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A new look at the role of fire-released moisture on the dynamics of atmospheric pyro-convection

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Short title: ROLE OF FIRE-RELEASED MOISTURE ON PYRO-CONVECTION DYNAMICS

Abstract. We investigate the contribution of the moisture released by wildland fires to the water budget and the convection dynamics of pyro-clouds forming atop of fires. Using an approach based on stoichiometric principles and parcel theory of convection, we assess the relative contribution of sensible heat and latent heat to the convection energy. We find that moisture release is of much lesser importance for the fire convection than the release of sensible heat from the combustion. We conclude from theoretical considerations that it is highly unlikely that the decrease of the cloud base of pyro-cumulus compared to that of ambient free convection is due to the fire-released moisture alone, in contrast to what has been suggested previously.

In addition to the analytical results, numerical simulations of a specific case study are presented. They show that the fire-released moisture accounts only for a small portion of the total water in the pyro-cumulus cloud. Also, the effect of the fire-released moisture on the convection dynamics and the height of injection is found to be small compared to the effect of the sensible heat release from the fire.

1. Introduction

Convection induced by large fires is a very efficient mechanism for the vertical transport of smoke to higher atmospheric layers. Depending on fire intensity and the meteorological conditions in the ambient atmosphere, smoky air parcels ascending above the fire can become saturated in water vapor. The latent heat resulting from the condensation of water vapor results in additional buoyancy and gives rise to substantially enhanced vertical development of convection. Such so-called pyro-cumulus clouds (Glickmann, 2000) are regularly observed for a variety of fire types and geographical locations, such as deforestation fires in the tropics (Reid *et al.*, 1999; Andreae *et al.*, 2004), mid-latitude and boreal forest fires (Radke *et al.*, 1991; Fromm and Servranckx, 2003; Fromm *et al.*, 2005), and under subtropical conditions (Fromm *et al.*, 2006).

Understanding of the dynamics of pyro-convection is highly relevant for both atmospheric research and fire management. It is well known that fire behavior is very sensitive to atmospheric conditions, and, in turn, atmospheric convection triggered by the fire has the potential to influence the fire. Because biomass burning plays a large role in atmospheric chemistry and climate (Crutzen and Andreae, 1990; Penner *et al.*, 1992; Andreae and Merlet, 2001), pyro-convection, as a highly efficient vertical transport mechanism, is of great importance for the spatial distribution of trace gases and aerosol particles emitted from biomass burning.

Recently the role of moisture released by wildfires and its influence on the convection dynamics of fire plumes has gained increased attention. Measurements of water vapor emissions from biomass combustion in the laboratory have indicated a substantial contribution of fuel moisture to the water vapor in fire plumes (Parmar *et al.*, 2008). There are, however, some concerns about this investigation, which are currently under discussion (Yokelson, 2008). In situ field observations from prescribed fires in Texas revealed an increase in the water vapor mixing ratio of 1 to 2.5 $\mathrm{g\,kg^{-1}}$ in the lower levels of fire plumes (about 10 m agl), while no distinct water vapor enhancement was found at 90 m agl (Clements *et al.*, 2006, 2007). Under stable atmospheric conditions the moisture released during the smoldering phase of forest burning has been found to contribute substantially to the atmospheric moisture content, and to potentially impact the location and timing of fog formation (Achtemeier, 2006, 2008).

A paper by Potter (2005) explicitly deals with the role of moisture released by wildfires, and its influence on the convection dynamics of fire plumes. Two hypothesis are stated: First, it is argued that moisture released by the fire can constitute a large portion of the total water content of fire plumes. Second, Potter (2005) hypothesizes that the fire moisture constitutes a dominant contribution to the dynamics, unless fire plumes are too small to result in condensation and cloud formation, or unless the convection is wind-induced.

In the following, we will present a framework to evaluate the potential impact of moisture emissions from vegetation fires on convective pyro-clouds considering the latent and sensible heat fluxes from the fire. The ratio of produced latent heat in the form of water vapor and sensible heat is constrained by the stoichiometric combustion equation, as well as reasonable values of fuel moisture and radiative losses. Based on this consideration, we will argue in the following sections that the combined effect of released moisture and heat from the fire almost always results in a higher cloud base compared to ambient conditions. In Section 3, we present results from numerical simulations and sensitivity studies of the Chisholm fire which confirm the findings from the analytical framework.

2. Theoretical Considerations

2.1. Fluxes of sensible and latent heat

Every combustion process, including the combustion of biomass in wildfires, releases sensible heat in the form of a temperature increase and latent heat in the form of water vapor into the atmosphere. Both fluxes contribute to the development of atmospheric pyro-convection.

There are two terms contributing to the moisture released from vegetation fires: First, the fuel moisture, i.e., the water already contained in the fuel. Second, water vapor that is released as a product of the chemical transformation of carbohydrates during the combustion process. This term is referred to as combustion moisture.

In the combustion equation as formulated by Ward (2001), both terms are represented explicitly:

$$\begin{aligned} &\mathrm{C_6H_9O_4} + \frac{25}{4}\,\mathrm{O_2} + [0.080\,M\,\mathrm{H_2O} + 23.5\,\mathrm{N_2}] \\ &\longrightarrow \frac{9}{2}\,\mathrm{H_2O} + 6\,\mathrm{CO_2} + [0.080\,M\,\mathrm{H_2O} + 23.5\,\mathrm{N_2}] \\ &\qquad + 3.9 \cdot 10^6\ \mathrm{J\ mol^{-1}}, \end{aligned} \tag{1}$$

where M is the wood moisture content in mass percent relative to the dry mass. Here, water from fuel moisture and nitrogen of the air are bracketed, since they are not chemically transformed. This equation somewhat simplifies biomass combustion. Since combustion is typically incomplete, and since biomass fuels contain a variety of components in addition to cellulose ($C_6H_9O_4$), there are further trace compounds emitted by the fire that are not considered in Eq. (1). They are, however, not relevant in the context of this study.

