Author's comments to anonymous Referee #1

The authors would like to thank the reviewer for the time spent on the manuscript and for providing comments and helpful suggestions. We have considered all comments carefully. Please find our detailed reply (italic) on the comments made below.

- I understand from the title that the conceptual model is tested in the paper rather than developed. Where has the conceptual model been developed originally? Perhaps this could be stated more clearly.

The conceptual model has been developed based on published studies, which found mineral dust particles within smoke plumes and/or suggested that fires should be considered as a source of mineral dust. Building on this, we framed the model and applied LES to test it. In order to address the reviewer's concern we clarified this in the paper.

- There seems to be an important difference between the schematic shown in Fig. 1 and the results of the LES experiments: In the LES experiments, the increased wind speeds (and increased turbulence) occur downwind from the fire while in the figure, the "intensive turbulence" is depicted upwind/behind of the fire (also described in the text in See also the p. 3 l.20-27). This difference is critical, because – if the fire moves with the wind as is suggested in the Figure and text – the areas with high winds downwind of the fire might still be covered by vegetation, as the fire has not passed these areas. In that case, the vegetation cover might prevent particle entrainment. The same applies to areas with high winds further to the side (the "vortex trail", Sec. 5, Fig. 8). I think it is important to discuss this in more detail or to highlight that the paper focuses solely on the aerodynamic aspects of the dust emission potential of wildfires, while the surface conditions remain undiscussed.

Thanks for pointing this out. Yes, it is correct that the outcomes of this study are slightly different from what the conceptual model is postulating – in particular regarding the location of the region of the highest wind speeds. The zone of convergence forms actually in front of the fire (downwind of the fire), however, the increased horizontal winds (as well as the increased turbulence) triggered by the fire updraft and the resulting confluence are also present within and upstream of the fire area. To illustrate this in a clearer way, we have replaced Figure 8 (former Fig. 7). The new figure shows PDFs calculated additionally for the direct fire area. A comparison between the fire-related impacts on the near-surface winds between the fire area and the boxes A-C is given in Table 2 using the relative fractions of exceedance of a horizontal threshold velocity. Soil conditions suitable for aeolian erosion and thus entrainment of mineral dust into the atmosphere can be expected as at least within the fire area a partly or complete removal of vegetation can be assumed. Additionally, we decided to adapt Fig. 1 in a way, which corresponds more with our approach and the results. However, the schematic remains an idealized picture of the real processes.

- On page 2, lines 23-27, the authors state that fire can affect the physical and chemical soil properties and conclude that this leads to "enhanced dust emission potential". How exactly does fire affect soil mineralogy, texture, and grain-size distribution? I could imagine that there are effects that enhance and others that reduce the dust emission potential and that the effect is not as clear as suggested. This relates to my previous comment about a more detailed discussion on the surface conditions.

It is correct that the surface conditions during and also after a fire event are an important aspect especially regarding to the dust emission potential and that lots of different effects play

a role, e.g., how the fire affects the soil conditions and finally the erodibility of the soil. However, most of the results presented in the literature suggest that the impacts of the fire on the soil surface increase the soil's vulnerability to dust mobilization. Since the impacts of the fire on the surface are important for the conclusion drawn from our findings, we have included a more detailed discussion concerning the fire impacts and its impacts on dust emission.

- I have the impression that there is a confusion of concepts regarding dust emission in the paper. It is not clear which process the authors assume to cause dust emission in the context of wildfires – sandblasting (saltation bombardment) or direct aerodynamic uplift. In Section 1.2, the authors give "threshold values for dust emission" (I suggest "threshold values of wind speed needed for dust emission to occur" or comparable), a concept that is usually applied for saltation rather than direct entrainment. Then in Section 5, particle settling velocities are estimated for particles ranging from small clay to large sand-particles to investigate whether such particles would remain suspended once entrained, suggesting that direct entrainment is the process considered. Otherwise, the settling-velocity criterion would not be needed, because the larger particles could also entrain dust through impaction on the surface if the fire-related vertical velocities are too weak to overcome the particles' settling velocities. Clarification is needed on the processes considered as well as on their relevance given the turbulent conditions around the fire and the (unknown) surface conditions. As a side note, Section 1.2 does not seems to be well embedded between Sections 1.1 and 1.3 and the transition to Sec. 1.3 is somewhat abrupt.

Thanks for pointing this out. We agree with the reviewer's point of view. The processes, which might play a role in fire-related dust emissions, were not well clarified. Especially in presence of the fire-induced turbulence the direct aerodynamic uplift seems to play a non-negligible role. However, also the saltation bombardment contributes to the total dust emission flux – in particular in areas where the wind field is predominantly influenced by the enhanced horizontal wind velocities rather than only by the turbulent updrafts. To address the reviewer's comment, we have now included a more detailed description of both processes in the introduction part of the paper. We further have revised the discussion part accordingly. The transition between the single parts of the introduction has been smoothed, too.

- It is not clear to me why the authors use wind speed to estimate the dust emission potential and not friction velocity. Friction velocity is directly related to surface drag, which is what drives particle entrainment, and is normally available from model simulations. In that case, the threshold friction velocity could be determined using a physics-based relationship (e.g. Shao and Lu, 2000) and there would be no need to use an empirical wind speed threshold. Depending on the vertical wind shear, the use of friction velocity could lead to different results regarding the areas of potential emission.

As we use ideal surface conditions that are constant in time and space here, we decided to estimate the potential for wind erosion via the surface wind speed. For cases representing real surface conditions (i.e. vegetation cover), indeed, the dust emission flux will be calculated using the wind friction velocity, which is dependent on the surface wind speed and the roughness.

- The passage from p. 4 L. 1 to p.5 line 10 seems more general and introductory compared to the previous paragraphs that describe the fire-processes that could potentially cause dust emissions. I would suggest to restructure this part and to move the mentioned passage to an earlier positions.

Thanks for your suggestion. We have restructured the paragraph to ensure a more logical order.

- General comments: Figure/results are discussed in great detail in the paper, which is good. Sometimes, however, this seems to lead to a repetition of aspects, e.g. increasing turbulence though the fire plume leading to peaks in wind speed etc. I believe it would be beneficial to go through the paper with a special emphasis on conciseness of the presentation.

Thanks for pointing this out. The manuscript was shortened where possible and appropriate.

- P. 8 l. 30-31: "Zones of strong convergence along with an acceleration of the horizontal wind" – the text and figure suggests that there is directional convergence and speed divergence, which would be "confluence" rather than "convergence".

Changed to "confluence".

- P. 10, l. 23: The weakening of horizontal wind speed with distance from the fire does not seem to occur between Box A and B. Can you comment on that?

The weakening occurs here only on the lowest model levels, whereas at higher levels (actual level depends on the mean ambient wind velocity) the weak horizontal winds are increased because of the downstream transport of fire-generated momentum respective turbulence and a downstream tilt of the fire updraft zone. Although the momentum is first mainly related to an upward motion, the subsequent generation of turbulent vortices leads also to an increase of the horizontal wind components. We have clarified this in the corresponding paragraph.

- P. 11 PDFs: I understand that the PDFs are calculated using different numbers of time steps. Does this effect the results?

Indeed. We have adapted the number of timesteps used for the calculation of the PDFs. The idea behind that is that the fire-induced turbulence needs some time to get transported downstream and with increasing distance to the fire area, the air masses remain longer uninfluenced. While the fire impacts on the wind in and around the fire area (e.g., box A) instantaneously, it takes some time until the areas further downstream (boxes B and C) become affected. Therefore, the number of time steps was reduced with increasing distance to the fire area. A consideration of all time steps since fire ignition would consequently reduce the fraction of time steps with wind speeds above the threshold especially in the "remote" box C.

- P. 12, l. 28: The numbers given here are specific to the case and should therefore not be given in such a general statement.

Removed.

- P. 18, L. 3-6: In my opinion, this paragraph contains several statements that are too strong. First, "This study gives a first introduction into the dust emission process during wildfires" should in my opinion rather be "This study investigates the potential of wildfires to created aerodynamic forces strong enough to emit dust" or similar. Second, "Further quantification" should be changed to "Quantification" given that no quantification has been done yet. Finally, while I understand that the estimation of fire-related dust emissions on continental and even

global scale and the study of their impacts are the eventual goal, I believe that it is a long way until then and that a study at local/regional scale would be the next step. The goal of an inclusion in large-scale models can (and should) be kept as a motivation, but I would suggest in a more moderate/realistic way.

Thanks for your suggestions. We agree, the statement reads very ambitious. We have rewritten the paragraph and explained possible applications of our findings in a more detailed way underlining the potential of the process and the results obtained from this study.

Minor comments (please see also annotated supplementary pdf for grammar and typos):

Many thanks for your very helpful corrections, which we have all taken into account.

- At several locations in the paper, the authors state that the numerical experiments are designed to "prove" the conceptual model. I believe this should be reworded to "test", because the outcome of an experiment should be open.

Changed to "test".

- P. 5 l. 15: It is stated that LES allows for "detailed process studies without interfering influences from the surrounding like topography or large-scale synoptic systems". While this might be beneficial on the one hand, it is unrealistic on the other hand. I suggest rephrasing this as "detailed process studies in an idealized setup, i.e. without effect such as topography or larger-scale synoptic systems".

Done. Thanks for your suggestion.

- In p. 5 l. 21 – 24: The authors contrast their approach/model to others like the WRF-Fire model, which can be used to study fire spreading and therefore includes an atmosphere-fire feedback. In the last sentence, it is explained that only the effect of fire on the atmosphere is considered in the present study (and not vice versa) and that therefore no atmosphere-fire feedback needs to be considered. The last part, however, is not currently mentioned, but should be added in my opinion and not left to the reader to conclude.

Thanks for pointing that out. We have rewritten and clarified these sentences.

- In my opinion, it would be better if Fig. 2 was true to scale.

Many thanks for this comment. We have carefully considered it, however, we have decided to keep the figure in its present form as the most relevant part of the analysis takes place within the first 1.3 km of the model domain so that this area should be represented more prominently compared to the rest of the model domain.

- If possible, it would be great to include a more meaningful labeling of each case in Figs. 3-5 and 8-11 that allows the reader to recognize the important aspect of each case like high-wind, large-file, etc. more easily than through comparison to Table 1.

Thanks for the suggestion. We have included a new labelling of the cases as follows:

old name	new name	description
case 0	NO-FIRE	control run (no fire)

case 1	WEAK-WIND	weaker ambient wind conditions
case 2	REF-CASE	Reference case (moderate wind conditions, averaged fire properties)
case 3	STRONG-WIND	stronger ambient wind conditions
case 4	WEAK-FIRE	less intense fire
case 5	STRONG-FIRE	more intense fire
case 6	SMALL-FIRE	smaller fire area
case 7	LARGE-FIRE	larger fire area
case 8	ORTHO-FIRE	perpendicular orientated line fire
case 9	PARA-FIRE	parallel orientated line fire

- Abstract: " – raised by strong turbulent winds related to the fire." I believe that this cannot be determined for sure and that the sentence should therefore read "- likely raised. . ."

Changed to "most likely raised".

- P. 4, l. 26: "such supergiant particles were present in all of the investigated fire sites". Is it clear that the large constituents were "particles" rather than ash? For ash, the size is not as surprising, is it?

The cited publication (Radke, 1991) claims for particles but does not distinguish explicitly between soil remains and ash. However, also other studies have found coarse-mode particles with sizes of some hundreds of nanometers up to one millimeter from crustal/soil origin within smoke plumes. Nevertheless, we reword the paragraph.

- P. 4 l. 35: "particle formation"?

Changed to "particle aging processes".

- P. 5 l. 30: atmospheric profiles of which quantities are specified?

I guess, P.6 l.30 was meant here. The initial profile consists of information on pressure, temperature, and humidity. We have included the information in the text.

- I suggest using "orthogonal" rather than "northerly", "southerly", etc. in the context of LES, as there is no need for the x-direction to be pointing toward the east.

Changed.

- While it is stated in the text that the fire temperatures listed in Table 1 correspond to the specified hear flux and do not directly translate into air temperatures, I recommend to also add a not in Table 1 explaining this.

We have decided to not show the additional temperature information in the table and explain the connection between heat flux and corresponding temperature only within the text.

- P. 8, l. 30: "small vortices" rather than "small turbulent eddies" to avoid confusion with small (diffusive) and large (energy-containing) eddies boundary-layer turbulence and large-eddy simulation.

Changed.

- P. 9 l. 4: "and causes strong turbulence around the area of the heated air" – I am not sure what is meant here. Perhaps downward mixing?

We clarified the sentence to "accompanied with downward mixing and a reallocation of the typical non-fire PBL structures."

- P. 10, l. 31: "quickly turn to the normal non-fire behavior" – not clear in the context, can you reword this?

We decided to remove the whole sentence.

- P. 10, l. 34: "horizontally longer present" – suggest rephrasing.

The sentence was changed to: "Thus, the atmospheric patterns are vertically less impacted but the faster downstream transport of the fire-generated turbulence impacts on a much larger area in flow direction."

- P. 12, l. 3-18: The discussion seems to be very long. Perhaps this can be shortened.

