and Blakeslee, R. J.: Gridded lightning climatology from TRMM-LIS and OTD: dataset description, Atmos. Res., 135–136, 404–414, doi:10.1016/j.atmosres.2012.06.028, 2014. 4261

Claussen, M.: Modeling bio-geophysical feedback in the African and Indian monsoon region, Clim. Dynam., 13, 247–257, 1997. 4262

Daniau, A. L., Bartlein, P. J., Harrison, S. P., Prentice, I. C., Brewer, S., Friedlingstein, P., Harrison-Prentice, T. I., Inoue, J., Izumi, K., Marlon, J. R., Mooney, S., Power, M. J., Stevenson, J., Tinner, W., Andrič, M., Atanassova, J., Behling, H., Black, M., Blarquez, O., Brown, K. J., Carcaillet, C., Colhoun, E. A., Colombaroli, D., Davis, B. A. S., D'Costa, D., Dodson, J., Dupont, L., Eshetu, Z., Gavin, D. G., Genries, A., Haberle, S., Hallett, D. J., Hope, G., Horn, S. P., Kassa, T. G., Katamura, F., Kennedy, L. M., Kershaw, P., Krivonogov, S., Long, C., Magri, D., Marinova, E., McKenzie, G. M., Moreno, P. I., Moss, P., Neumann, F. H.,

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Norström, E., Paitre, C., Rius, D., Roberts, N., Robinson, G. S., Sasaki, N., Scott, L., Takahara, H., Terwilliger, V., Thevenon, F., Turner, R., Valsecchi, V. G., Vannière, B., Walsh, M., Williams, N., and Zhang, Y.: Predictability of biomass burning in response to climate changes, Global Biogeochem. Cy., 26, GB4007, doi: 10.1029/2011GB004249, 2012. 4266

Dwyer, E., Grégoire, J.-M., and Pereira, J.: Climate and vegetation as driving factors in global fire activity, in: Biomass Burning and its Inter-Relationships with the Climate System, edited by: Innes, J., Beniston, M., and Verstraete, M., vol. 3, Adv. Glob. Change Res., Springer Netherlands, 171–191, 2000. 4259

Ganopolski, A. and Rahmstorf, S.: Rapid changes of glacial climate simulated in a coupled climate model, Nature, 409, 153–158, 2001. 4260

Giglio, L., Randerson, J. T., and van der Werf, G. R.: Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4), J. Geophys. Res.-Biogeo., 118, 317–328, 2013. 4259, 4262

Giorgetta, M. A., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Ilyina, T., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Mueller, W., Notz, D., Pithan, F., Raddatz, T., Rast, S., Redler, R., Roeckner, E., Schmidt, H., Schnur, R., Segschneider, J., Six, K. D., Stockhause, M., Timmreck, C., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J., and Stevens, B.: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5, J. Adv. Model. Earth Syst., 5, 572–597, 2013. 4260

Harrison, S., Marlon, J., and Bartlein, P.: Fire in the Earth System, in: Changing Climates, Earth Systems and Society, edited by: Dodson, J., International Year of Planet Earth, Springer Netherlands, 21–48, doi:10.1007/978-90-481-8716-4_3, 2010. 4259

Keywood, M., Kanakidou, M., Stohl, A., Dentener, F., Grassi, G., Meyer, C. P., Torseth, K., Edwards, D., Thompson, A. M., Lohmann, U., and Burrows, J.: Fire in the air: Biomass burning impacts in a changing climate, Crit. Rev. Env. Sci. Tec, 43, 40–83, 2013. 4259

Kleinen, T., Brovkin, V., von Bloh, W., Archer, D., and Munhoven, G.: Holocene carbon cycle dynamics, Geophys. Res. Lett., 37, 2, doi:10.1029/2009GL041391, 2010. 4260

Kloster, S., Mahowald, N. M., Randerson, J. T., Thornton, P. E., Hoffman, F. M., Levis, S., Lawrence, P. J., Feddema, J. J., Oleson, K. W., and Lawrence, D. M.: Fire dynamics during the 20th century simulated by the Community Land Model, Biogeosciences, 7, 1877–1902, doi:10.5194/bg-7-1877-2010, 2010. 4260, 4261, 4266