There is significant uncertainty about fuel moistures characteristic under wildfire conditions. The biomass fuel that burns in wildfires consists of many different types, each of which has its own fuel moisture. Living green fuel, such as leaves of needles, have a substantially higher moisture content than dead fuel or branches (Van Wagner, 1987). Especially in boreal regions, the comparatively moist duff can contribute substantially to the biomass that is combusted during a wildfire event (e.g., FIRESCAN, 1996). The fuel moisture of a wildfire is the mass-weighted-average moisture content of the different types of fuel that are combusted during the wildfire. Typically, the fuel moisture in boreal fires is in the 10% range (Potter, 2005). However, when duff and living fuel make up a larger fraction of the combusted biomass, the effective fuel moisture can rise up to 60-80% (BM Wotton, personal communication, January 2007).

Eq. (1) allows us to compare the relative contributions of the production of sensible heat and latent heat in the form of water vapor from the fire. With the molecular weights of water and $C_6H_9O_4$, it yields a total water vapor emission factor (EF) per unit dry fuel mass of $EF_{\mathrm{H_2O}} = (0.56 + 0.01M)\ \mathrm{kg_{H_2O}\ kg_{fuel}^{-1}}$. With the latent heat of vaporization

$L = 2.5 \cdot 10^6 \mathrm{J\ kg}_{\mathrm{H_2O}}^{-1}$ this corresponds to a latent heat production of

$$EF_{\mathrm{LH}} = L \cdot EF_{\mathrm{H_2O}} = (1.4 + 0.025M)\ \mathrm{MJ\ kg}_{\mathrm{fuel}}^{-1}. \tag{2}$$

From Eq. (1), the heat of combustion can be also calculated as

$$EF_{\mathrm{H}} = (20.0 - 0.025M)\ \mathrm{MJ\ kg}_{\mathrm{fuel}}^{-1}, \tag{3}$$

where the subtrahend is introduced to account for the consumption of a certain portion of the combustion energy released by the fire for the vaporization of fuel moisture. For dry to moderately dry fuels, the combustion moisture dominates the fire released moisture. For effective fuel moistures larger than 56%, by contrast, the release of fuel moisture exceeds that of combustion moisture. Typically, wildfires feature fuel moistures of less than 80%. It is important to note that for such conditions, according to Eqs. (2) and (3), total latent heat accounts only for less than 20% of the total fire energy.

Part of the energy produced by the fire is lost to conduction of heat into the ground, heating of unburned fuel, and thermal radiation, hence not all of the heat released becomes available for atmospheric convection. While the conduction of heat into the ground is rather insignificant (Byram, 1959), a substantial fraction of the fire energy is lost by radiative processes. There is significant uncertainty about the radiative losses. Estimates based on laboratory studies and field experiments with small fires range from values close to zero (Wooster, 2002; Wooster *et al.*, 2005) to values as high as 50% (McCarter and Broido, 1965; Packham, 1969).

For the further derivations, it is useful to introduce the perturbation ratio r between temperature increase due to sensible heating, and humidity increase due to released moisture, which is constrained by their respective emission factors:

$$r \equiv \frac{\Delta T}{\Delta q} = \frac{(1-0.01l)\ EF_{\mathrm{H}}}{c_p\ EF_{\mathrm{H_2O}}} = \frac{(1-0.01l)(20.0-0.025M)}{1.005(0.56+0.01M)} \ \left[\mathrm{K\,g^{-1}\,kg}\right], \tag{4}$$

where l is the radiative loss in percent and a value of $c_p = 1005\,\mathrm{J\,kg^{-1}\,K^{-1}}$ was used for the specific heat capacity of air. The perturbation ratio concept relies on two assumptions, which make it possible to derive properties on a macroscale, namely those of air parcels in the smoke column, based on processes on the microscale, i.e. the stoichiometry of combustion. First, it is assumed that radiative cooling and other losses of sensible heat are confined to the region very close to the fire, and second, sensible heat and fire moisture are assumed to dilute at the same rate over the further course of the plume development. The first assumption is justified by the fact that the temperature anomalies above the fire decrease rapidly with increasing altitude (Byram, 1959; Trentmann *et al.*, 2006) and the short timescales of pyro-convection. Typically, the time span needed for an air parcel to travel from ground level at the fire to its level of neutral buoyancy is 10-20 min (Trentmann *et al.*, 2006), while timescales for radiative equilibration in the atmosphere are on the order of days (Thomas and Stamnes, 1999). The second assumption is consistent with observational evidence that the eddy diffusivity for heat and trace gases are equal under neutrally stratified conditions (Stull, 1988). For the complex dynamics present in convection, by contrast, the eddy diffusivity for heat tends to exceed that of trace gases such as water vapor (Deardorff, 1980). This is a key limitation of our approach and requires further study. However, the results of numerical simulations presented in Section 3, which account for the difference between turbulent transport of heat and moisture, suggest that this effect is not important.