Done. The paragraph was shortened and adapted to the new Fig. 7 (PDFs of the fire area).

- P. 16 l. 2: What size is meant by super-micrometer particles?

We mean coarse-mode particles in general. We have clarified this.

Author's comments to anonymous Referee #2

The authors would like to thank the reviewer for the time spent on the manuscript and for providing constructive comments and suggestions. We have considered all comments carefully. Please find our detailed reply (italic) on the comments made below.

1) The aim of the paper is unclear, beyond demonstrating that a significant heat flux applied over a specific region does create localized convergence. This is a known fact, which has been shown already in the literature. The authors should be more specific and clear on what the objective and novelty of their research is. While the authors present systematic description of the differences among the 9 cases, there is no specific findings besides "bigger and more intense fires will lead to stronger convergence and therefore larger velocities at the surface".

The aim of our paper is to show and to test the conceptual model describing how mineral dust particles can be mobilized and raised by fire-driven wind regimes and finally be injected into the atmosphere by the fire updrafts. Therefore, a detailed understanding of the fire impacts on the near-surface wind pattern is necessary because the near-surface winds are inevitable for particle mobilisation. To estimate the dust emission potential of typical grass-/shrubland fires and eventually the amount of dust emitted, the impacts of different fire setups have to be tested too.
In order to address the reviewer's concerns, we have strengthened the discussion and conclusion section aiming at highlighting the ability of wildfires to modulate the near-surface winds in a way stimulating dust particle mobilization and entrainment into the atmosphere. Hence, findings from this study contribute to the efforts on improving estimates on atmospheric aerosol loads and their feedbacks.

2) The focus of the analysis seems to be on the near-surface velocities (and probabilities of exceedance of a certain threshold). While this is one aspect, the problem is more fundamentally governed by turbulent processes, so there are other magnitudes that should be incorporated to the analysis. For example the authors should look at vertical fluxes of horizontal momentum, and potential temperature, as well as turbulent kinetic energy. At the end, dust mobilization is tied to turbulent mixing, since there are not going to be steady uniform horizontal and vertical components to mobilize the dust. In that regard, it is expected that enhanced TKE regions will highly correlate with the results presented in Fig. 10.

We have predominately focussed on the near-surface wind velocities, since this quantity is crucial for the mobilization and emission of mineral dust particles – the main focus of the paper as mentioned in more detail above. TKE was indirectly taken into account since the turbulence finally governs the increased horizontal and vertical wind velocity near the surface. To address the reviewer's concern we now show vertical profiles of maximum TKE values for all case simulations (new Fig. 7).

3) The authors attribute the more efficient penetration of the heat plume into the free atmosphere to the ambient wind conditions, and they in all cases find the fire propagating above the ABL irrespective of the strength of the imposed heat flux. This is likely to be also influenced by the strength of the stabilizing capping inversion. The authors should at least acknowledge this aspect and include information about their setup (currently missing). In fact, there are many real fires in which the plume remains within the ABL.

Thanks for pointing this out. We are aware that lots of the "real" fire plumes do not penetrate into the free atmosphere (see also the given references in Section 1.3) and that the likelihood that and how deep a fire plume penetrates into the free atmosphere depends on several

factors like fire properties as well as the current state of the atmosphere/ABL. We have rewritten the concerning paragraphs and weakened the statement in order to make clear that we discuss specific model results. We further highlight that the main focus of this study is on dust particle mobilization potential near the surface. To support this, we have removed Fig. 11 dealing with updraft strengths from the paper and have shortened the discussion thereon significantly.

4) Introduction is excessively long. 1.1 can be removed, as well as most of 1.3 (first long paragraph). It is a nice review of related matters, but not really pertinent to the specific research carried out by the authors.

We have decided to provide the reader with a quite detailed introduction including a substantial review of the relevant studies as dust emission related to wild fires is often not considered. This applies all the more since the topic addresses aspects of quite different research communities (dust research as well as fire research) so that a comprehensive introduction part seems to be needed. However, we went carefully through the introduction part and shortened where it was possible and appropriated.

Minor/specific comments

1. Page 1, line 6: "highly".

Changed to "high-resolution".

2. Page 3, line 9: "rapidly".

Changed.

3. Page 3, lines 9-10: ABL typically presents shear. It would be perhaps more correct to say: "possible increasing wind shear".

Changed.

4. Page 3, line 20: "partial".

The concerning paragraph was removed during rewriting.

5. Page 4, lines 1-30: This paragraph is too long and not specifically related to the work presented herein. It should be significantly shorten and focused into what is relevant to the paper.

Thanks for your suggestion, which we have considered carefully. However, we have the opinion that a detailed review of the important studies dealing with dust emissions related to wildfires should be given, although they are often related to a broader context (see also other comments to major comment #4). Nevertheless, we went through the paragraph and removed/shortened some details which we considered as redundant.

6. Page 6, line 20: If the code is fully compressible, this should be more like 0.02 s. Also, what do you mean by "initial"? Is it adaptive time scheme?

Thanks for pointing this out. The word "initial" was a typo and is now corrected. For our simulations, we used a split-explicit Runge-Kutta scheme, where the sound wave part is

integrated with a smaller time step satisfying the CFL constraint for the sound speed. Applying the CFL criterion and using the highest occurring (updraft) wind velocity of 28.5 m/s (STRONG-FIRE case) in our simulations, we obtain with a spatial resolution of $\Delta x=\Delta y=\Delta z$ of 10 m and the time step of $\Delta t = 0.2$ s a maximum CFL number of $c = 0.57$, which is still below the threshold of 1.

7. Page 7, line 10: How is wind at 10 m specified? Is it through a geostrophic forcing? Please explain. It would be good to include the geostrophic wind speed so the reader can have a better understanding about the strangth of winds above the ABL (as well as within the rest of the ABL). Also, including ABL height in the table would be useful.

Thank you for your hint. We applied a time-height independent u-wind of 3 m/s („ambient mean wind velocity" in the text) as initial condition. Since this should represent the geostophic forcing and not the 10 m wind speed, we accordingly changed the labeling to u_g instead of u_{10m}. Vertical profiles of horizontal and vertical wind for selected areas of the domain are shown in Fig. 6. Additionally, we have now included a more detailed discussion of the "undisturbed" NO-FIRE simulation concerning the structure of the atmosphere and the height of the ABL before we discuss the fire impacts on the wind fields. Vertical profiles of the TKE, and temperature are now shown (new Fig. 5b). Since the ambient conditions are similar for all other simulations but case 1 and 3 for which the ambient wind velocity is different, we think it is sufficient enough to provide the information on the ABL height exemplarily for the NO-FIRE simulation which is the baseline for all fire simulations.

8. Page 9, lines 2-4:
The authors do not discuss the potential temperature distribution of the incoming ABL (in particular strength of capping inversion). This will have a strong impact on whether the fire-generated updraft can reach the free troposphere. The authors should include this information and incorporate to the analysis/conclusions sections of the manuscript.

Thanks for the suggestion. As suggested, we included a profile of the potential temperature and the TKE of the NO-FIRE simulation to give a more detailed overview of the structure of the ABL and their capping inversion. It is correct that the state of the ABL has a strong impact on whether the fire plume and the fire-induced turbulence can reach the free troposphere or not. However, the main focus of our study lies in the ability of fire-driven winds to mobilize dust particles from the surface and not in the injection of particles into the free troposphere. Because of that, we do not describe the upper ABL atmospheric conditions excessively. To clarify this, we went through the manuscript and revisited our statements on particle entrainment into the free troposphere to present more strongly the limitation of our findings from this idealized model approach.

9. Page 9, line 35: "perpendicularly".

Thanks. However, the concerning paragraph was removed during rewriting.

10. Page 11, lines 3-4: "spreading" may not be the best word to use. It can be confused with "fire spread", which is not the case here. Please find a better word.

Changed to "distribution".

11. Page 11, line 4: "near-surface".

Changed.

12. Page 11, line 18:
Is that the right quantity? Vertical wind or TKE will likely be better estimates of dust mobilization at the surface.

To our knowledge, the horizontal wind velocity is the appropriate quantity here and a very commonly used measure for identifying the threshold for dust mobilisation and finally the dust emission potential. There exist lots of studies (e.g., Bagnold, 1941; Marticorena and Bergametti, 1995; Kok et al., 2012), which explain and highlight the horizontal component of the wind vector (parallel to the surface) as the main driver for the mobilization of dust particles at the surface – in particular via saltation. It is correct that under turbulent conditions also a direct entrainment of dust particles into the atmosphere can take place where the vertical component plays a more important role. This is taken into account via the calculations of areas where suitable vertical velocities occur (Table 3 and Figure 9). Additionally, we include a more detailed explanation of the different dust emission processes in the introduction part of the paper and mention the processes involved explicitly during the discussion of the results.

13. Page 11, line 28: Is this the expected behavior in the surface layer where structures are going to be predominantly anisotropic?

The PDFs shown in Fig.7 consider only the horizontal wind velocity and no information is given concerning the wind direction.

14. Page 11, line 34: Last 2 lines in page 11 should either go with previous or following paragraph, not as a stand-alone paragraph.

The paragraph is shifted to the following paragraph.

15. Page 13, lines 15-20: Any explanation/speculation of why that happens?

We contemplate that the long perpendicular (in y-direction, perpendicular to the mean ambient wind velocity) extent of the fire line leads to a much broader area of fire-induced turbulence behind the fire line. Although the total impact concerning the peak values is smaller compared to the rectangular fire setup, the long fire line preclude/impede a mixing of the fire-induced atmospheric pattern with uninfluenced non-fire flow, which means that the fire-induced patterns are much longer present in x-direction before a weakening and mixing of the impacts takes place. Thus, the creation of higher wind velocities is downstream of the fire area much stronger impacted then in fire area itself. We have included an explanation in the paper.

16. Page 13, lines 26-27: Horizontal component, correct? This is clarified layer in the discussion but it should be explicitly mentioned when reference to the threshold velocity is first made.

Yes, the horizontal component. We have clarified the sentence.

Wildfires as a source of airborne mineral dust – Revisiting a conceptual model using Large-Eddy ~~simulations~~ simulation (LES)

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Abstract.

Airborne mineral dust is a key player in the Earth system and shows manifold ~~of~~ impacts on atmospheric properties such as the radiation budget and cloud micro-physics. Investigations of smoke plumes originating from wildfires found significant fractions of mineral dust within these plumes - most likely raised by strong turbulent ~~winds related to the fire. The present study revisits the~~ fire-related winds. This study presents and revisits a conceptual model describing the emission of mineral dust particles during wildfires~~by pyro-convection as described by the literature~~. This is achieved by means of ~~high resolved~~ high-resolution Large-Eddy ~~simulations~~ simulation (LES), conducted with the All Scale Atmospheric Model (ASAM). The impact of (a) different fire properties representing ~~typical~~ idealized grassland and shrubland fires, ~~and different ambient atmospheric conditions on the fire-driven winds and their~~ (b) different ambient wind conditions modulated by the fire's energy flux, and (c) the wind's capability to mobilize mineral dust particles were investigated. Results from this study illustrate that the energy release of the fire leads to a ~~strong increase in strength and frequency of occurrence of intense~~ significant increase in near-surface ~~winds, which exceed typical threshold velocities inevitably required for dust emissions. The fire-induced modulations of the wind field can be transported up to some kilometers downstream of~~ wind speed, which consequently enhances the dust uplift potential. This is in particular the case within the fire area ~~and are able to favor dust emissions also in some distance to the fire area.~~ where vegetation can be assumed to be widely removed and uncovered soil is prone to wind erosion. The dust uplift potential is very sensitive to fire properties, such as fire size, shape, and intensity, but also depends on the ambient wind velocity. Although measurements showed already the importance of wildfires ~~on~~ for dust emissions, pyro-convection is so far neglected as a dust emission process in atmosphere-aerosol models. The results presented in this study can be seen as the first step towards a systematic parameterization representing the connection between typical fire properties and related dust emissions~~, which eventually can be implemented in larger-scale aerosol models ultimately contributing to the reduction of uncertainties in the aerosol-climate feedback.~~.

1 Introduction

1.1 Occurrence and characteristics of wildfires

Biomass burning and other types of natural and prescribed wildland fires (in the following referred to altogether as wildfires) are ~~a very common phenomenon~~ very common in semi-arid regions almost all over the world. In particular, tropical savan-
nas, shrublands, grasslands, croplands, and rain forests are frequently burned ecosystems during dry seasons or under drought conditions (e.g., Gatebe et al., 2014; Roberts et al., 2009). ~~This includes for example the Sahel zone in Northern Africa, the savannas in Southern Africa, the Amazons region, and Indonesia to name some hotspot regions. But also in other areas of the world, like North American and Siberian forests, and agricultural lands in south-eastern Europe, fires are quite often present. The burning regime differs significantly depending on local politics and climatic conditions as well as on the dominant land cover class, which determines the available combustion material and the dissemination of fires in general. The~~ The overwhelm-
ing majority of these fires are caused by human activity ~~like~~ such as fire clearing of natural landscapes for agriculture and domestic uses ~~, especially popular in developing countries with a less intense agriculture. The fraction of natural fires (e.g., due to lightening) is mostly insignificant compared to the anthropogenic caused (Haywood et al., 2008) .~~ (Haywood et al., 2008) .

