Silvia Kloster works as a Klaus Hasselmann post–doctoral fellow in the department Land in the Earth System at the Max Planck Institute for Meteorology in Hamburg, Germany. She received her PhD from the Max Planck Institute for Meteorology in 2006 investigating the role of dimethylsulfide produced by phytoplankton within the Earth System. She continued her research with a focus on aerosol–climate interactions at the Joint Research Centre of the European Commission in Italy. During her post–doc time at the Cornell University, Ithaca, New York, USA, she shifted her research into the field of global terrestrial biosphere modelling with a focus on fires.

Silvia Kloster
Max Planck Institute for Meteorology, Hamburg, Germany

Towards assessing fire feedbacks in the Earth system: Global process–based fire modelling

Fire is a mixture of heat, fuel, and oxygen. The particular mixture of these terms determines whether and how different materials burn. Fires have appeared on Earth when atmospheric oxygen reached levels sufficient to sustain a fire (about 400 million years ago) and have been an integral part of the Earth system since.

Climate affects vegetation fires directly, by controlling the incidence of ignitions, fuel moisture, and fire spread rates, as well as indirectly through changing vegetation types, plant productivity and hence fuel load availability.

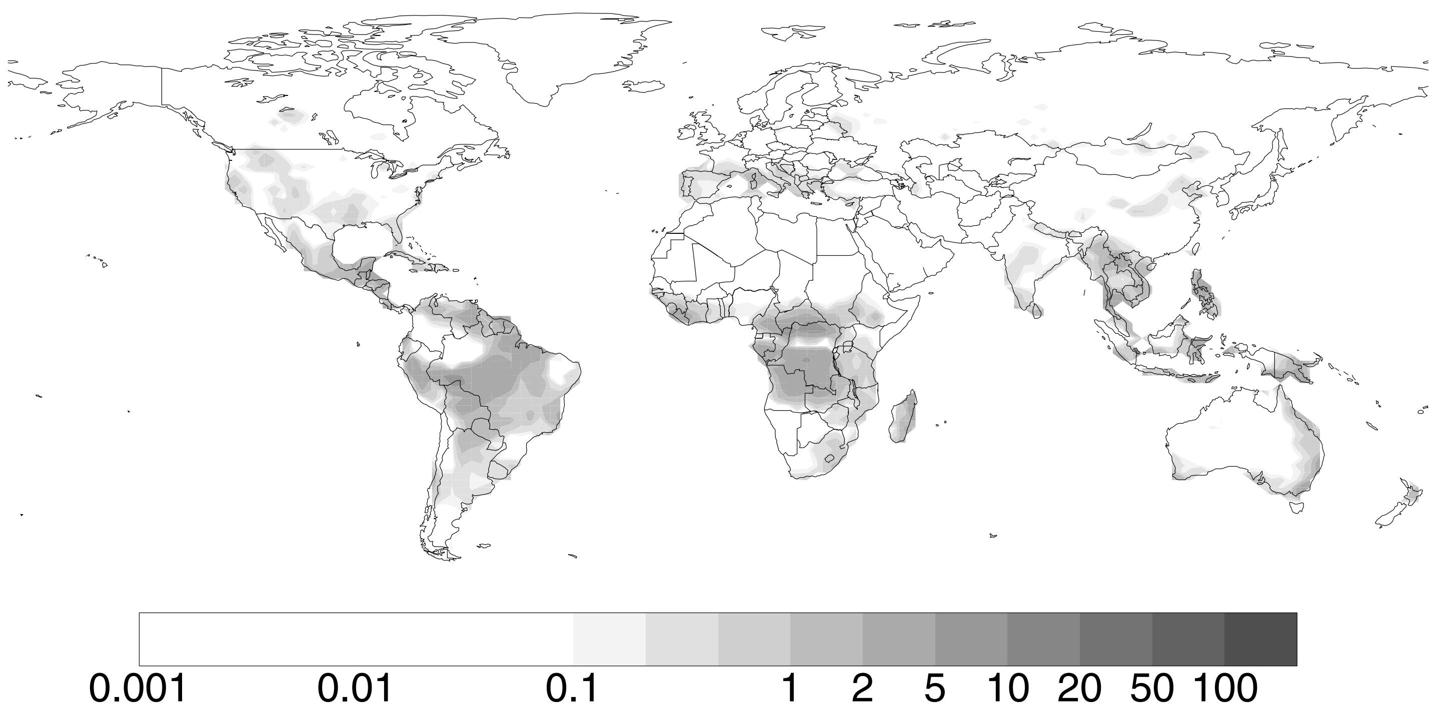
Fires, in turn, control climate in various ways, *e.g.* through the emission of combustion products (greenhouse gases, chemically active trace gases and aerosols) to the atmosphere and changes in surface albedo. As such, fires form a feedback mechanism in the Earth system, which might amplify or dampen climate change.