The perturbation ratio r as a function of the radiative loss is given in Fig. 1 for three different fuel moistures. For reasonable ranges of fuel moisture (0-80%) and radiative losses (0-50%), the perturbation ratio is in the range of 6.6-35 $\mathrm{K\,g^{-1}\,kg}$. In other words, a humidity increase of 1 $\mathrm{g\,kg^{-1}}$ corresponds to a temperature increase of at least 6.6 K. Since 1 $\mathrm{g\,kg^{-1}}$ of water vapor corresponds to 2.5 K of latent heat, this means also that, even for extreme assumptions on both radiative loss rate (50%) and fuel moisture (80%), the release of sensible heat exceeds that of latent heat by a factor of 2.6.

There are few observational results on temperature and humidity enhancements in fire plumes. Clements *et al.* (2006) conducted measurements of water vapor and heat fluxes from a prescribed grass fire. They report that the fire enhanced the sensible heat flux by 1155 W $\mathrm{m^{-2}}$ while the latent heat flux was increased by 347 W $\mathrm{m^{-2}}$, corresponding to a perturbation ratio of 8.3 $\mathrm{K\,g^{-1}\,kg}$, i.e., at the lower end of our theoretically derived range of values for the perturbation ratio. Achtemeier (2006, 2008) reports very high moisture enhancements for smoldering fires but acknowledges that these are not representative for smoke from flaming fires, when much more air is ventilated through the combustion. It is important to note that, in contrast to our theoretical considerations, observations account not only for the moisture released directly by the fire but also for enhanced moisture fluxes due to drying of soil and unburned material or from open surface water (ponds, lakes, rivers). Clements *et al.* (2006), for instance, conducted the measurements in the morning when significant amounts of moisture might have been released by the soil and vegetation, thus their perturbation ratio probably overestimates the amount of fire moisture released.

The possible values of the perturbation ratio derived from our theoretical approach and the field measurements are substantially larger than the values used by Potter (2005). He employs a perturbation ratio of $1\ \mathrm{K\,g^{-1}\,kg}$ (e.g., an increase in the moisture of $2\,\mathrm{g\,kg^{-1}}$ and a temperature increase of $2\,\mathrm{K}$) to estimate the impact of sensible and latent heat flux on the convective potential of the atmosphere. This assumption significantly exaggerates the role of latent heat compared to that of sensible heat from wildfires and hence renders the conclusions drawn from the quantitative analysis questionable.

2.2. Impact on the condensation level

The lifting condensation level (LCL), i.e., the vertical level at which condensation occurs in a rising plume from a wildfire is important for its subsequent evolution since above it additional energy is released from condensation. The fire influences the LCL in two ways: On the one hand, the increased temperature within the plume tends to result in higher saturation vapor pressures, hence delayed condensation. The released moisture, on the other hand, tends to result in decreased LCL.

This leads to the question of which effect dominates for given parameters such as ambient humidity, temperature and fuel moisture. We can address this issue analytically in terms of parcel theory of convection (Rogers and Yau, 1989). Let us consider the pressure at the LCL, p_{LCL}, for which we can make use of the saturation condition (e.g., Rogers and Yau, 1989)

$$p_{LCL} = \frac{\epsilon\, e_s(T_{LCL})}{q}, \tag{5}$$

where $\epsilon \approx 0.622$ is the ratio between the molar mass of water vapor and that of air, $e_s(T_{LCL})$

the saturation vapor pressure at the parcel temperature at the LCL, and q the air parcel's specific humidity.

Assuming that the air parcel ascends adiabatically from a reference level with pressure p and temperature T we can also make use of

$$T_{LCL} = T \cdot \left(\frac{p_{LCL}}{p}\right)^{\kappa}, \tag{6}$$

where $\kappa \approx 0.286$ is the ratio between the gas constant and specific heat at constant pressure (e.g., Rogers and Yau, 1989).

We can assess the effect of increases of temperature ΔT and humidity Δq by applying a linearization approach to Eq. (5). As described in the Appendix, a functional relationship between the relative change of the pressure lifting condensation level and the temperature and humidity perturbations can be derived from Eqs. (5) and (6):

$$\frac{\Delta p_{LCL}}{p_{LCL}} = \left(\frac{\Delta q}{q} - \frac{L}{R_v T_{LCL}} \frac{\Delta T}{T}\right) \left(\frac{\kappa L}{R_v T_{LCL}} - 1\right)^{-1}. \tag{7}$$

Assuming that the humidity perturbation is proportional to the temperature perturbation according to Eq. (4), we can assess the *combined effect* of temperature and humidity perturbation on the lifting condensation level. Substituting $\Delta q = \Delta T / r$ and rearranging Eq. (7) yields a change in pressure lifting condensation level per unit fire heating of

$$\frac{\Delta p_{LCL}}{\Delta T} = \left(\frac{1}{rq} - \frac{L}{R_v T T_{LCL}}\right) \left(\frac{\kappa L}{R_v T_{LCL}} - 1\right)^{-1} p_{LCL}. \tag{8}$$

A positive value of $\Delta p_{LCL}/\Delta T$ would indicate a decrease in cloud base altitude due to the fire effect, while a negative value would indicate a higher cloud base. Fig. 2 shows

$\Delta p_{LCL}/\Delta T$ as a function of q and r, where reference temperature $T = 300$ K and pressure $p = 1000$ hPa were assumed, T_{LCL} and p_{LCL} were calculated from T and q, and $\Delta q = \Delta T/r$ was used. For temperatures lower than 1500 K and hence for all conditions in ambient tropospheric air, the denominator on the right side of Eq. (8) is positive. The sign of (8) is therefore equal to the right side's numerator's sign. It is positive if and only if the perturbation ratio satisfies the inequality

$$r = \frac{\Delta T}{\Delta q} < \frac{R_v T\, T_{LCL}}{q\, L}. \tag{9}$$

Since the relative variability of q is much greater than that of T, inequality (9) is mostly dependent on specific humidity and r. Fig. 2 shows that $\Delta p_{LCL}/\Delta T$ is only positive for extremely dry conditions $q < 2.5\ \mathrm{g\,kg^{-1}}$ and very low perturbation ratios. For most realistic values of q and r negative values are obtained for $\Delta p_{LCL}/\Delta T$. Thus, the combined effect of released moisture and heat from the fire forcing almost always results in a decrease of p_{LCL}, i.e., a higher cloud base compared to ambient conditions.