The vulnerability of a landscape ~~for~~ to wildfires in general and the destructiveness of fires depend strongly on the local climatic conditions and predominant weather regimes. A necessary condition for the development of a fire is the availability of a sufficient amount of biofuel (biomass). The higher the fuel load, the stronger a fire can develop. Grassland and shrubland fires are usually smaller in size and intensity compared to forest fires, ~~whereas~~ where the typical forest vegetation provides a higher fuel load~~and finally~~, resulting in a higher energy consumption by the fire ~~occurs~~ (Reid et al., 2005). Although a greener and denser vegetation may provide more biofuel, the higher moisture content ~~going along with dense and green vegetation~~ counteracts the fire risk. Compared to this, dried vegetation provides a lower fuel load~~,~~; however, it is much more vulnerable for fire ignition~~and results into a faster fire spreading than a green and thus more humid vegetation. This leads to the strong contrast between bio-productivity building up a stock of biomass during wet seasons and the fire activity during dry seasons. For example, the North African savannas show a high fire activity during the dry season, whereas the number of fires during the wet season is usually small. Concerning the Sahel, ? suggest a decline in number and size of fires as a consequence of a transfer towards more capital-intensive agriculture and efforts to improve local air quality. In other parts of the world, an increase in fire frequency, size, and destructiveness of wildfires was observed due to increasing drought conditions, or changes in vegetation cover and land use (Chalbot et al., 2013; ?) .~~ .

Wildfires have large impacts on the environment via altering ~~atmospheric and ground~~ of atmospheric and surface properties. The heat of the fire and the corresponding fire updraft ~~represent~~ result in a major disturbance in the tropospheric wind and tem-
perature fields ~~, which can lead in extreme cases to a total reversal of the current weather regime culminating for example in the formation of pyro-cumulunimbus clouds from convective fire updrafts (e.g., ?) . Furthermore, the~~ (Clements et al., 2008) . Furthermore, fires impact strongly the surface properties in the fire-affected area~~. This leads to an increase in the vulnerability~~, which can change the vulnerability of that area to wind erosion ~~also after a fireevent, since the heat of the fire removes the vegetation cover effectively and also modifies the physical and chemical soil properties like soil moisture content,~~ during and

after the fire. The fire consumes the vegetation cover quite effectively, however, the completeness of the removal depends also on the fire intensity. Especially in the case of low-intensity fires, trees and shrubs can resist the fire whereas the ground-covering plants and organic matter are usually completely removed (e.g., McNabb and Swanson, 1990; Levin et al., 2012) . Other effects of fires on soil surfaces which were observed during prescribed and natural fires include mineralogy, texture, ~~and~~ porosity,

5   grain size distribution~~(Chalbot et al., 2013; Albalasmeh et al., 2013; Merino-Martín et al., 2014) . This again could result in an enhanced dust emission potential during and after a fire event, especially in already semi-arid regions.~~, and water capability of the soils (e.g., Atanassova and Doerr , 2011; McNabb and Swanson, 1990; Pérez-Cabello et al., 2006) . In the case of high-intensity fires an aggregation of finer particles such as clay minerals to larger particles such as silt and sand was found (Giovannini et al., 2001; McNa In contrast, also during such high-intensity fires a breakdown of soil structures and crusts was observed, which would increase

10 the number of particles available for mobilization (McNabb and Swanson, 1990; Levin et al., 2012) . Thus, it appears that fires can lead to quite effective conditions for the mobilization of soil and dust particles. The higher vulnerability of burned landscapes to dust emission was also found by other studies (e.g., Whickler et al., 2002, 2006; Ravi et al., 2012; Merino-Martín et al., 2014 suggesting this as a possible important source of airborne mineral dust.

1.2   Emission of mineral dust

15 The emission of mineral dust into the atmosphere is primarily a wind-driven process and can be considered as a threshold problem ~~(Marticorena and Bergametti, 1995)~~ (e.g., Marticorena and Bergametti, 1995) . To uplift dust particles from the ground and entrain them into the atmosphere, the internal cohesive forces and binding energies between the soil particles as well as gravitation forces have to be ~~broken~~ overcome by the energy supplied by the wind drag ~~(Kok et al., 2012)~~ (e.g., Kok et al., 2012; Bagnold, 1 The amount of energy necessary to mobilize soil particles depends on parameters such as soil moisture, soil texture, grain size,

20 and vegetation cover ~~(Shao, 2001) .~~ (e.g., Shao, 2001) . Consequently, a threshold wind speed has to be exceeded in order to set particles into motion.

However, there are different modes of dust entrainment into the atmosphere. The most common approach is the so-called saltation process, which can be considered as a quite important and relatively well-established approach for in particular strong dust emission events. Here, the wind drag mobilizes first particles with a size of around 70 μm, resulting in a "jumping" along

25 the surface. This enables even smaller partciles ($< 70 \mu$m) to get entrained into the atmosphere (suspension). Supported by wind tunnel experiments and field measurements, typical threshold values of wind speed needed for dust emission to occur lie in the range between 6 and 7 m s^{-1} ~~(Kalma et al., 1988) .~~ (e.g., Kalma et al., 1988; Gilette, 1978) . Despite the dust entrainment via saltation, also other processes can be relevant for dust injection into the atmosphere. This involves direct aerodynamic lifting via turbulent eddies, which can be an important mechanism especially under weak ambient wind conditions as well as in the case of

30 micro-scale emission phenomena (Klose and Shao, 2012, 2013) . Here, the convective turbulent lifting of dust can occur also under conditions where the horizontal wind velocities are too small to initialize saltation (Loosmore and Hunt, 2000) . Using Large-Eddy Simulation (LES), Klose and Shao (2013) showed that turbulent dust emissions are enhanced along convergence lines with updrafts, within downdraft areas, and in vortices. As these are typical features observed in fire-induced wind fields, turbulent dust emission is likely to contribute to fire-driven dust emissions.

1.3 Dust emissions related to wildfires

~~Wildfires can effectively disturb the~~ As already stated, fire impacts on the soil/surface conditions and the lower tropospheric circulation ~~and have a strong impact on near-surface wind patterns related to a~~ can lead to conditions which are favorable for dust emissions. Thus, it is not surprising that several studies found enhanced fractions of mineral dust particles or rather enhanced concentrations of typical soil tracer species within smoke plumes originating from different fire types in different areas of the world (e.g., Nisantzi et al., 2014; Kavouras et al., 2012; Diapouli et al., 2014; Maudlin et al., 2015; Alves et al., 2010; Pio et al., 2008). For example, Nisantzi et al. (2014) found dust fractions in the smoke plumes varying between 50 % for fresh plumes with an age of approximately one day and 10 % for aged plumes with an atmospheric lifetime greater than four days. The corresponding mass fraction varies between 25 % (aged plumes) and 80 % (fresh plumes), which is mainly related to coarse-mode dust particles (particle diameter > 500 nm, which are removed during the atmospheric transport of the plume due to gravitational settling. A dominance of coarse-mode dust particles was also found by ground-based in-situ measurements near fire locations (Gaudichet et al., 1995; Maenhaut et al., 1996). Both studies found a significant increase in the concentration and the mean size of typical mineral dust elements and soil particles, mostly clay and some feldspar minerals in a size range of several micrometers in fire-related samples compared to non-fire background samples. By investigating prescribed fires in desert regions in the Western U.S., Kavouras et al. (2012) found that more than 10 % of the PM10 fire emissions can be linked to a resuspension of soil particles related to the high turbulent fire winds. The strongly increased turbulence ~~around the fire with the formation of vertical and horizontal vortices (Clements et al., 2008). Figure 1 illustrates the~~ and wind velocities in and nearby the fire as a source of uplifted soil and dust particles was already highlighted by Palmer (1981) and Susott et al. (1991), which are able to raise even supergiant particles with a size up to 1 mm and larger consisting of ash and soil remains (Radke, 1991).

The high fire activity in arid and semi-arid regions can lead to an amount of fire-related dust emission, which could be significant on a global scale (Kavouras et al., 2012). Schlosser et al. (2017) investigated the aerosol composition of western U.S. wildfires plumes and found significantly enhanced levels of fine soil components and coarse mode dust particles from crustal origin within these plumes. An exemplary model simulation, performed with a global aerosol model, could not capture the increased dust emission during the fires since these models were not designed to resolve the small-scale processes responsible for dust uptake in wildfires.

Based on these findings, we have developed a conceptual model of ~~mineral dust particle entrainment via~~ the entrainment of mineral dust particles into the atmosphere via the pyro-convective updraft ~~.~~ as illustrated in Fig. 1. The fire radiative energy released by the combustion of the vegetation heats strongly the near-surface air layers. The heated air begins to ~~raise following the fluid dynamics of warmer air within a cooler surrounding~~ rise and eventually a ~~strong~~ convective updraft forms. This upward motion ~~results in a~~ can result in a significant pressure drop of ~~the order of~~ up to 1 hPa at the surface within or near the fire center (Clements et al., 2008). Subsequently, a zone of strong convergence forms and surrounding air flows towards the fire replacing the ~~raising~~ rising air. Since the ascent of the heated air above the fire area occurs quite ~~rapid~~ rapidly, a strong acceleration of the horizontal near-surface winds into the fire updraft region establishes, accompanied by significantly increased turbulence, enhanced vortices and ~~possibly forming~~ possible increasing wind shear within the boundary layer (Chalbot et

al., 2013; Clements et al., 2008). Together with the ~~de-vegetation~~ removal of vegetation during the burning process and the accompanied dehydration and modification of the soil~~surface~~, the resulting accelerated horizontal winds and the increased level of atmospheric turbulence ~~are~~ appears to be able to mobilize soil and dust particles~~for wind speeds exceeding the local threshold for dust mobilization.~~. Depending on the acting buoyancy forces balancing the particles gravitation, the mobilized dust particles

5 may reside in the atmosphere long enough to be ~~caught up by turbulent updrafts~~ further lifted up by the updraft motion and may mix with the combustion aerosols. Depending on the strength of the updrafts and the atmospheric background conditions, the dust particles may be injected into ~~the free atmosphere~~ higher atmospheric levels also above the planetary boundary layer (PBL). Reaching the free atmosphere, long-distance transport of the particles by the general atmospheric circulation ~~is possible~~ can become possible accompanied with increased impacts on the atmospheric properties (Amiridis et al., 2010; Nisantzi et al.,

10 2014; Ansmann et al., 2009). However, Veira et al. (2015) showed that up to 50 % of the fire plumes remain in the PBL and do not reach the free atmosphere.

~~The process of dust mobilization during the fire is supported by an at least partly removal of the protecting vegetation cover in the burning area. Since the fire usually moves towards the unconsumed fuel, it leaves an area of more or less bare soil behind. There, the turbulent and by the fire accelerated winds can raise efficiently soil particles due to a reduction of the local roughness~~

15 ~~length. As bare soil is more susceptible for wind erosion than vegetated soil the required threshold velocity is lower there. An~~ Despite the mobilization of dust particles from the ground, an additional source for dust particles emitted during wildfires are dust particles deposited on the vegetation during previous dust ~~storms~~events. This aspect may apply to wild fires occurring in desert margin regions ~~like~~ such as the Sahel. During combustion, these particles can be mixed directly into the heated updraft and ~~contributed~~ contribute to the dust load of the smoke plume (Paris et al., 2010; Cachier et al., 1995).