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10, 4257–4275, 2014

Kloster, S., Mahowald, N. M., Randerson, J. T., and Lawrence, P. J.: The impacts of climate, land use, and demography on fires during the 21st century simulated by CLM-CN, Biogeosciences, 9, 509–525, doi:10.5194/bg-9-509-2012, 2012. 4259

Krause, A., Kloster, S., Wilkenskjeld, S., and Paeth, H.: The sensitivity of global wildfires to simulated past, present, and future lightning frequency, J. Geophys. Res.-Biogeo., 119, 312–322, 2014. 4261

Li, F., Zeng, X. D., and Levis, S.: A process-based fire parameterization of intermediate complexity in a Dynamic Global Vegetation Model, Biogeosciences, 9, 2761–2780, doi:10.5194/bg-9-2761-2012, 2012. 4261

Marlon, J. R., Bartlein, P. J., Carcaillet, C., Gavin, D. G., Harrison, S. P., Higuera, P. E., Joos, F., Power, M. J., and Prentice, I. C.: Climate and human influences on global biomass burning over the past two millennia, Nat. Geosci., 1, 697–702, 2008. 4259, 4265

Marlon, J. R., Bartlein, P. J., Walsh, M. K., Harrison, S. P., Brown, K. J., Edwards, M. E., Higuera, P. E., Power, M. J., Anderson, R. S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F. S., Lavoie, M., Long, C., Minckley, T., Richard, P. J. H., Scott, A. C., Shafer, D. S., Tinner, W., Umbanhowar, C. E., and Whitlock, C.: Wildfire responses to abrupt climate change in North America, P. Natl. Acad. Sci. USA, 106, 2519–2524, 2009. 4259, 4265, 4275

Marlon, J. R., Bartlein, P. J., Daniau, A.-L., Harrison, S. P., Maezumi, S. Y., Power, M. J., Tinner, W., and Vanniére, B.: Global biomass burning: a synthesis and review of Holocene paleofire records and their controls, Quaternary Sci. Rev., 65, 5–25, 2013. 4260, 4263, 4273

Martin Calvo, M., Prentice, I. C., and Harrison, S. P.: Climate vs. carbon dioxide controls on biomass burning: a model analysis of the glacial-interglacial contrast, Biogeosciences Discuss., 11, 2569–2593, doi:10.5194/bgd-11-2569-2014, 2014. 4259

Patterson, W. A. I., Edwards, K. J., and MacGuire, D. J.: Microscopic charcoal as a fossil indicator of fire, Quaternary Sci. Rev., 6, 3–23, 1987. 4259

Pechony, O. and Shindell, D. T.: Driving forces of global wildfires over the past millennium and the forthcoming century., P. Natl. Acad. Sci. USA, 107, 19167–19170, 2010. 4259, 4266

Petoukhov, V., Ganopolski, A., Brovkin, V., Claussen, M., Eliseev, A., Kubatzki, C., and Rahmstorf, S.: CLIMBER-2: a climate system model of intermediate complexity. Part I: model description and performance for present climate, Clim. Dynam., 16, 1–17, 2000. 4260

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10, 4257–4275, 2014

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Pfeiffer, M., Spessa, A., and Kaplan, J. O.: A model for global biomass burning in preindustrial time: LPJ-LMfire (v1.0), Geosci. Model Dev., 6, 643–685, doi:10.5194/gmd-6-643-2013, 2013. 4266

Power, M. J., Marlon, J., Ortiz, N., Bartlein, P. J., Harrison, S. P., Mayle, F. E., Ballouche, A., Bradshaw, R. H. W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P. I., Prentice, I. C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A. A., Anderson, R. S., Beer, R., Behling, H., Briles, C., Brown, K. J., Brunelle, A., Bush, M., Camill, P., Chu, G. Q., Clark, J., Colombaroli, D., Connor, S., Daniau, A. L., Daniels, M., Dodson, J., Doughty, E., Edwards, M. E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M. J., Gavin, D. G., Gobet, E., Haberle, S., Hallett, D. J., HIGUERA, P., Hope, G., Horn, S., Inoue, J., Kaltenrieder, P., Kennedy, L., Kong, Z. C., Larsen, C., Long, C. J., Lynch, J., Lynch, E. A., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D. M., New, J., Newnham, R., Noti, R., Oswald, W., Pierce, J., Richard, P. J. H., Rowe, C., Sánchez Goñi, M. F., Shuman, B. N., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D. H., Umbanhowar, C., Vandergoes, M., Vannière, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., and Zhang, J. H.: Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data, Clim. Dynam., 30, 887–907, 2007. 4259