There are very few references to cloud bases of pyro-convection relative to ambient convection, and they are inconclusive. While Taylor *et al.* (1973) reports of pyro-convections whose cloud base is 500 m higher than the ambient soundings LCL, Reid *et al.* (1999) report of a tropical pyro-cumulus with a cloud base "only slightly lower than the other clouds in the region". Potter (2005) invokes a case of boreal pyro-convection, the Mack Lake fire (Simard *et al.*, 1983), for which he estimates a cloud base decrease of the pyro-cloud of more than 800 m relative to the LCL of the background atmosphere. It is rather difficult to reconcile this observation with our results. Possibly, the radiosonde profile used by Potter (2005) to determine the LCL of free convection in the background atmosphere is not representative of the conditions at the sit of pyro-cloud observation. The sounding was recorded at 185 km distance from the fire and six hours later, and a possible explanation would be that the atmospheric humidity and temperature profiles at the time and location of the photograph used for the estimate of the cloud base were different than those from the radiosonde. Very intensive pyro-cumulus convection is typically observed to coincide with the passage of synoptic cold fronts (Fromm and Servranckx, 2003; Fromm *et al.*, 2005). As documented by Simard *et al.* (1983), the major run of the Mack Lake fire occurred just before the passage of a dry cold front, hence the temperature and humidity profiles were subject to rapid change.

It is also conceivable that the fire radiation and surface winds induced by the pyro-convection significantly enhance the moisture flux from the soil and other unburned material. This additional moisture is not part of the fire-released moisture, yet it could significantly contribute to the moisture excess in pyro-convection compared to free convection. This effect is not accounted for in the approach presented here nor in Po05. Such convection-induced inflow of additional environmental moisture can also, at least to some extent, explain the observed lowering of the cloud base because it decreases the temperature due to evaporative cooling and increases the humidity of the air flowing into the convective updraft. The effect on convection dynamics, by contrast, is small since the drying of unburned material merely results in a redistribution between sensible and latent heat budgets.

3. Results from Numerical Simulations

In order to study the relative importance of fire heating and fire moisture taking into full consideration the complex effects of turbulence, dilution, convection dynamics and cloud microphysics, it is necessary to perform numerical simulations of the fire plume development. For a specific case study, Luderer *et al.* (2006) present a detailed investigation of the sensitivity of the dynamical development of pyro-convection and subsequent stratospheric injection to various parameters, such as fire emissions of heat and moisture, cloud microphysical effects induced by aerosol particles contained in the smoke, and background meteorology.

Numerical simulations of pyro-convection, performed using the Active Tracer High resolution Atmospheric Model (ATHAM) similar to those given in Trentmann *et al.* (2006) and Luderer *et al.* (2006) are considered here in order to specifically focus on the role of fire moisture in the water budget and the convection dynamics of the fire plume. ATHAM is a cloud-resolving model especially designed for the simulation of the extreme dynamics associated with eruptive events such as volcanic eruptions and fire convections (Oberhuber *et al.*, 1998; Herzog *et al.*, 2003; Trentmann *et al.*, 2002). The Chisholm wildfire, a very large forest fire that burned in Alberta, Canada, in May 2001 (ASRD, 2001), and resulted in injection of smoke into the upper troposphere and lower stratosphere by pyro-convection (Fromm and Servranckx, 2003), is used as a case study. The Chisholm fire is well studied in terms of its fire characteristics (ASRD, 2001) as well as its atmospheric impacts (Fromm and Servranckx, 2003; Trentmann *et al.*, 2006; Luderer *et al.*, 2006, 2007; Rosenfeld *et al.*, 2006). We operated ATHAM in a three-dimensional setup with a model domain of 85 km x 65 km x 26 km and 110 x 85 x 100 grid boxes in the x-, y- and z-directions, respectively. A focusing grid was used with a maximum resolution at the location of the fire with a grid size 500 m along the fire front, 100 m in the direction perpendicular to the fire front, and 50 m in the vertical. The fire is represented as a prescribed forcing with fuel consumption, rate of spread and fuel moisture based on observational values. From these assumption, fluxes of sensible heat, moisture and smoke aerosol are calculated. The total integration time was 40 min. The model setup was equal to that used in Trentmann *et al.* (2006) and is described in detail therein.