20 The strength and efficiency of dust entrainment during wildfires depend on several aspects, ~~in~~ of which fire properties, soil conditions and the state of the atmosphere ~~are~~ appear to be the most important. The fire properties ~~like~~ such as fire size, shape, intensity, and spreading rate determine the strength of the heated updraft and consequently the strength of convergence, the triggered turbulence around the fire, and finally the strength of the accelerated horizontal winds and its gustiness. ~~However, the strength of the convective updraft determines also the plume injection height, which is most relevant for long-range transport~~

25 ~~of the injected particles, their atmospheric residence time, and their impacts on the atmospheric properties such as stability and dynamics, radiation budget, and cloud and precipitation forming processes.~~

~~Several studies have proven that enhanced fractions of mineral dust particles respective enhanced concentrations of typical soil tracer species were found in numerous smoke plumes originating from different fire types such as grassland and forest fires in different areas of the world (e.g., Nisantzi et al., 2014; Kavouras et al., 2012; Diapouli et al., 2014; Maudlin et al., 2015; Alves et al., 20~~

30 ~~Nisantzi et al. (2014) used a polarization lidar located in Limassol (Cyprus) to investigate the properties of smoke plumes originating from biomass burning activity in Turkey and agriculture related fires in the region north of the Black Sea. Using the depolarization rate of the back-scattered laser light, they were able to distinguish between spherical shaped smoke particles (e.g., soot) and irregular shaped dust particles. They found dust fractions in the smoke plumes varying between 50% for fresh plumes with an age of approximately one day and 10% for aged plumes with an atmospheric lifetime greater than~~

35 ~~four days. The corresponding mass fraction even varies between 25% (aged plumes) and 80% (fresh plumes). This is mainly~~

related to coarse-mode dust particles, which were removed during the atmospheric transport of the plume due to gravitational settlement. The dominance of coarse-mode dust particles was also found with ground-based in-situ measurements near fire locations (Gaudichet et al., 1995; Maenhaut et al., 1996). Maenhaut et al. (1996) analyzed the composition of fire-influenced particle samples in the Kruger National Park (South Africa) with "unpolluted" background samples and found a significant

5   increase in the concentration and the mean size of typical mineral dust elements like aluminum (Al), silicon (Si), titanium (Ti), and iron (Fe) compared to the non-fire samples. The study of Gaudichet et al. (1995) points in a similar direction. By analyzing aerosol particles emitted during prescribed savanna fires in Ivory Coast, a high amount of soil particles, mostly clay and some feldspar minerals in a size range of several micrometer were found. The concentration of these soil-related minerals (Al, Ti, Fe) in fire plumes was again higher compared to background conditions with only residuals of dust particles originating from

10 desert dust storms, suggesting that the savanna fires mobilize dust particles at the fire place or/and lead to a re-entrainment of dust particles from remote areas due to the forced upward motion above the fire area. By investigating prescribed fires in desert regions in the Western U.S., Kavouras et al. (2012) found that more than 10% of the PM10 fire emissions can be linked to a resuspension of soil particles related to the high turbulent fire winds. Palmer (1981) already investigated the dynamics of prescribed experimental fires and highlighted the importance of the high fire-related winds in the combustion area as a source

15 of lifted soil and dust particles. Furthermore, Radke (1991) investigated smoke plumes from prescribed and natural U.S. forest fires using airborne measurements and found particles with a size up to 1mm and larger consisting of ash and soil remains. Despite changes in the concentration, such supergiant particles were present in all of the investigated fire sites. This underlines the importance of savanna fires as a mobilizer of dust particles, related to the high turbulence and strongly increased wind velocities in and near the fire (Susott et al., 1991). Kavouras et al. (2012) pointed that the absolute amount of dust-related

20 emission in arid regions during fire events can be significant on a global scale, since such fires are always connected with high wind velocities and have the potential to emit mineral dust particles.

Although Although some studies indicate the importance of such wildfires to the atmospheric dust load, the process of the dust uplift during such fire events is not well quantified understood so far and currently not considered as a source of airborne mineral dust in climate or aerosol models. This is all the more astonishing since the mixture of raised dust particles with fresh

25 combustion aerosol like such as soot or black carbon can lead to changes in the chemical, optical, and microphysical properties of the dust particles. This has would have impacts on the particle formation aging processes, the dust-radiative forcing, the suitability of dust particles to act as an Ice Nuclei Particle Ice Nuclei Particles (INP) or as a Cloud Condensation Nuclei (CCN), which finally influence atmospheric residence time and microphysical properties of clouds and is related to health hazards (e.g., Chalbot et al., 2013; Hand et al., 2010; McCluskey et al., 2014; Levin et al., 1996; Winton et al., 2016). Such

30 mixtures of mineral dust and biomass burning aerosol are often observed in outflows of African air masses towards the Atlantic especially in mid-tropospheric levels (e.g., Johnson et al., 2008), whereby the origin of the dust particles is not always clear and mixtures of dust and smoke can occur also during the transport (Haywood et al., 2008). Schlosser et al. (2017) investigated the aerosol composition of western U.S. wildfires plumes and found significantly enhanced levels of fine soil components and coarse mode dust particles from crustal origin within these plumes. An exemplary model simulation, done with a global

35 aerosol model, could not capture the increased dust emission during the fires since these models were not designed to resolve

~~the small-scale processes responsible for dust uptake in wildfires (Schlosser et al., 2017) . Therefore, a better understanding of~~ ~~the processes is necessary to include the dust emission mechanism in aerosol models.~~

1.4 Usage of Large-Eddy ~~simulations~~ simulation (LES) to resolve fire dynamics

~~Motivated by Schlosser et al. (2017) , this study aims to revisit the~~ This study aims at revisiting the above introduced (cf.
5 Sec. 1.3 and Fig. 1) conceptual model of mineral dust particle entrainment during fire events. To achieve this, models with a high spatial and temporal resolution are essential ~~since~~ to describe the acting forces and ~~processes leading to~~ small-scale processes responsible for fire-related dust emissions ~~occurring on very small spatial scales~~(Schlosser et al., 2017) . A suitable ~~and commonly used tool are~~ tool is Large-Eddy ~~simulations~~ simulation (LES), which ~~are~~ is able to resolve turbulent ~~motions~~ ~~within the atmosphere and allow~~ atmospheric motions and allows for detailed process studies ~~without interfering influences~~
10 ~~from the surrounding like topography or large-scale synoptic systems. Therefore, LES are useful to prove hypothesis and~~ ~~highlight particular~~ in an idealized setup, to test hypotheses and investigate connections between small-scale effects.

In this context, LES ~~are~~ is commonly used to simulate fire behaviors in different fields of application. Most of these ~~high-resolved~~ high-resolution model studies aim ~~to understand~~ at understanding the spread of wildfires as a function of fuel consumption and ambient atmospheric forces to allow for a better prediction of the fire spreading, ~~primary to support the~~
15 ~~extinguishing strategies of~~ primarily to support strategies to extinguish and limit the fires (e.g., Sun et al., 2009; Mell et al., 2008; Morvan et al., 2009; Cunningham and Linn, 2007; Linn and Cunningham, 2005). In these cases a feedback ~~of a~~ between fire and atmosphere within the model is necessary, which takes into account the complex interaction between the fire behavior, the burning vegetation (availability of biofuel), and its environment as ~~for example~~ is done in the WRF-Fire model (Coen et al., 2013) for example. However, this study ~~investigates~~ aims at investigating the impacts of ~~a fire~~ fire-induced disturbance on
20 the near-surface wind fields and consequent potential for dust mobilization ~~.~~ only, which allows a reduced complexity applied in this first approach. This means that only fire effects on the atmosphere but not the feedback of the atmosphere on the fire needs to be considered.

This paper is structured as follows: Section 2 describes the general model setup and the application to the fire simulations. Section 3 deals with the performed case studies and their ~~representativity~~ representativeness for real wildfires. In Section 4,
25 the results are presented; this means in particular the impacts of the fires on the near-surface wind dynamics for different ~~cases~~ case simulations are shown and compared to each other. Section 5 discusses the results in a broader context with respect to the dust emission potential. The conclusion closes the paper.

2 Fire simulations with the All Scale Atmospheric Model (ASAM)

The All Scale Atmospheric Model (ASAM; Jähn et al., 2015, 2016) is a numerical solver developed at the Leibniz Institute for
30 Tropospheric Research (TROPOS), in Leipzig, Germany. ASAM can be used for atmospheric applications over a wide range of scales. It solves the three-dimensional, fully compressible Euler equations. Different time integration schemes are available, e.g., a split-explicit Runge-Kutta scheme (Knoth and Wensch, 2014) or an implicit Rosenbrock-type method. In the present

study, ASAM is deployed as a LES model, where part of the turbulent motion is resolved directly and the remaining part is parameterized by a subgrid-scale model.

As this study focuses on the fundamental understanding of the acting processes in order to test the basic conceptual model of fire-driven dust emissions, the complexity of the study design is kept low. To simulate the impacts of wildfires on the wind patterns, ASAM was set up as follows: the fire itself is assumed to be stationary and represented by a constant flux of sensible heat as a measure for the fire intensity following the assumption of an ideal blackbody. This approach omits the feedback mechanism from the atmosphere acting on the fire development, which for example would drive the fire spreading and fuel consumption. The fire heat source was specified as a lower boundary condition of the model as it is typical for grassland and shrubland fires.

The horizontal extent of the model domain was set to 6.4×1.2 km^2. This size ensures that the fire-induced atmospheric dynamics can develop undisturbed within the model domain and are not influenced by boundary effects. The longer extent in x-direction is aligned with the mean flow direction. The atmospheric flow was initialized in the x-direction (u-component of the wind) only, whereas in the y-direction only turbulent fluctuations of the wind occur. A schematic plot of the x-y-plane of the model domain is given in Fig. 2. The fire area is located 100 m away from the inflow boundary and centered in the y-direction. Using periodic boundary conditions, valuable for the formation of a turbulent PBL, the position of the fire area would be in principle unimportant. The top of the model domain is set to 4,000 m with a damping layer at the upper 200 m, which allows for an undisturbed spreading of the fire-related updraft. The horizontal grid spacing was set to 10 m, the vertical grid spacing was set to 10 m from ground-level to 1,000 m altitude, to 20 m for 1,000 to 2,000 km altitude, and to 40 m for altitudes above 2,000 km. Using an explicit Runge-Kutta scheme, the model time step was set to 0.2 s.

To investigate the impacts of the fire on the near-surface winds as realistically as possible, the fire was ignited already in a turbulent PBL as suggested by the model study of Sun et al. (2009), who found that the usage of a time-averaged wind within the PBL does not map the fire properties and the interaction with the atmosphere in such a correct way, as a more realistic turbulent PBL does. The formation of such a turbulent PBL requires a spin-up time of the model while the turbulent nature of the PBL can develop. After forcing initial perturbation of the temperature field of 0.2 K, two hours later it can be guaranteed that a well-mixed and representative PBL with a largely constant depth has developed, so that the fire could be initialized. Due to the periodic boundary conditions, the simulations were stopped at the time when the fire-influenced atmospheric field transported downstream by the ambient air flow reaches the end of the model domain or at latest 40 min after fire ignition. Thus, in total each simulation covers 2 h 40 min.

Since the occurrence of fires peaks in semi-arid regions, a typical Sahelian dry-season atmospheric profile consisting of pressure, temperature, and humidity fields, one of the global fire hotspots, was representatively used. This profile was compiled using model outputs of the meso-scale model COSMO-MUSCAT (Tegen et al., 2013; Wagner et al., 2016) by averaging the wintertime atmospheric fields 2007/08 of the Sahel region.

In order to further elaborate the impact of the fire on the wind fields at different distances to the fire, three equally sized (84,000 m^2) areas (boxes A, B, and C) located at different distances to the fire area were defined and illustrated in Fig. 2. Each box has a size of 84,000 m^2. Box A covers the fire area and its surroundings with an extent of 240×350 m^2, Box B is shifted

slightly downstream to $x = 400\,\mathrm{m}$ and has an extent of $120 \times 700\,\mathrm{m}^2$, whereas Box C is located $1{,}000\,\mathrm{m}$ downwind from the fire area at $x = 1{,}200\,\mathrm{m}$ and covers an area of $70 \times 1{,}200\,\mathrm{m}^2$.

3 Sensitivity studies of different controlling factors

To ~~prove~~ test the conceptual model of dust ~~emission~~ emissions related to wildfires in general and to investigate the influence of possible ~~fire-related~~ controlling factors, sensitivity studies with different input parameters were conducted. The main focus lies on the variation of the fire properties and the ambient wind velocity as ~~the probably~~ probably the most important factors influencing the fire-related wind ~~pattern~~ patterns. Additionally, a non-fire simulation (~~case 0~~NO-FIRE) with an undisturbed non-fire PBL was performed as a reference. An overview of all performed case studies is given in Table 1. If not affected by the chosen setup (see Table 1), the following parameters were kept constant for all other case simulations:

(1) roughness length: ~~$z_0 = 0.1$~~$z_0 = 0.1\,\mathrm{m}$
(2) ambient mean wind velocity: ~~$|u_{10\mathrm{m}}| = 3$~~$|u_g| = 3\,\mathrm{m\,s^{-1}}$
(3) fire sensible heat flux: ~~$F_{\mathrm{fire}} = 150$~~$F_{\mathrm{fire}} = 150\,\mathrm{kW\,m^{-2}}$
(4) fire size: $A_{\mathrm{fire}} =$ ~~70~~70×100 ~~x m$^2 = 7{,}000$~~ $100\,\mathrm{m}^2 = 7{,}000\,\mathrm{m}^2$
(5) fire shape: rectangular

The roughness length was set to 0.1 m as a typical mean value for grassland and shrubland dominated landscapes, the primarily burned vegetation classes (Roberts et al., 2009; Gatebe et al., 2014). The average wind velocity of ~~$u_{10\mathrm{m}} = 3$~~$u_g = 3\,\mathrm{m\,s^{-1}}$ was chosen ~~,~~ since this value represents a well-balanced equivalent to typical atmospheric conditions and within a range often reported as background wind conditions during wildfires (e.g., Coen et al., 2004; Clements et al., 2007; Clark et al., 1999; Frankman et al., 2013; Lareau and Clements, 2017). To cover a broader range and investigate the impacts of different ambient wind velocities on fire-related dust emission potential also weaker (~~$u_{10\mathrm{m}}$~~u_g = $1\,\mathrm{m\,s^{-1}}$, ~~case 1~~WEAK-WIND simulation) and stronger (~~$u_{10\mathrm{m}} = 5$~~$u_g = 5\,\mathrm{m\,s^{-1}}$, ~~case 3~~STRONG-WIND) ambient wind conditions were simulated. The ambient wind was forced with a logarithmic wind profile only in x-direction, so that due to the turbulent nature of the simulated PBL, the values of the ambient wind velocity represent the mean wind velocities in x-direction before fire ignition. The average wind speed in y-direction is around zero due to a compensation of positive ~~(northern) and negative (southern)~~ and negative orthogonal fluctuations.