At present, this feedback is not well understood nor is it represented in current–generation Earth system models used to study climate change. To improve our understanding of the importance of the fire–climate feedback, we will require global modelling approaches that include process-based terrestrial biosphere fire models that account for the climate control over fires [1].

We integrated a process–based fire model into a global vegetation model (CLM–CN; Community Land Model with Carbon and Nitrogen cycle) and simulated the carbon emissions of fires over the 20th century [2]. The process-based fire model accounted for natural wildfires that were induced either by lightning or accidentally by humans. In addition to this, we used land–use–change transition scenarios to include deforestation fires used for land clearing.

We applied the model with time–varying population density, land–use transition, nitrogen deposition, and atmospheric carbon dioxide concentrations for the years 1850 to 2004. Climate input data (such as precipitation, wind speed, and temperature) was prescribed from NCEP/NCAR (National Centers for Environmental Prediction/ National Center for Atmospheric Research) reanalysis data for the years 1948–2004. Before the year 1948, we used a 25–year repeat cycle (1948–1972).

Fig. 1 shows simulated fire emissions averaged over the 1990s. In the model, fire emissions depend on fuel moisture, fuel load,



wind speed and ignition sources. The simulation showed high levels of fire carbon emissions for North America, tropical America, Africa, Southeast Asia, and Australia. A comparison of model results and burned area estimated from satellite products revealed that, overall, the model captured much of the present–day observed spatial distribution and interannual variability. The simulated global annual mean fire carbon emissions for the 1990s of 1.9 Pg (C) yr^{-1} lie within the range of satellite–based estimates. However, when we compared to a range of observationally based estimates we consistently found an overestimation of the simulated fire carbon emission for South America and an underestimation for Africa.

In the 20th century, global fire emissions slightly decreased between the 1960s and 1990s (Fig. 2). The last three decades of the 20th century showed an upward trend in fire carbon emissions. This trend is generally in line with estimates based on sedimentary charcoal records [3] and historical reconstructions making use of published data on land–use practices, qualitative reports, sediment records and tree ring analysis [4].

To disentangle the importance of single driving factors that control the simulated fire carbon emissions, we performed a number of sensitivity experiments keeping single drivers, such as population density or land use, constant at the 1850 value.

These experiments showed that the decreasing trend simulated in the early 20th century was to large parts explained by land–use activities. Land-use change took place partly in the form of deforestation fires in the model. However, this additional fire source was not large enough to compensate for the decrease in natural fire emissions.

This decrease in the number of natural fires was due to land–use change that resulted in less available biomass for burning. The upward trend simulated over the last three decades was climate–controlled; there were increasing fire emissions over large

Figure 1. Simulated mean annual fire emissions averaged over 1990–1999 in g (C) m^{-2} s^{-1} [2]. The contour map is overlaid on a Blue Marble Next generation image (NASA's Earth Observatory, Visible Earth (*http://visibleearth.nasa.gov*).