Here we present a set of four simulations in order to demonstrate the relative importance of the fire emissions of sensible heat and water vapor. For the reference simulation, H2O/SH50, the water release from the fire was fully considered and the radiative loss was assumed to be 50%, hence only half of the combustion energy becomes available for convection. It is possible to assess the contribution of the fire-released moisture by comparing H2O/SH50 to a second simulation, noH2O/SH50, for which the fire emissions of moisture are set to zero, while the sensible heat release is kept at 50% of the combustion energy. A second pair of simulations, H2O/SH100 and noH2O/SH100, allow us to study the moisture effect under the assumption of zero radiative losses. For the simulations H2O/SH100 and H2O/SH50, we assumed a value of 40% for the fuel moisture content. According to Eq. (4), this corresponds to perturbation ratios of 18 $\mathrm{K\,g^{-1}\,kg}$ for H2O/SH100 and 10 $\mathrm{K\,g^{-1}\,kg}$ for H2O/SH50. Finally, a variant of the noH2O/SH50 simulation was performed. In this experiment, LH2SH, the fire released moisture was set to zero, while the sensible heat flux was augmented by the latent heat flux that would have corresponded to the fire's moisture release. This simulation allows to assess whether energy release in the form of sensible heat or in the form of latent heat is more effective in supporting atmospheric convection. The emissions of sensible heat and moisture assumed for the various model runs are summarized in Table 1.

Based on the model results, the relative contribution of the fire released moisture to the total water (i.e., water vapor and condensed water) within the fire plume can be estimated. Fig. 3 shows a cross section of the ratio between fire moisture and total water obtained for the H2O/SH100 and H2O/SH50 runs. It shows that the water vapor emitted by the fire is rapidly diluted before reaching the condensation level. Within the pyro-cumulus, the fire moisture is small compared to the moisture entrained from the environment. With values of up to 10% in the updraft region, the relative contribution of the fire-released moisture in H2O/SH50 is slightly greater than in H2O/SH100, where the maximum value is 7%. This is due to the enhanced entrainment of environmental air in the more vigorous case of higher sensible heat release.

The vertical aerosol mass distributions for the five cases after 40 min simulation time are depicted in Fig. 4, both as a function of altitude and as a function of potential temperature. From these results, it is evident that the influence of the fire-released moisture is small compared to the influence of the sensible heat released by the fire. Whereas the reduction of the sensible heat flux by 50% results in a decrease in the maximum plume altitude of about 1.5 km, neglecting the fire moisture release results in a decrease of only 200 m between the H2O/SH100 and noH2O/SH100 simulations, and 600 m between the H2O/SH50 and the noH2O/SH50 simulations Fig. 4(a). Hence, the sensible heat release from the fire plays a much more important role for the vertical plume development than the release of latent heat. For the two simulation runs H2O/SH50 and noH2O/SH50, the reduced sensible heat flux corresponds to a radiative loss of 50%. The difference in the plume height between H2O/SH100 and noH2O/SH100 is smaller compared to the decrease between H2O/SH50 and noH2O/SH50. This is due to the fact that the SH100 simulations top out in the tropopause and lower stratosphere. Because of the stable stratification at this level, the incremental energy due to the latent heat from the fire has a smaller effect than in the case of the SH50 simulations, where the clouds top out in the upper troposphere. This becomes evident when the vertical aerosol distribution as a function of potential temperature is considered, a metric that factors out the effect of the background temperature profile: For both the SH50 and the SH100 simulations, the fire-released moisture results in a potential temperature enhancement of about 2 K.

The simulation LH2SH with fire-produced latent heat converted to sensible heat shows a vertical structure of the smoke plume that is very similar to that obtained in the reference simulation H2O/SH50. While the cloud base in the LH2SH experiment is 400 m higher than that in the reference simulation, plume top altitudes are almost equal for both cases. This can be attributed to the lack of fire-released moisture in LH2SH. This result suggests that the vertical dynamics of atmospheric pyro-convection is rather insensitive to the relative distribution of available energy between sensible heat and latent heat. In LH2SH, the decrease of convective destabilization due to the lack of fire-moisture is fully compensated by the additional sensible heat.

The reference simulation H2O/SH50 results in 10% lower aerosol mass at the main outflow level at 7-10 km altitude than LH2SH, while there is somewhat less aerosol mass at sub-anvil altitude levels. Plausible explanations for this result are (1) increased precipitation in H2O/SH50 due to the fire-released moisture resulting in stronger aerosol scavenging, and (2) increased detrainment at low levels compared to LH2SH, where the increased sensible heat release results in a more pronounced updraft core.

For the background atmosphere, the LCL was located at an altitude of 3250 m. The cloud base in the updraft column is at 3900 m for the simulation run H2O/SH50 and at 4200 m for H2O/SH100. Hence, the combined effect of fire heating and moisture release results in a substantial increase in cloud base altitude, rather than a decrease as reported by Po05. The higher cloud base for the case without radiative loss (H2O/SH100) compared to the simulation with 50% radiative loss is consistent with the derivation presented in Section 2.2.

4. Summary and Conclusions

We have presented different approaches to investigate the role of fire-released moisture in the dynamical development of atmospheric pyro-convection. The impact of fire-released moisture on pyro-clouds is found to be much less significant than suggested in previous studies. Specifically, in contrast to Potter (2005) we find that the latent heat production from the fire tends to be small compared to the sensible heating. Moreover, using an analytical model we find that it is highly unlikely that the combined effect of fire-moisture and sensible heating results in a decreased cloud base as reported by Potter (2005).

Based on the stoichiometric release ratio between fire sensible heat and moisture, we conclude that, under all reasonable assumptions for the fuel moisture and the radiative losses, the perturbation ratios (defined as the ratio between the temperature and the moisture increase in the fire plume) must be in the range of 6.6-35 $\mathrm{K\,g^{-1}\,kg}$. These perturbation ratios exceed those used by Potter (2005) by more than a factor of six.