In order to investigate the influence of different fire properties on the fire-related wind fields as broadly as possible, the fire intensity, size, and shape were modified. One of the main fire ~~quantities~~ characteristics is the fire intensity, expressed by a flux of sensible heat released by the fuel consumption. Values reported in the literature vary quite substantially in orders of magnitude depending on the fuel type, the atmospheric conditions, and fire behaviors as well as the measuring procedure and are in a range of $8\,\mathrm{kW\,m^{-2}}$ to $3\,\mathrm{MW\,m^{-2}}$ (Lareau and Clements, 2017), whereby the intensity is usually increasing from small grassland fires to stronger forest (crown) fires (Frankman et al., 2013). ~~Peak fluctuations of the heat flux can reach in heavy~~

~~crown fires values of up to 11MWm^{-2} (Coen et al., 2004)~~. In general, the heat fluxes within one fire can fluctuate strongly, making it difficult to link one fire type with an exact corresponding heat flux. But nevertheless some representative scenarios can be applied. Since the focus of this study lies on grassland and shrubland fires, corresponding to the fire types heat fluxes of 75 kW m^{-2} (~~case 4~~WEAK-FIRE), 150 kW m^{-2} (~~standard value, case 2~~REF-CASE), and 270 kW m^{-2} (~~case 5~~STRONG-FIRE) were chosen. These heat fluxes represent typical values for a weaker grassland fire, moderate and more intense shrubland fires (Frankman et al., 2013; Clements et al., 2007; Lareau and Clements, 2017). The corresponding fire radiative temperatures (assuming a perfect blackbody with an emissivity of 1) are approximately 800, 1,000 or 1,200 °C, respectively. Since the fire is only represented by a heat flux from the surface, the fire temperatures are not directly reflected in the same order of magnitude in the near-surface air temperature fields.

The fire size does not correspond directly to any ~~physical~~ physically determined fire properties and can vary by orders of magnitude from case to case. Therefore, the values here are more or less randomly set and will only represent the impacts of differently large fire areas. Originating from the standard fire size of 7,000 m^2 (~~case 2~~REF-CASE), a smaller (~~40x60~~$40 \times 60 = 1,800$ ~~=1,800~~m^2, ~~case 6~~SMALL-FIRE) and a larger (~~90x130~~$90 \times 130 = 11,700$ ~~=11,700~~m^2, ~~case 7~~LARGE-FIRE) fire area were simulated.

Additionally, the fire shape was investigated using two line fires of the same size but with a length of 350 m and a width of only 20 m. Their only difference is the orientation of the fire line with respect to the mean flow direction; one fire is orientated ~~perpendicular (case 8~~orthogonal (ORTHO-FIRE), the other one parallel to the wind direction (~~case 9~~PARA-FIRE). The line fire setup was chosen since prescribed grassland fires are often ignited in a line and such fires will most probably interact in a different way with the atmospheric dynamics. Thus, in total 9 different ~~model setups were investigated .~~ fire setups are investigated (cf. Tab. 1 for a summary).

4   Results – impacts of fires on the wind fields

In the following section the impacts of the fires on the near-surface wind ~~pattern~~ patterns and some other atmospheric properties will be analyzed and the importance ~~on the dust emission potential will be characterized. First, a~~ of different influencing parameters characterized. However, before focusing on the fire impacts, the NO-FIRE simulation as the baseline for the majority of the fire setups will be described. To support this, Fig. 3 shows a vertical cross section of the turbulent kinetic energy (TKE) as well as averaged TKE and temperature profiles. The structure of the simulated atmospheric behavior can be clearly observed. A well-mixed PBL with a mean potential temperature of 302 K and a depth of 860 m has developed. Above this height, the free troposphere with a widely laminar low indicated by very low TKE values is present.

Now, a representative overview of the fire-influenced ~~near-surface wind pattern~~ wind patterns around the fire center is given for all case simulations 20 minutes after fire ignition. Therefore, Fig. 4 presents horizontal cross sections of the x-y-plane for the lowest model level ($z = 5$ ~~z = 5~~ m) and vertical cross sections of the x-z-plane through the center of the fire ($y = 600$ ~~y = 600~~ m) are presented in Fig. 5. Beside the wind vectors also the air temperature fields are shown in order to indicate the position of the simulated fire and highlight the fire updraft~~region, respectively~~. Focusing on the horizontal cross sections (Fig. 4), the fire areas are clearly visible as zones of strongly enhanced temperatures, a consequence of the intense flux of sensible heat warming

the near-surface air layers. Here, 5 m above ground level, air temperatures are increased by up to more than 150 K compared to the ambient conditions. Variations in the size and extent of the fire areas between the different simulation setups become obvious. They are related to differences in the original fire size (SMALL/LARGE-FIRE, Fig. 4f, g) and shape (ORTHO/PARA-FIRE, Fig. 4h, i) but also due to impacts of the ambient wind velocity (REF-CASE, WEAK/STRONG-FIRE, Fig. 4a-c). Whereas in the case of calm ambient conditions (WEAK-WIND, Fig. 4b) the original rectangular fire shape remains more or less unchanged within the air temperature fields, a strong deformation with a bulge in flow direction occurs under STRONG-WIND conditions (Fig. 4c) but also in the ORTHO-FIRE setup (Fig. 4h). Regarding both horizontal and vertical wind fields (Figs. 4 and 5), on average a rightward wind (wind flow parallel to the x-axis) is present, resulting from the inflow wind velocity forced in the x-direction. Additionally, some areas of convergence and divergence, increased and decreased velocities resulting in small vortices are present as is typical for a well-mixed PBL. Zones of strong confluence along with an acceleration of the horizontal winds can be found at and in front of the leading fire edges for the majority of the case simulations (Fig. 4). These areas of confluence develop due to the intense updrafts over the heated fire areas, consistent with the findings of Sun et al. (2009). The corresponding upward motions are clearly visible in the vertical cross sections (Fig. 5), where the initial flows widely parallel to the models x-axis are interrupted by upward oriented winds embedded within a defined band of increased air temperatures. These areas of strongly increased upward motion are not continuously, and at higher altitudes mostly not located directly, above the fire area. Here, the impact of the ambient wind flow leads to a downstream tilt of the fire updraft, accompanied with downward mixing and a reallocation of the typical non-fire PBL structures. This turbulence generates large vortices, which result in a strong relocation of the atmospheric patterns around the fire updraft. Although Fig. 5 shows only snapshots of the highly turbulent fire-induced wind fields, some differences concerning the orientation and strength of the fire updrafts can be derived. Weak ambient wind velocities (Fig. 5b, WEAK-WIND) lead to a defined vertical orientation of the fire updraft with only small impacts on the remaining atmosphere. In contrast to that, stronger ambient wind conditions (with the maximum of 5 m s^{-1} in the STRONG-WIND scenario, Fig. 5c) are related to a more downstream tilted flow direction of the heated air and do not reach high altitudes above the fire area. Hence, calm ambient wind conditions lead to an intense upward motion of the heated air, stronger winds impact more the lower tropospheric levels downstream of the fire. Major differences between the remaining simulations (different fire properties, Fig. 5d-i) affect mainly the strength of the winds originating from the fire area. As expected, they are more pronounced during the STRONG-FIRE (Fig. 5e) and LARGE-FIRE (Fig. 5g) cases, which provide a higher energy release, and comparably

weak for the ~~weaker~~ WEAK-FIRE (Fig. 5d~~, case 4) and smaller~~) and SMALL-FIRE (Fig. 5f~~, case 6) fires~~) situations. Also the line fires, especially the ~~perpendicular~~ orthogonal orientated one (Fig. 5h, ~~case 8~~ORTHO-FIRE), generate weaker updrafts.

~~The increased atmospheric turbulence triggered by the fire updraft can be expressed by the turbulent kinetic energy (TKE) as shown in Fig. 7 for all simulations including the non-fire simulation (case 0), again 20min after fire ignition. The TKE is a measure for the turbulence of a wind field compared to a laminar, undisturbed flow. Regarding the non-fire situation~~ As diverse as the development of the fire updrafts is the strength of the horizontal convergence near the surface (Fig. ~~7a, case 0), a well mixed turbulent PBL developed with a vertical extent of roughly 900m. Here, the typical structure of the PBL is dominated by some defined vortices. Above the PBL, a largely undisturbed free atmosphere is present with very low TKE values. Differing from that, the TKE in all other simulations is strongly enhanced by up to a factor of 50 within the fire-influenced atmosphere, whose horizontal extent varies from 1,000 to 3,000m downstream of the fire area depending on the chosen setup. For all simulations the zone of substantially increased turbulence exceeds the modeled PBL and interacts with the free troposphere. Due to the forcing of the ambient wind flow, the enhanced turbulence is transported downstream and weakens only slowly with growing distance to the fire area. This downwind transport of TKE results in an increased level of turbulence which also affects areas in some distance to the fire. There, the development of wind gusts can be favored due to downward mixing of momentum and a modification of the "normal" non-fire atmospheric wind conditions occur. Comparing the individual simulations, differences in strength and extent of the fire influenced pattern become obvious. The penetration depth of the fire updraft into the free troposphere differs quite substantially and is strongest under weak ambient wind conditions~~ 4). Comparable to the updraft strength the convergence is particularly strong in the STRONG-FIRE (Fig. ~~7b, case 1) but also above average in case of larger and more intense fires~~ 4e) and LARGE-FIRE (Fig. ~~7f and g, case 5 7) . The impacts of weaker and smaller fires~~ 4g) cases. In the presence of higher ambient winds, the convergence zone is shifted further downstream (Fig. ~~7e and f, case 4 6)are more limited to the simulated PBL but here as well connected with a strong disturbance of the atmospheric layering. The downstream horizontal extent of the fire related turbulence is driven by the strength of the ambient wind velocity but surprisingly the fire shape seems important as well. The perpendicular oriented line fire~~ 4c, STRONG-WIND), while during calm conditions the convergence takes place right within the fire area and leads partly to a reversal of the flow direction (Fig. ~~7j, case 8) leads to a strongly increased near-surface turbulence also some kilometers downstream of~~ 4a, WEAK-WIND) back to the fire area~~, while areas of increased TKE are much more lifted in the other setups~~.

~~Differences in the updraft orientation with respect to the ambient wind and the fields of the TKE can also be expressed by vertical~~ The different impacts of the ambient wind velocity on the distribution of the fire-related winds can be expressed more clearly by profiles of the horizontal and vertical peak wind ~~velocity (case 1-3)~~ speeds as depicted in Fig. 6. Here, vertical profiles are shown for the areas (box A-C) with respect to the distance to the fire ~~. In order to further elaborate the impact of the fire on the wind fields at different distances to the fire, three zones (boxes A, B, and C) located at different distances to the fire area are defined as illustrated in~~ as described in Section 2 and shown in Fig. 2. ~~Each box has a size of 84,000m^2. BoxA covers the fire area itself with an extent of 240x350m^2, BoxB is shifted slightly downstream to x=400m and has an extent of 120x700m^2, whereas BoxC is located 1,000m remote from the fire area at x=1,200m and covers an area of 70x1,200m^2.~~

Figure 6 demonstrates the vertical profiles of maximum wind velocities for the three boxes representing areas of different distance to the fire and thus the source of atmospheric disturbances. Although Although only maximum values are given, these values still represent an average of the highest wind speeds that occur at every time step once the box-area is affected by the fire peak wind velocities before and after fire ignition. This approach is chosen in order to avoid a allows a better representation of the fire-related winds without a vanishing of the particular high fire-affected wind velocities peak values due to a merge merging with the uninfluenced wind field around the fire updraft or corresponding downdrafts. Figures 6a and 6d show the vertical profiles of both wind components (horizontal and vertical wind) directly around and above the fire center (box A in Fig. 6), Figs. 6b and 6e do the same for the area a bit downstream of the fire region (box B) and Figs. 6c and 6f illustrate the situation further away from the fire (box C). Compared are the profiles of the undisturbed non-fire PBL (dashed lines) with the profiles after fire ignition (solid lines) for the scenarios with a different ambient wind velocity (case 1-3) WEAK-WIND, REF-CASE, STRONG-WIND) varying from 1 to 5 m s^{-1}.

First, with regard to the The undisturbed non-fire wind profiles (dashed lines), the height of are well separated by the different ambient wind velocities and show quite clearly the modeled PBL height of roughly 900 m is quite visible. Above this altitude, the horizontal wind peaks are close to the average ambient wind velocity and the vertical wind velocity close to zero, representing together a widely undisturbed, laminar flow. After fire ignition, drastic changes develop in all scenarios but show large differences between the cases and with respect to the fire distance. By comparing the profiles Below, turbulent fluctuations result in peak wind values on average up to 2 m s^{-1} above the mean flow velocity. The fire impacts change the situation drastically. Now much higher peak values can be observed, whereby with increasing distance to the fire area (box A-C) a weakening and a lifting of the regions with the highest values happen. While close to the fire region the strongest impacts occur in the near-surface levels (up to 100-200m), the influences a weakening of the peak winds near the surface are largely insignificant for distances >1 and a continuous lifting of the most impacted air layers occurs. During WEAK-WIND conditions, 000m but higher atmospheric levels become much more influenced by downstream and upward transport of the fire-related turbulence, also above the PBL.