Power, M. J., Marlon, J. R., Bartlein, P. J., and Harrison, S. P.: Fire history and the Global Charcoal Database: a new tool for hypothesis testing and data exploration, Palaeogeogr. Palaeocl., 291, 52–59, 2010. 4259, 4263

Prentice, I. C., Cramer, W., Harrison, S. P., Leemans, R., Monserud, R. A., and Solomon, A. M.: Special paper: a global biome model based on plant physiology and dominance, soil properties and climate, J. Biogeogr., 19, 117–134, 1992. 4262

Prentice, I. C., Kelley, D. I., Foster, P. N., Friedlingstein, P., Harrison, S. P., and Bartlein, P. J.: Modeling fire and the terrestrial carbon balance, Global Biogeochem. Cy., 25, 3, doi:10.1029/2010GB003906, 2011. 4261

Price, C. and Rind, D.: The impact of a $2 \times CO_2$ climate on lightning-caused fires, J. Climate, 7, 1484–1494, 1994. 4259, 4261, 4266

Raddatz, T. J., Reick, C. H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., Schnitzler, K. G., Wetzel, P., and Jungclaus, J.: Will the tropical land biosphere dominate the climate–carbon cycle feedback during the twenty-first century?, Clim. Dynam., 29, 565–574, 2007. 4260

Randerson, J. T., Liu, H., Flanner, M. G., Chambers, S. D., Jin, Y., Hess, P. G., Pfister, G., Mack, M. C., Treseder, K. K., Welp, L. R., Chapin, F. S., Harden, J. W., Goulden, M. L., Lyons, E., Neff, J. C., Schuur, E. A. G., and Zender, C. S.: The impact of boreal forest fire on climate warming, Science, 314, 1130–1132, 2006. 4259

Reick, C. H., Raddatz, T., Brovkin, V., and Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM, J. Adv. Model. Earth Syst., 5,3, doi:10.1002/jame.20022, 2013. 4260

Scheiter, S. and Higgins, S. I.: Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach, Glob. Change Biol., 15, 2224–2246, 2009. 4259

Scholze, M., Knorr, W., Arnell, N. W., and Prentice, I. C.: A climate-change risk analysis for world ecosystems, P. Natl. Acad. Sci. USA, 103, 13116–13120, 2006. 4259

Scott, L.: Microscopic charcoal in sediments: quaternary fire history of the grassland and savanna regions in South Africa, J. Quaternary Sci., 17, 77–86, 2002. 4259

van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), Atmos. Chem. Phys., 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010. 4260

Ward, D. S., Kloster, S., Mahowald, N. M., Rogers, B. M., Randerson, J. T., and Hess, P. G.: The changing radiative forcing of fires: global model estimates for past, present and future, Atmos. Chem. Phys., 12, 10857–10886, doi:10.5194/acp-12-10857-2012, 2012. 4259

Westerling, A. L.: Warming and earlier spring increase Western US forest wildfire activity, Science, 313, 940–943, 2006. 4259

Westerling, A. L., Gershunov, A., Brown, T. J., Cayan, D. R., and Dettinger, M. D.: Climate and wildfire in the Western United States, B. Am. Meteorol. Soc., 84, 595–604, 2003. 4259

Whitlock, C. and Millspaugh, S. H.: Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA, The Holocene, 6, 7–15, 1996. 4259

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Table 1. Experiments performed for this study keeping single forcing factors controlling simulated fire activity constant or varying over the simulation period 8000 to 200 cal yr BP.

	fuel availability	fuel moisture	wind speed
F	varying	constant	constant
M	constant	varying	constant
W	constant	constant	varying
FMW	varying	varying	varying

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Table 2. Difference in burned area between 200 and 8000 cal yr BP state (100–199 minus 7900–7999) relative to the 8000 cal yr BP state in [%] for different regions and experiments (F: fuel availability varying, M: moisture varying; W: wind speed varying; FMW: fuel availability, moisture and wind speed varying = control simulation). Regions are chosen according to Marlon et al. (2013). Significant values (confidence level higher than 95 % determined with a student-*t* test) are printed in bold.