Using an analytical model based on parcel theory, we also assessed the combined effects of fuel moisture and fire heating on the cloud base level. Our results show that the fire moisture has the potential to lower the cloud base level only for a rather unlikely combination of extremely dry background atmosphere ($q < 2.5\,\mathrm{g\,kg^{-1}}$) and a moderate to high fuel moisture content, in conjunction with high radiative losses. For all other cases, the increase in the lifting condensation level due to the heat input from the fire dominates over the decrease due to fire moisture.

Numerical simulations performed for a specific case study with the three-dimensional cloud-resolving model ATHAM also suggest that the role of fire moisture is of rather low significance. For the Chisholm fire, we found that the fire moisture accounts for only about 10% of the total water in the plume, with the remainder of the water originating from the background atmosphere. From sensitivity studies, we conclude that the effect of the moisture release from the fire is small compared to the effect from the fire heating. While reductions of either sensible heat or latent heat result in reduced vertical development, the injection height is rather insensitive to the relative distribution between sensible heat and latent heat. This suggests that the presence of additional sources of moisture, such as soil water or surface water, does not have a large effect on the convection since any enhancement in latent heat is offset by an equivalent reduction of sensible heat for the evaporation. The change in microphysical properties due to the fire-released moisture and changes in detrainment in the updraft region, however, may affect the vertical transport of smoke particles. Our results suggest that the fire-released moisture results in smaller amounts of smoke transported to the upper atmosphere. This issue should be subject to further investigations.

The theoretical derivations presented in Section 2 are based on universal principles, and are therefore generally valid under the assumptions made. The simulations of a specific case study presented in Section 3 additionally support these analytical results based on a complex numerical model fully accounting for entrainment and dilution due to turbulence. Additionally, the model results show that the water budget of the cloud formed by the pyro-convection is strongly dominated by moisture entrained from the environment, while the fire moisture only contributes a small fraction.

In order to further advance our understanding of the different factors contributing to the dynamics of pyro-convection, more observational and modeling efforts are both required. More in-situ or remote sensing measurements of temperature and moisture perturbation in biomass burning plumes would be of great use for the validation of models. There is still large uncertainty about the transfer of energy in the form of radiation. Also, the possible increase of environmental moisture, because of enhanced evaporation due to fire radiation and the surface wind shear induced by the pyro-convection, should be investigated in more detail.

Appendix

In order to assess the respective effects of temperature and humidity perturbations on the lifting condensation level, we can apply a linearization approach

$$\Delta p_{LCL} = \frac{\partial p_{LCL}(T_{LCL}, q)}{\partial q}\,\Delta q \;+\; \frac{\partial p_{LCL}(T_{LCL}, q)}{\partial T_{LCL}}\,\Delta T_{LCL} \tag{A1}$$

to Eq. (5):

$$\Delta p_{LCL} = -\frac{\epsilon\, e_s(T_{LCL})}{q^2}\Delta q + \frac{\epsilon}{q}\frac{\mathrm{d}e_s(T_{LCL})}{\mathrm{d}T_{LCL}}\left(\frac{\partial T_{LCL}}{\partial p_{LCL}}\,\Delta p_{LCL} + \frac{\partial T_{LCL}}{\partial T}\Delta T\right). \tag{A2}$$

Note that T_{LCL} itself is a function of the temperature at the reference level T and the lifting condensation level p_{LCL}, hence both its partial derivatives need to be considered as well. From Eq. (6), they can be calculated as

$$\frac{\partial T_{LCL}}{\partial T} = \left(\frac{p_{LCL}}{p}\right)^{\kappa} = \frac{T_{LCL}}{T} \tag{A3}$$

$$\frac{\partial T_{LCL}}{\partial p_{LCL}} = \frac{\kappa T}{p_{LCL}}\left(\frac{p_{LCL}}{p}\right)^{\kappa} = \kappa\frac{T_{LCL}}{p_{LCL}}. \tag{A4}$$

The differential temperature dependence of the saturation water vapor partial pressure is given by the Clausius-Clapeyron equation (e.g., Rogers and Yau, 1989)

$$\frac{\mathrm{d}e_s(T)}{\mathrm{d}T} = \frac{Le_s}{R_v T^2}, \tag{A5}$$

so we can convert

$$\frac{\epsilon}{q}\frac{\mathrm{d}e_s(T_{LCL})}{\mathrm{d}T_{LCL}} = \frac{\epsilon e_s L}{R_v q T_{LCL}^2} = \frac{p_{LCL}L}{R_v T_{LCL}^2}. \tag{A6}$$

Substituting Eqs. (5), (A6), (A4), and (A3) into Eq. (A2) yields

$$\Delta p_{LCL} = -p_{LCL}\frac{\Delta q}{q} + \frac{p_{LCL}L}{R_v T_{LCL}^2}\left(\kappa\frac{T_{LCL}}{p_{LCL}}\Delta p_{LCL} + \frac{T_{LCL}}{T}\Delta T\right). \tag{A7}$$

Rearranging results then in the form presented in Eq. (7):

$$\frac{\Delta p_{LCL}}{p_{LCL}} = \left(\frac{\Delta q}{q} - \frac{L}{R_v T_{LCL}}\frac{\Delta T}{T}\right)\left(\frac{\kappa L}{R_v T_{LCL}} - 1\right)^{-1}. \tag{A8}$$

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Figure Captions

Figure 1. Ratio between temperature and humidity perturbation as a function of radiative loss for different values of fuel moisture M.

Figure 2. Sensitivity of p_{LCL} to the combined effects of released moisture and fire heating. Contours show $\Delta p_{LCL}/\Delta T$ in hPa/K as a function of perturbation ratio r=$\Delta T/\Delta q$ and specific humidity.