The patterns of the fire impact on the horizontal and vertical wind maximums depend considerably on the ambient wind velocity. During calm conditions(case 1), the fire energy is mainly transformed into an upward motion, which means results in a strong modification of the atmospheric circulation patterns up to a height of around 2,000m above ground level some kilometers. Due to the strong turbulence occurring around the fire updraft also the horizontal winds are affected, leading to enhanced horizontal wind peaks, whereas in case of higher ambient wind velocities the conditions in these levels quickly turn to the normal non-fire behavior become enhanced too. In contrast to the weak ambient wind scenario, in , in the presence of higher ambient wind forces (case 2 and such as 3) the updraft strength m s^{-1} (REF-CASE) or 5 m s^{-1} (STRONG-WIND), the updraft is much weaker but modulations in the near-surface horizontal winds are stronger. Due to the more pronounced. Thus, the atmospheric patterns are vertically less impacted but the faster downstream transport of the fire-generated turbulence , the vertical extent of the fire impacts is smaller but horizontally longer present.

impacts a much larger area in the flow direction. The fire properties modulate the scenario in the expected way that a larger and stronger fire and the perpendicular orientated line fire an expected way such that a LARGE-FIRE and STRONG-FIRE, but

~~also the ORTHO-FIRE,~~ also the ORTHO-FIRE, lead generally to higher ~~horizontal and vertical~~ peak wind velocities, and impact also higher ~~altitudes of the atmosphere~~ tropospheric levels. But they are, concerning the general behavior, widely comparable ~~to the case 2-scenario, which suggests~~ with the REF-CASE scenario, suggesting that the ambient wind velocity is the main driver of the different ~~spreading~~ atmospheric distribution of fire-induced ~~winds within the atmosphere~~ turbulence.

5   ~~The quantity of the change of the atmospheric wind pattern apart from the direct surface-near levels is particular important for the distribution and further transport of once emitted particles. Especially in the presence of a non-negligible ambient wind, the occurring downstream and vertical transport of the~~ The increased atmospheric turbulence triggered by the fire updraft can also be expressed by the turbulent kinetic energy (TKE). Therefore, Fig. 7 shows the vertical profiles of fire-generated peak-TKE values computed similarly as the wind profiles shown in Fig. 6. All setups have the commonality that the fire-

10 induced ~~turbulence can still affect the atmospheric layering in some distance to the fire and can lead to an exchange between the PBL and the free troposphere, which may be important for the transport of particles, injected first only into the PBL before such processes may allow a further atmospheric distribution.~~

   ~~As diverse as the fire updrafts have developed, the strength of the horizontal convergence near the surface differs~~ turbulence generates peak TKE values of 3-12 $\mathrm{m^2\,s^{-2}}$, which is more than one order of magnitude higher than the NO-FIRE peak values

15 of $0.4\,\mathrm{m^2\,s^{-2}}$. Additionally, each setup shows enhanced values above the modeled PBL suggesting a turbulent mixing also above the PBL. However, a strong decline with increasing height is often present and the highest values occur within the lowest 100-200 m directly above and around the fire area. The only exception is again the WEAK-WIND simulation (Fig. ~~4)~~. ~~Comparably to the updraft strength the convergence is particular heavy during the more intense (Fig. 4e, case 5) and the larger (Fig. 4g, case 7) fires. In the presence of higher ambient winds, the convergence zone is shifted further downstream (Fig. 4c,~~

20 ~~case 3), while during calm conditions the convergence takes place right within the fire area and leads partly to a reversal of the flow direction~~ 7a) where the strong updraft induces the strongest turbulence in higher altitudes. As expected, the stronger and larger a fire, the higher the peak TKE values and the deeper the fire-induced turbulence penetrates into the atmosphere. The line fires (ORTHO/PARA-FIRE) are related with a weaker turbulence compared to the rectangular fire of the same size and intensity (REF-CASE), since the fire energy release to the atmosphere is more distributed over a larger area and is less

25 concentrated, which results in less strong peak TKE values. However, this feature impacts only the lowest tropospheric levels and is not present above (Fig. ~~4a, case 1)~~ ~~back to the fire area~~ 7d).

   Since the focus of this study lies ~~predominately~~ predominantly on the potential of wildfires to mobilize soil dust particles and the emission of mineral dust is ~~a threshold phenomenon~~ primary a threshold problem, the crucial point is the occurrence of high wind speeds at the surface. To investigate the frequency of occurrence and the strength of such strong winds or gusts,

30 Probability Density Functions (PDFs) of the horizontal wind velocity 5 m above ground ~~were~~ are calculated. In order to analyze the impacts of the fire, the fire-affected wind PDFs are compared to the PDFs of the undisturbed non-fire winds. The non-fire wind PDFs are calculated from the last 5 minutes before fire ignition ~~,~~ when the PBL is fully developed. Accordingly, the calculation of the PDFs, representing the fire-induced wind fields directly within the fire area and with respect to different distances to the fire ~~area~~ (boxes A-C), uses all time steps ~~directly~~ immediately after fire ignition (fire area, box A) or even later

35 after it can be guaranteed that the downstream transported fire-induced wind patterns reach the area of interest, which means

10 min after fire ignition for box B and a further 10 min later for box C. In Figure 8, PDFs of the horizontal near-surface wind velocity within the direct fire area are shown for all case simulations. Additionally, fractions of wind velocities exceeding a non-fire limit of usually 6 m s^{-1} (except for the WEAK-WIND and STRONG-WIND simulations with 4 or 8 m s^{-1}, respectively) are given in Table 2 also for the other distances to the fire area (boxes A-C, cf. Fig. 2).

The non-fire wind speed distribution as illustrated by dashed lines in Fig. 8 follows a gaussian distribution with the most frequently occurring wind velocities within an order of magnitude of the initial ambient wind velocity (1 and 5 m s^{-1} for, respectively, the WEAK-WIND and STRONG-WIND setups; 3 m s^{-1} for all other cases). These wind velocities fluctuate up to 3 m s^{-1} around the average due to the turbulent nature of the simulated PBL. During the presence of a fire, the whole distributions are shifted significantly towards higher values with a huge frequency of high wind velocities, which were not present before fire ignition in the non-fire PBL.

Figure 8a contrasts the wind PDFs for the fire-scenarios under different ambient wind velocities. It stands out that the by 2 m s^{-1} increased mean wind velocity between the individual scenarios leads to a nearly perfect shift of the undisturbed non-fire wind PDFs towards 2 m s^{-1} higher wind velocities. However, the fire PDFs behave differently. Although the PDF for the STRONG-WIND setup is still that one which is related to the highest wind velocities, the differences between all three scenarios become smaller. The WEAK-WIND distribution is shifted by 4 m s^{-1} to higher wind velocities, whereas the STRONG-WIND distribution only by 2 m s^{-1}, which leads to a reduction between the single PDFs of originally 4 m s^{-1} to only 2 m s^{-1}. This indicates that the fire impact on the fire-induced near-surface winds is much stronger compared to the influence of the mean ambient wind velocity. In the case of the WEAK-WIND simulation this become particularly obvious, where the fire-influenced and non-fire PDFs show nearly no overlap (86 % of the wind velocities exceed the non-fire threshold). However, a higher ambient

wind ~~velocities lead to a more intense turbulence caused by the more horizontally orientated plume and downward mixing of momentum.The increased turbulence can disturb the evolution of very strong wind peaks but also leads to an in total much more frequent occurrence of higher wind gusts near the surface~~velocity increases the likelihood to reach certain (threshold) wind velocities at similar fire properties, although the maximum velocities are comparable (cf. Table 3), but the frequency of occurrence differs.

~~Figure 8b compares the change of~~ The impacts of different fire intensities on the wind speed distribution ~~related to different fire intensities.In all cases~~in the fire area are given by Fig. 8b. Again, a distinct ~~and quite similar~~ shift of the whole ~~fire-affected~~ PDFs towards higher ~~velocities occurs, in total only slightly stronger for~~ wind velocities occurs in all cases. However, this is most dominant for the more intense fires~~like case 5. Generally, the maximum wind speeds reveal a clear connection between the fire intensity and the fraction of such wind velocities. More intense fires have a more frequent occurrence of strong above-average wind velocities (up to 20~~. In our setup, the STRONG-FIRE leads to maximum wind velocities within the fire area of up to 11 ~~% in our strongest setup compared to 6m~~ % in the weaker fire~~simulation) and are in general connected to stronger accelerations of the horizontal~~ s^{-1}, whereas the WEAK-FIRE accelerates the near-surface ~~winds.~~ winds here only up to 8 m s^{-1}. An additional feature, which can be derived from Fig. 8b is that with increasing fire intensity, the distribution is getting wider. This means that the increase in the occurrence of the highest wind speeds does not lead to a reduction of the lowest wind velocities in the same order of magnitude. But to conclude the sub-figure; the more intense the fire, the more frequent wind velocities above the non-fire limit occur and the stronger they are.

The dependency of the ~~wind speed distribution~~ fire-PDFs on the fire size ~~as~~ is shown in Fig. 8c for the rectangular fires with a size of 1,800 (SMALL-FIRE), 7,000 (REF-CASE), and 11,700 m^2 (~~case 6, 2, and 7)is slightly different~~LARGE-FIRE). In general, the following connection is obvious: the larger the fire, the stronger the shift in the wind speed distribution within the fire area towards higher values. ~~Especially larger fires (case 7) are related to a very pronounced shift of the whole wind speed PDF by up to 2ms^{-1} and a significant portion of winds is above 10ms^{-1}. Compared to the dependency on the~~ Comparably to the impact of the fire intensity, an increase in the fire size ~~appears to affect more the whole wind speed distribution rather than the wind maximums only. Here, the range of wind velocities exceeding the non-fire limit varies between only 3.2% in case of the small fire and more than 25% for the largest fire setup; much more than the variation of the fire intensity(7-21%). Thus, the increase in the~~ is also related to a broadening of the fire PDFs, which means that the occurring wind velocities in a larger fire area covers a wider range compared to smaller ones. The highest wind velocities, however, appear to be not that strongly impacted by the fire size as by the fire intensity.

Finally, also the fire shape impacts the strength and frequency of occurrence of wind ~~velocities~~ speeds above the non-fire ~~distribution is more pronounced, although the highest values occur in the more intense fire scenario.~~

~~The impacts of the fire shape~~ limit (Fig. 8d)~~are a bit more diverse. Comparing the line fires perpendicular (case 8~~. Comparing line fires orthogonal (ORTHO-FIRE) and parallel (~~case 9~~PARA-FIRE) to the flow direction with ~~the~~ a rectangular fire of the same size ~~(case 2~~and intensity (REF-CASE), differences in the shape of the fire-influenced wind PDFs stand out. Both ~~wind distributions for the line fire case have a quite similar shape compared to the non-fire distribution, only~~ line fire PDFs behave quite similarly with only small differences. They are both shifted by roughly ~~1ms^{-1} (parallel fire, case 9) or~~ 2 m s^{-1}

(perpendicular fire , case 8) towards higher values. This means that the peak winds are stronger in case of a rectangular fire with a more concentrated heat source. But the frequency of occurrence of winds towards higher wind velocities, however, the highest values are much weaker compared to the rectangular fire, where the fire area and thus the heat source modulating the wind patterns is more concentrated, which supports the creation of higher wind velocities.

5   Since the fire-related updrafts develop often first downstream of the direct fire area (cf. Figs. 4/5), the fire surrounding might be with regard to the occurrence of high winds of interest too. Therefore, the fraction of the exceedances of wind velocities above the non-fire limits are given for box A (covering the fire area plus the surrounding as shown in Fig. 2) in Table 2 compared to that of the direct fire area. As expected, for the majority of cases the occurrence of wind velocities above the non-fire case in total is in case of the perpendicular orientated fire (case 8) with a fraction of 18limit decreases significantly

10 as now also regions which are not influenced by the fire go into the PDF calculation . However, especially in the case of a STRONG-FIRE and a LARGE-FIRE, a remarkable fraction of wind velocities exceeds still the non-fire limit. The behavior of the perpendicular orientated line fire (ORTHO-FIRE) stands out. In this case, a significant increase of wind velocities greater than 6 % larger compared to a fraction of 12m % for the rectangular shaped fire (case 2). However, the fractions are again much higher than for the parallel orientated line fire (case 9) with less than 5% above the s^{-1} happens. The long orthogonal extent of

15 the fire line leads to a much broader area of fire-induced turbulence behind the fire line. Although the total impacts concerning the maximum wind values are smaller compared to the rectangular fire setup, the long fire line precludes/impedes a mixing of the fire-induced atmospheric pattern with uninfluenced non-fire case's wind velocitiesflow effectively for a long distance, which means that the fire-induced patterns are present much longer in the x-direction before a weakening of the impacts takes place. Thus, the creation of higher wind velocities is downstream of the fire area much more strongly impacted than in the

20 small fire area itself.