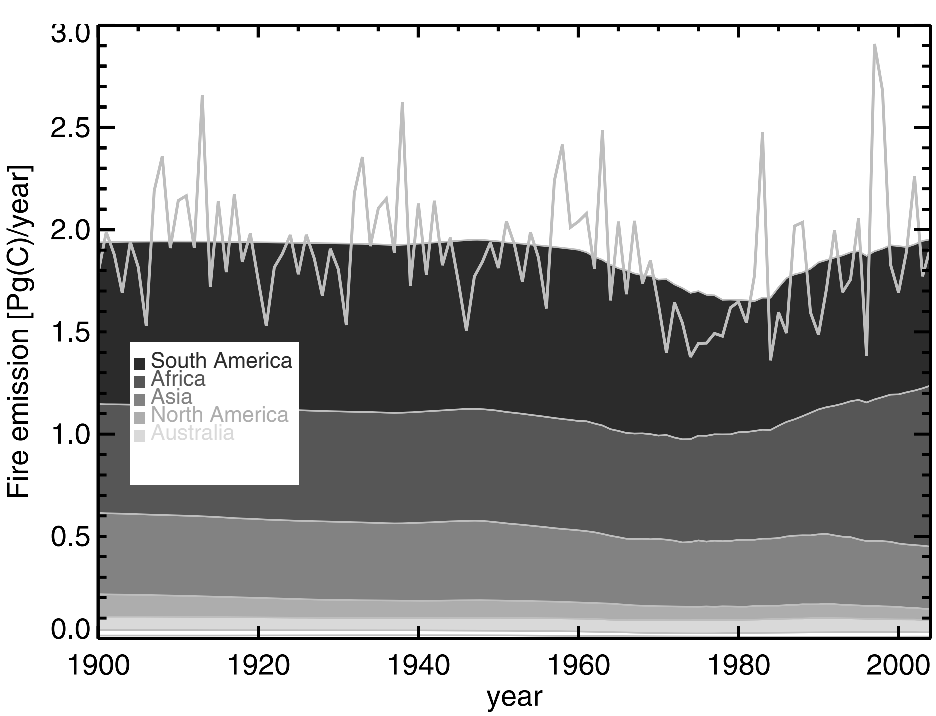


Figure 2. Simulated timeseries and regional contributions of mean fire emissions for different world regions between 1900 and 2004 in Pg (C) yr^{-1} [2]. The gray line represents global annual mean emissions. The contributions from the different regions are smoothed (25-year running mean).

Table 1. Mean annual fire emissions averaged over different decades for selected compounds in Tg (species) yr^{-1}.

portions of Africa and a number of strong El Niño events that caused high fire emissions especially in Equatorial Asia.

We can convert the simulated fire carbon emissions into emissions of chemically active trace gases and aerosols by making use of emission factors that relate the amount of dry matter consumed during a fire to the amount of trace gas emitted for multiple measured species [5]. Table 1 summarises global annual mean emissions of selected trace species from fires for several decades of the 20th century. These emission estimates can be applied in global chemistry and aerosol models to assess the fire climate impact induced by fire emissions.

Previous studies derived fire emission inventories using various parameters, such as land–use [6] or population [7, 8] change, to scale present-day fire emissions back in time. These scaling methods usually result in strong differences between pre–industrial and present–day fire emissions, as, for example, a threefold increase in black carbon (BC) emissions (1.0 to 3.0 Tg (BC) yr^{-1} [8]).

On the contrary, our model simulation results in only a small difference between pre–industrial and present–day fire emissions. Consequently, previous estimates of the anthropogenic fire impact on climate might be exaggerated and should be reconsidered in the future.

This study showed that a process–based fire model is generally capable of producing contemporary observed fire patterns and agrees with the observed trends in fire carbon emissions for the 20th century. However, the main advantage will be that such a model can be fully integrated in an Earth System Model (ESM) framework.

In such a framework, the fire model will respond to simulated changes in climate and at the same time influence the climate. However, the climate impact of fire is inherently complex as fires are a cross–disciplinary process linking the atmosphere, ocean, cryosphere, and land biosphere. To develop a better understanding of the role of fire in the Earth system and the fire–climate feedback will require combined efforts in future interdisciplinary Earth system research.

silvia.kloster@zmaw.de

References

1. Bowman DMJS *et al.* 2009. Fire in the Earth System. Science 324 (481), doi: 10.1126/science.1163886.
2. Kloster S *et al.* 2010. Fire dynamics during the 20th century simulated by the Community Land Model. Biogeosciences Discussions 7, 565–630.
3. Marlon JR *et al.* 2008. Climate and human influence on global biomass burning over the past two millennia. Nature Geoscience 1, doi:10.1038/ngeo313.
4. Mieville A *et al.* 2010. Emissions of gases and particles from biomass burning using satellite data and an historical reconstruction. Atmospheric Environment 44, 1469–1477, doi:10.1016/j.atmosenv.2010.01.011.
5. Andreae MO and Merlet P 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15(4), 955–966.
6. Ito A and Penner JE 2005. Historical emissions of carbonaceous aerosols from biomass and fossil fuel burning for the period 1870–2000. Global Biogeochemical Cycles 19, GB(2028), doi:1029/2004GB002374.
7. Van Aardenne JA *et al.* 2001. A High resolution dataset of historical anthropogenic trace gas emissions for the period 1890–1990. Global Biogeochemical Cycles 15(4), 909–928.
8. Dentener F *et al.* 2006. Emissions of primary aerosol and precursor gases in the years 2000 and 1750 prescribed data–sets for AeroCom. Atmospheric Chemistry and Physics 6, 4321–4344.