Figure 3. Relative contribution of the fire-released moisture to the total water content simulated for the Chisholm fire plume for the assumptions that (a) 100% of the fire energy becomes available for convection or (b) 50% becomes available for convection. The black solid lines indicate isolines of aerosol concentration. Partially adopted from Trentmann *et al.* (2006).

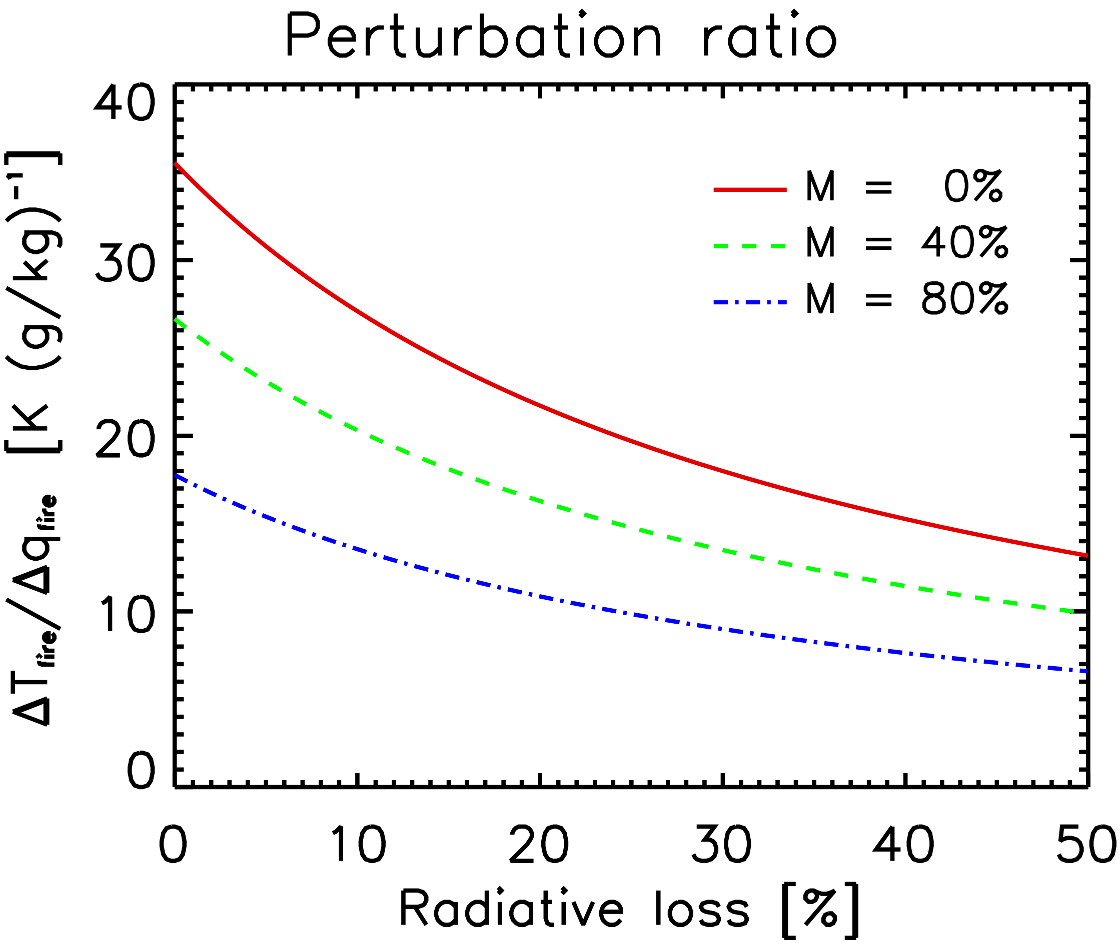
Figure 4. Vertical distribution of aerosol mass (a) as a function of altitude and (b) as a function of potential temperature for four numerical simulations of the Chisholm pyroCb with varying assumptions on the release of fire moisture and sensible heat.

Tables

Simulation run	Heat 10^6 W m^{-1}	Moisture kg (m s)$^{-1}$	Latent Heat 10^6 W m^{-1}
H2O/SH100	239	12.2	30.5
noH2O/SH100	239	0.	0.
H2O/SH50	119	12.2	30.5
noH2O/SH50	119	0.	0.
LH2SH	149.5	0.	0.

Table 1. Values of fire emissions of sensible heat and moisture, as well as corresponding latent heat fluxes assumed in the numerical experiments.