The effects With an increasing distance to the fire area the impacts of the fire on the near-surface wind fields weaken drastically with increasing distance to the fire area but are often still present due to a further downstream transport of fire-related turbulence and momentum. Table 2 provides the fraction of wind velocities larger than the non-fire peak wind velocities (6ms^{-1}, except of the cases 1 and 3 with 4.5 or 8ms^{-1}, respectively) for the zones with different distances , which favors the

25 occurrence of higher wind velocities also in some distance to the fireregion (boxes A-C in Fig. 2). Already in the near-by . Already some hundreds of meters downstream of the fire area, in box B, the shift of the wind PDFs and occurrence of above-average wind velocities are mostly is mostly very small or nearly insignificant in case of weak ambient wind winds (case 1) and a smaller fire size (case 6)the case of WEAK-WIND conditions and at SMALL-FIRE sizes. Only the stronger fire (case 5), the larger fire (case 7), and the perpendicular orientated line fire (case 8) STRONG-FIRE, the LARGE-FIRE, as

30 well as again the ORTHO-FIRE show noteworthy impacts also further ahead of the fire areadue , because these fire setups are related to a stronger generation of turbulence, which is transported downstream and can affect the wind field there much more effective effectively than the weaker turbulence of smaller or and weaker fires does. A surprising behavior can be observed for the perpendicular orientated line fire (case 8). Here, the strongest impact on the near-surface wind velocity (concerning the peak winds with 8.7 to 8.2ms^{-1}) does not occur directly around the fire area but further downstream in In the case of

35 the ORTHO-FIRE, the effect is again most pronounced and even the highest wind velocities near the surface can be found

first within box B ~~. Furthermore, also the fraction of wind velocities above the non-fire winds is with 5.4% in box B most pronounced compared to the other setups~~and thereby some hundreds of meters away from the actual fire area. Surprisingly, the fraction of wind velocities above the non-fire limit is for most of the fire setups with 1-2 % still enhanced also more than one kilometer away from the fire area (box C). This feature will be analyzed in more detail in the following section, where maps of spatial distributions are shown.

~~Since especially the high wind speeds are important for dust emission, the substantial increase in the frequency of occurrence of wind velocities larger than 6ms^{-1} indicate a strongly increased dust emission potential during wildfires.~~

5 Discussion with regard to dust emission potential

The analysis of the near-surface wind ~~pattern~~ patterns has already illustrated that wildfires lead, depending on the state of the atmosphere and the fire properties, to a significant increase in the strength and frequency of occurrence of peak wind velocities. ~~To validate~~ Since especially these high wind speeds are important for dust emission, the substantial increase in the frequency of occurrence of wind velocities larger than $6\,\mathrm{m\,s^{-1}}$ indicates a strongly increased dust emission potential during wildfires. To test the conceptual model of ~~the dust emission via by wildfires modulated wind fields~~fire-related dust emissions, a simplified approach was used. For the dust ~~emission~~ mobilization itself a representative horizontal threshold velocity of ~~6.5~~6 $\mathrm{m\,s^{-1}}$ ~~is applied.~~ was applied, although in reality the exact value depends on several surface characteristics. However, this value is commonly used and can be linked to a high likelihood of a dust emission event. The spatial distribution of areas where and how often ~~the threshold velocity of 6.5~~this threshold of 6 $\mathrm{m\,s^{-1}}$ is exceeded is given in Fig. 9 for all ~~case simulations. Considering the non-fire~~cases, including the NO-FIRE simulation. Additionally, the frequency of exceedance of this threshold velocity summed up over the leftmost 2 km of the model domain as shown in Fig. 9 is given in Table 3 (first column).

Considering the NO-FIRE simulation (Fig. 9a~~, case 0~~), it becomes evident that already the turbulent fluctuations around the mean ambient wind velocity of $3\,\mathrm{m\,s^{-1}}$ lead to an ~~excess~~ exceedance of the chosen threshold velocity in rare cases. However, these ~~small areas are~~areas are small and randomly distributed over the model domain and at best only once affected by such ~~a high wind velocity~~an exceedance, which means that ~~an efficient~~ a significant contribution to dust emission cannot be expected, independent of the predominant surface conditions. All other simulations show a highly increased occurrence of horizontal wind velocities above the ~~chosen~~threshold within and around the fire area up to 100 %, whereas the number and spatial extent ~~of such events~~ depend on the chosen setup. The ~~frequency of exceeding the threshold velocity of 6.5~~spatial extent of wind velocities above the threshold of 6 $\mathrm{m\,s^{-1}}$ ~~within the most westward 2km of the model domain is given in Table 3 (first column). The efficiency of generating wind velocities above the threshold intensifies with increasing fire intensity~~ is greatest during the STRONG-FIRE (Fig. 9f~~, case 5), fire size~~), LARGE-FIRE (Fig. 9h~~, case 7) and increasing ambient wind velocity~~), ORTHO-FIRE (Fig. 9i) as well as in the STRONG-FIRE (Fig. 9~~c/d, case 2/3) . The extreme case 3~~d) setup. Concerning the STRONG-WIND simulation with an average wind velocity of $5\,\mathrm{m\,s^{-1}}$~~is already suitable to exceed the~~, the chosen threshold velocity of ~~6.5~~6 $\mathrm{m\,s^{-1}}$ ~~regularly~~ is already regularly exceeded nearly all over the model domain by the normal non-fire turbulent fluctuations. However, also here the frequency of occurrence of such horizontal peak winds is drastically strengthened in the

fire surrounding and further downstream. Although already the non-fire winds would be able to generate dust emissions in general, the likelihood and the strength of possible dust emissions is strongly enhanced here as well, especially with regard to the fire-related vegetation removal and modification of the soil conditions within the fire area. In particular the cases with an increasing fire size, intensity, and ambient wind velocity show usually a fraction of more than 90 % exceedance of the threshold velocity within the direct fire area. Since the fire here usually consumes the vegetation cover, a mobilization of soil dust particles would be expected to take place quite efficiently.

Beside the general exceedance of the threshold velocity in the fire surroundings, an interesting behavior occurs for simulations with an averaged ambient wind velocity of $3\,\mathrm{m\,s^{-1}}$ and a rectangular fire shape. While during WEAK-WIND conditions (Fig. 9b) the potential of the fire to generate wind velocities above the threshold is limited to the direct fire area, such favorable zones have evolved in the other setups also some distance from the fire. Patterns of enhanced wind velocities, similar to a vortex trail behind an island, have developed downstream of the fire area (cf. Fig. 9b, 9e-h). The evolution of this pattern might be caused by the strong fire updraft acting as an obstacle within the ambient flow, which has to be circumflowed by the winds. The resulting strong turbulence at the edges of the fire updraft propagates now downstream, can be mixed downward and finally leads to enhanced surface winds togehter with an exceedance of the threshold also in some distance to the fire area. Provided that suitable surface conditions exist there, the dust emission potential would be increased there as well.

Whereas in these cases right in front of the fire area, in the lee of the fire updraft, no above-average wind velocities occur, the situation is quite different in case of the ORTHO-FIRE (Fig. 9i). Although the fraction of exceedances of the threshold velocity is comparably low (only 30-40 %), a large area is affected by such events right downstream of the fire area. Since all other parameters are kept constant, the orientation of the fire to the ambient wind flow direction appears to play an important role by increasing the effective surface prone to wind erosion. The ORTHO-FIRE heats the lower atmospheric levels on a wide front along with modulations of the wind patterns there so that a mixing with undisturbed non-fire influenced air masses occurs in this case first much further downstream. Thus, the fire-induced turbulence can be transported much more efficiently in the flow direction and impacts a much larger area compared to the other setups. This area could be prone to dust emission as well - suitable surface conditions assumed. This special behavior is remarkable insofar as especially here a dust mobilization potential arises, which is not only directly linked to the fire plume but emissions can take place also independently and a mixture with combustion aerosol would not be always satisfied.

~~scenario drastically, which means that also dust sources in some distance to the fire area can be affected and activated to emit mineral dust into the atmosphere.~~

~~The atmospheric relevance of emitted particles depend strongly on their injection height, which determine interactions with atmospheric properties and the long-range transport. The injection~~ An efficient injection of mineral dust particles into

5 higher atmospheric levels requires beside ~~the excess of a~~ an exceedance of the horizontal threshold velocity also a ~~certain strong enough~~ vertical wind velocity, ~~essential to transport these particles into higher atmospheric levels~~. Necessary updraft velocities to lift dust particles in the air are based significantly on ~~the~~ particle size and mass. For simplification, sedimentation velocities of representative particle sizes are used to estimate the needed updraft velocities, which must be greater than the sedimentation velocity resulting from gravitational forces to get and hold the particles in the air. The following

10 particle diameters were chosen ~~representatively (Tegen and Fung, 1994) , namely d_1 = 1.46~~ for the calculation exemplarily, namely $d_1 = 1.46$ μm (clay), ~~d_2 = 12.2~~$d_2 = 12.2$ μm (small silt), ~~d_3 = 36~~$d_3 = 36$ μm (large silt), ~~d_4 = 76~~$d_4 = 76$ μm (small sand) ~~, and d_5 = 1,000~~(Tegen and Fung, 1994) , and $d_5 = 1,000$ μm (giant particles, large sand). The corresponding sedimentation velocities v_{sed} of these particle diameters d_1-d_5 result, using the calculations with slip and shape correction based on Hinds (1982)~~in $v_{\text{sed}}(d_1)$ = 0.00014,~~ in $v_{\text{sed}}(d_1) = 0.00014$ m s^{-1}, ~~$v_{\text{sed}}(d_2)$ = 0.009~~$v_{\text{sed}}(d_2) = 0.009$ m s^{-1}, ~~$v_{\text{sed}}(d_3)$ =~~

15 ~~0.08~~$v_{\text{sed}}(d_3) = 0.08$ m s^{-1}, ~~$v_{\text{sed}}(d_4)$ = 0.27~~$v_{\text{sed}}(d_4) = 0.27$ m s^{-1}, and ~~$v_{\text{sed}}(d_5)$ = 5.06~~$v_{\text{sed}}(d_5) = 5.06$ m s^{-1}. ~~To~~ This means, to hold and raise particles of such a size in the atmosphere, these velocities have to be ~~definitely exceeded by the fire or atmospheric updraft velocities~~exceeded by a fire or an atmospheric updraft. Consequently, they are used here as a simplified ~~estimation~~ assessment of necessary updraft velocities w_1-w_5, which ~~have to be occurring coincidently~~ should be occurring together with an ~~excess of the threshold velocity to get particles emitted into higher levels of the atmosphere.~~ exceedance

20 of the horizontal threshold velocity v_{tres} to get dust particles effectively emitted into the atmosphere, although under some circumstances already lower horizontal wind velocities can be linked to a direct particle injection. However, here we will focus mainly on the dust emission potential with respect to the saltation process, which requires a higher horizontal threshold velocity.

The probabilities of the occurrence of simultaneous incidences of a horizontal wind velocity above ~~6.5~~6 m s^{-1} and ~~a~~ an

25 updraft velocity w_1-w_5 ~~greater than the calculated sedimentation velocities~~ for the chosen particle diameters are given in Tab. 3 for all case simulations. ~~Representatively~~Exemplarily, for a particle diameter of ~~d_4 = 76~~$d_4 = 76$ μm, the spatial distribution of the frequency of occurrence of the vertical velocity ~~w_4 > 0.27~~$w_4 > 0.27$ m s^{-1} in the lowest model level at $z = 5$ m is shown in Fig. 10 and the corresponding overlap with areas where the horizontal threshold velocity is exceeded as well (Fig. 9) is ~~shown~~ given in Fig. 11. As visible in the NO-FIRE simulation (Fig. 10~~, a~~vertical a), such an updraft velocity w_4 ~~> 0.27 ms^{-1} occurs for~~

30 occurs for nearly every grid cell with a frequency of 5-30 % already without any fire influence~~(cf. Fig. 10a, case 0). .~~ However, the impact of the fire leads in general to ~~an~~a significant increase in the occurrence of such updraft velocities up to 100 % directly above and in front of the fire area~~and also to .~~ Zones where nearly no updrafts developed can be identified at the flanks and upstream of the fire area. Here, the corresponding downdrafts dominate, which get accelerated in horizontal near-surface winds and finally merged in the fire updrafts. Clearly visible is also the formation of an area of enhanced ~~probabilities of occurrence~~

35 updraft occurrences within some hundreds of meters up to 1 km downstream of the fire area ~~. Due to the effect of the ambient~~

~~wind, the strongest updrafts occur slightly downstream of the actual fire center~~most pronounced again in the ORTHO-FIRE simulation, related to the downstream transport of fire-generated turbulence by the forcing of the ambient winds.