	F	M	W	FMW
North America	1.31	**5.61**	−0.04	**3.75**
Europe	**−10.12**	**−24.82**	−1.24	**−22.79**
Asian-Monsoon	**1.91**	15.16	**0.52**	10.43
American Tropics/Subtropics	**3.97**	0.62	−0.18	**4.04**
Sub-Saharan Africa	**−3.85**	**4.99**	−1.13	**−2.25**
Australia-Monsoon	**9.39**	0.05	1.29	**7.80**

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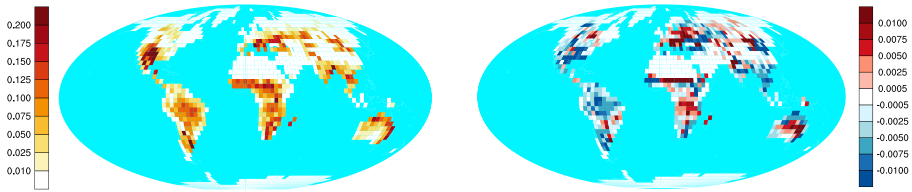

Figure 1. Simulated annual burned fraction of grid cell area [$m^2\,m^{-2}$] of natural fire activity for 8000 cal yr BP (left) and differences between 8000 and 200 cal yr BP (7900–7999 minus 100–199, right).

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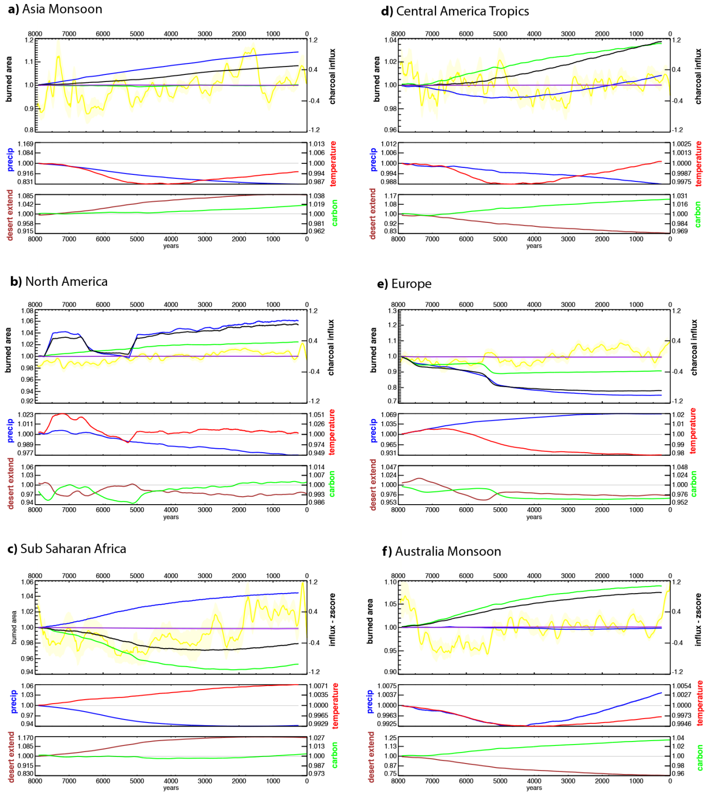

Figure 2. Transient changes in burned area between 8000 and 200 cal yr BP averaged over continental scale regions (upper panels) for the experiments: FMW (black), M (blue), F (green), W (purple). The lower panels show changes in climate (precipitation (blue), surface temperature (red)) and vegetation state variables (land carbon storage (green), desert extent (brown)). The definition of the domains is taken from Marlon et al. (2009). Changes are normalized with respect to the 8000 cal yr BP state and smoothed with a 250 year running mean similar to Brücher et al. (2014); Marlon et al. (2009).

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Controls on fire activity over the Holocene

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