Figures



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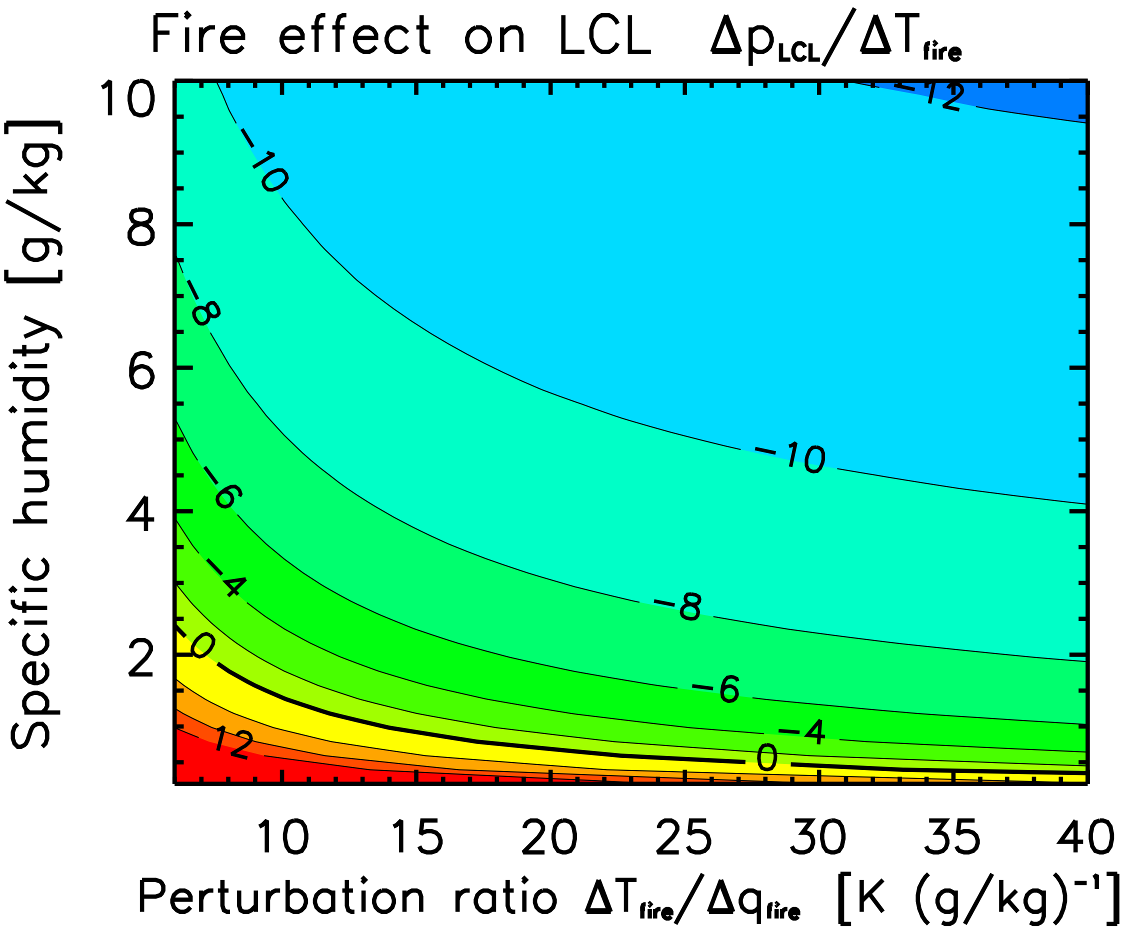

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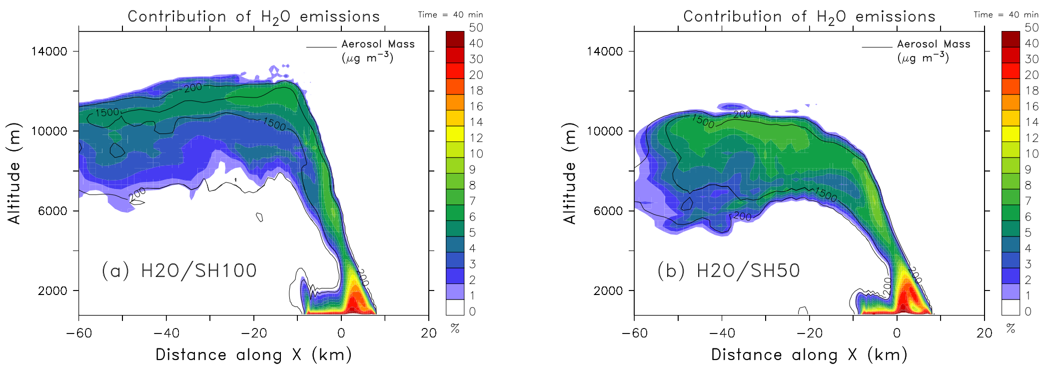

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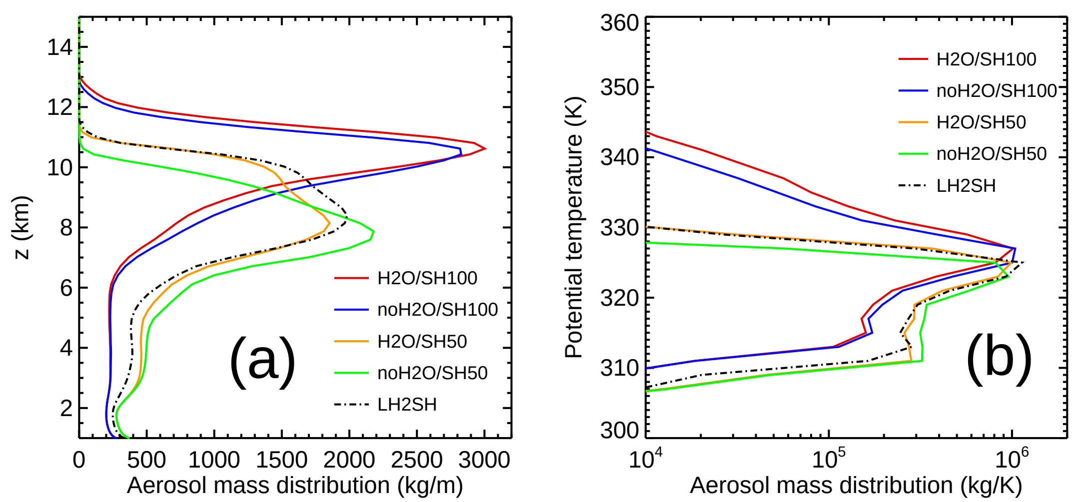

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