~~Regions where the horizontal threshold velocity and the updraft velocity w_4 are exceeded simultaneously are shown in Fig. 11. As expected, the suitable zones decrease significantly .~~ By combining these regions with the areas of a threshold velocity $v_{tres} \geq 6\,\mathrm{m\,s^{-1}}$, the fraction of suitable zones decreases significantly (Fig. 11). For the majority of the cases, now only the immediate fire area remains to a large extent suitable for the injection of dust particles ~~up to a size of $d_4 = 76$~~of the given size of $d_4 = 76\,\mu$m into the atmosphere, whereas the intensity and extent of such areas depend again mainly on the fire properties. Larger and more intense fires tend to have a much higher probability to ~~inject dust particles of this size~~mobilize and inject such dust particles compared to weaker and smaller fires. ~~The~~ However, the behavior of the ~~perpendicular orientated line fire~~ ORTHO-FIRE (Fig. 11i~~, case 8~~) stands out again, in particular concerning the suitable area of dust uplift. Although here no region with a constant high updraft velocity exists (Fig. 10i), the area where horizontal ~~excesses~~ exceedances of the threshold velocity occur together with suitable updrafts extends up to 500 m ahead of the original fire line. In total, more than 9 % of the grid cells within the ~~most westward~~ leftmost two kilometers of the domain are affected at least once by such a suitable combination, which is by far the highest value apart from ~~case 3 with its high ambient wind velocity~~the STRONG-WIND scenario. Since such line fires appear to represent a quite realistic scenario for agriculture related grassland and cropland fires, the high ~~area~~ coverage of possible regions acting as dust sources also in ~~the~~ a larger surrounding of the fire area is remarkable and ~~increase~~ would mean that the dust emission potential ~~drastically.~~ is drastically increased there, again under the assumption of suitable surface conditions favorable for dust mobilization (e.g., a bare or ploughed field, etc.).

In general, it can be concluded that ~~the combination of sufficient~~ a combination of sufficiently strong horizontal and vertical wind velocities ~~occur~~ occurs quite frequently, especially ~~in fire surroundings, which mean~~ within and around the direct fire area, which means that the fire ~~produce~~ setups used in this study produce usually suitable conditions for the mobilization and injection of dust particles up to a size range of small sand particles~~(Tab. 3). However, within the~~ . However, above the direct fire area the ~~updrafts reach~~ fire updrafts can reach such high velocities, which are ~~so strong that also dust~~ strong enough that also sand particles of a size of ~~up to~~ one millimeter or even larger ~~can~~ could be raised and ~~inject~~ injected into the atmosphere. Although these events are quite rare and limited to the direct fire area, for the majority of ~~the scenarios horizontal wind velocities above the threshold and updrafts with $w_5 > 5.1$~~our scenarios such necessary updrafts with $w_5 > 5.1\,\mathrm{m\,s^{-1}}$ can be ~~observed.~~~~Since updraft velocities larger~~ found occasionally (Tab. 3). Since the fire updrafts reach in higher atmospheric levels (up to a height of roughly 1 km) velocities of usually more than $10\,\mathrm{m\,s^{-1}}$ ~~, with extreme values reaching nearly 30ms^{-1}~~ (cf. peak values in Tab. 3), ~~always develop above the fire area (cf. Fig. ??) and reaching altitudes of more than 1km, the in the literature described raise of super-micrometer particles~~ an injection of dust particles - reaching from small to large size ranges - into the PBL, and depending on the fire properties and PBL structures, also into higher atmospheric levels appears to be possible. Also the rise of coarse-mode particles as was found in some studies (e.g., Radke, 1991; Nisantzi et al., 2014) can be explained quite well with the development of the strong ~~fire-updraft winds. Contrasting the vertical motions of the fire simulations 20min after fire ignition in Fig. ?? with that of the non-fire conditions (Fig. ??a, case 0), the fire impacts are evident. Significant updraft velocities derive from the fire convective plume are present close to the fire area and were already~~

~~transported downstream due to the impacts of the ambient wind. The strong restructuring of the "normal" atmospheric pattern happening after fire ignition within the lower 1-2km of the atmosphere allows an efficient injection of~~ fire-related horizontal and vertical winds. Once lifted from the surface especially small dust particles with low sedimentation velocities ~~in these altitudes where~~ can be further distributed by larger- or synoptic-scale processes ~~, which are~~ and interact with the atmospheric properties. However, this topic remains for further investigation and is not tackled by the setup of this study~~, can lead to a further transport and distribution within the free atmosphere. Larger particles with much higher sedimentation velocities, by contrast, will start to settle down again already close to the fire area when the fire updraft loses power. .~~

~~Regarding the intensity of the peak upward motion, all fire simulations have a significant increased vertical velocity, compared to the non-fire simulation by a factor of 3-6. The strongest updrafts were produced at calm conditions (case 1) as well as during more intense (case 5) and larger (case 7) fires. Whereas the connection to fire size and intensity is quite obvious, the comparable updraft velocity under weak background winds is related to the widely absence of downstream drifts so that the upward motion of the heated air can develop much more undisturbed as shown in the vertical profiles in Fig. 6d. Thus, the total emission potential as well as the maximum injection height are assumed to be intensify with increasing fire size and strength, resulting from a more efficient acceleration of the near-surface winds and a stronger updraft velocity and thus a more efficient injection into the free troposphere, while the weaker and smaller fires as well as a stronger ambient velocity lead to lower maximum possible injection heights. However, the fire generated turbulence penetrates always much deeper into the atmosphere than the non-fire turbulence, suggesting an efficient exchange of the fire plume with higher altitudes can take place in each case.~~

~~Concerning the total emission potential of wildfires, it becomes clear that it also depends strongly on the ambient wind velocity. In case of stronger ambient winds the likelihood of exceeding the threshold velocity is much higher since already a small intensification of the winds due to the fire is sufficient enough to reach the threshold and mobilize dust particles. Under conditions of high ambient wind velocities the excess of the chosen threshold can occur partly also without any fire-related impacts. Apart of that, an increase in both fire intensity and size enhances the dust emission potential drastically via providing a higher energy release, the development of a stronger updraft and finally a higher acceleration of the near-surface winds can take place. In contrast, small and weak fires result only in a weak increase of the near-surface wind velocities and have a more limited emission potential. But nevertheless, they are able to raise dust particles too and inject them within the atmosphere.~~

6 Conclusions

The conceptual model of how wildfires can act as a source of mineral dust particles emitted into the atmosphere ~~was analyzed~~ has been presented and tested within this study. To ~~quantify~~ analyze the impacts of the ~~so-called~~ pyro-convection mechanism on the near-surface wind patterns in an already turbulent PBL, Large-Eddy ~~simulations with ASAM~~ Simulation (LES) with the All Scale Atmospheric Model (ASAM) were performed. In total, 9 different model setups were applied to describe varying ambient meteorological wind conditions as well as fire properties representing typical grassland and shrubland fires in order to investigate the impacts concerning their ability to mobilize and raise mineral dust particles.

The ~~analysis has~~ simulations have shown that the energy released by the fires ~~modulates strongly~~ strongly modulates the near-surface wind ~~velocities and~~ patterns. The rising air of the fire updraft is related to ~~a significant increase in the occurrence of high horizontal wind peaks. These high wind~~ an evolution of a zone of strong confluence within or slightly downstream of the fire area. Thus, horizontal near-surface winds are accelerated significantly and peak in wind velocities, which are ~~up to~~

5 ~~4~~much more intense compared to non-fire conditions. Especially within the direct fire area, the fire-driven near-surface winds of our setups can reach values which are up to $5\,\mathrm{m\,s^{-1}}$ higher ~~than normally in a non-fire influenced PBL~~occurring wind ~~velocities and have a fraction of up to 100~~compared to normal fluctuations within the modeled PBL. Assuming a commonly used threshold wind velocity of 6 ~~% in the direct surrounding of~~ $\mathrm{m\,s^{-1}}$ necessary to mobilize dust particles via saltation, it was found that such a value is frequently exceeded within and nearby the fire area. On the basis of suitable surface conditions

10 at least within the fire area ~~. These strong interaction with lower tropospheric properties and here in particular the occurrence of the high peak winds, which are most crucial for dust mobilization, shows that~~ (removal of vegetation, soil modification) to allow dust emission, these fire-related winds supply the opportunity to mobilize dust particles. In interaction with the ~~potential of mineral dust emissions during wildfires is increased drastically~~fire updraft, which provides the necessary upward motion to lift dust particles to higher atmospheric levels, it was shown that wildfires can increase the dust emission potential drastically

15 as depicted by the conceptual model and should be taken into account as a source of airborne mineral dust.

~~While the fire impacts lead to an excess of a wind velocity of 6.5ms^{-1}, typically sufficient for dust emission, the~~To which extent such fires are able to mobilize and raise dust particles depends primarily on the fire properties such as fire size, intensity, and shape, and, secondly, also from the ambient wind velocities. Both impact the strength and frequency of occurrence of ~~such the~~ peak wind velocities ~~depend strongly on the fire properties. The larger and the more intense the fire, the more pronounced~~

20 ~~the increase in~~ and the dust emission potential, whereas the fire properties appears to be more effective by modulating the wind fields. However also the ambient wind forcing plays a role. A stronger ambient wind increases the likelihood of exceeding the threshold velocity already under weaker fires since already a small fire-related intensification of the wind patterns is sufficient to exceed the threshold and mobilize dust particles. Nevertheless, the chosen setups of grass- and shrubland fires have always led to an exceedance of the typical threshold velocity of $6\,\mathrm{m\,s^{-1}}$. Despite the fact that larger and more intense fires are related to

25 a more pronounced increase in the near-surface wind velocities~~and consequently the strength of dust mobilization potential are. A~~, a quite important parameter appears to be the shape and orientation of a fire to the ambient wind direction. ~~The distribution of the heat source on a broad line perpendicular to the~~ For example, a line fire orthogonal to the ambient flow direction leads to a much stronger downstream transport of the fire-induced turbulence compared to a more aggregated, e.g. rectangular shaped fire of the same size. This increases the dust emission potential also up to one kilometer and more ahead of the actual fire area ~~,~~

30 ~~and thus can impact~~ and might be able to activate also non-fire related dust sources~~.~~, suitable soil and surface conditions there assumed.

~~The interplay of the fire with the strength of the ambient wind velocity is impacting the plume characteristics, the possible injection height and the atmospheric transport of once lifted dust particles, which finally determine the atmospheric impacts. Under calm conditions , the fire updraft with the raised participles can penetrate much deeper into the (free) atmosphere, where~~

35 ~~stronger ambient winds lead rather to a downstream transport of the fire induced air. But nevertheless, the fire plumes of the~~

~~chosen setups always exceeded the top of the modeled PBL and led to an injection into the free atmosphere, which is crucial for~~
~~the long-range transport and the interactions with atmospheric properties like radiation budget and cloud microphysics. Smaller~~
~~and weaker fires show less strong effects on the near-surface winds and a reduced dust emission potential but are still able to~~
~~raise particles and inject them into the (lower) troposphere where synoptic-scale processes can lead to a further distribution~~
5 ~~and also to an exchange between the PBL and the free atmosphere.~~

~~Since the outcomes of this study illustrate that wildfires~~ As this study has shown, wildfires can have a strong potential ~~of~~
to favoring the emission of mineral dust by modifying the near-surface winds~~,~~. However, until now they are not considered
as a source of airborne dust in aerosol-climate models, which often show large uncertainties and discrepancies concerning
the atmospheric dust load and its impacts. Thus, an implementation of the fire-related dust emission process in meso-scale
10 atmosphere-aerosol models ~~is necessary to achieve~~ appears to be necessary to allow a more accurate estimation of the total
atmospheric dust load and dust-associated impacts on radiation budget, cloud and precipitation formation processes especially
on larger ~~spatial scales.~~ scales. This can finally contribute to a reduction of the uncertainty in the aerosol-climate feedback,
especially regarding the highly variable anthropogenic part, the main cause of wildfires. Since these models cannot resolve
directly the small-scale fire-related turbulence, responsible for dust entrainment, ~~the development of~~ a parameterization of ~~the~~
15 ~~process is necessary~~ this process is needed. Therefore, the results gained here can be used to derive a first relation between the
fire properties and the resulting modulations of the wind speed distribution~~, which can be applied afterwards in~~. This can be
achieved via coupling them with a dust emission scheme to determine the strength of the fire-related dust ~~emission fluxes~~ fluxes,
where both the emission processes via saltation and direct turbulent entrainment should be considered. To describe this process
and the subsequent atmospheric fire-driven pathways as ~~accurate~~ accurately as possible, additional information on basic fire
20 properties (e.g., fire radiative power, fire size) and ~~land~~ surface characteristics (e.g., soil type, vegetation cover) are required,
which can be obtained from satellite products for wildfire monitoring and land cover maps. ~~Using that, a comparison of the~~
~~modeled~~ However, further investigations are needed before the process of fire-related dust ~~emission with airborne or remote~~
~~sensing measurements of the dust content in smoke plumes become possible.~~

~~This study gives a first introduction into the dust emission process during wildfires. Further quantification will allow for~~
25 ~~an estimation~~ emissions can be included in such large-scale aerosol models. Before reaching that ambitious long-term goal,
a quantification of the amount of fire-related dust emissions ~~at a continental or global scale and can finally contribute to a~~
~~reduction of the uncertainty in the aerosol-climate feedback, especially regarding the highly variable anthropogenic part, the~~
~~main cause of wildfires~~ via coupling of the LES fire winds with offline dust emission models will be the next step. As this
is done, regional/small-scale test cases can be computed and validated against measurements to prove the accuracy of the
30 approach.

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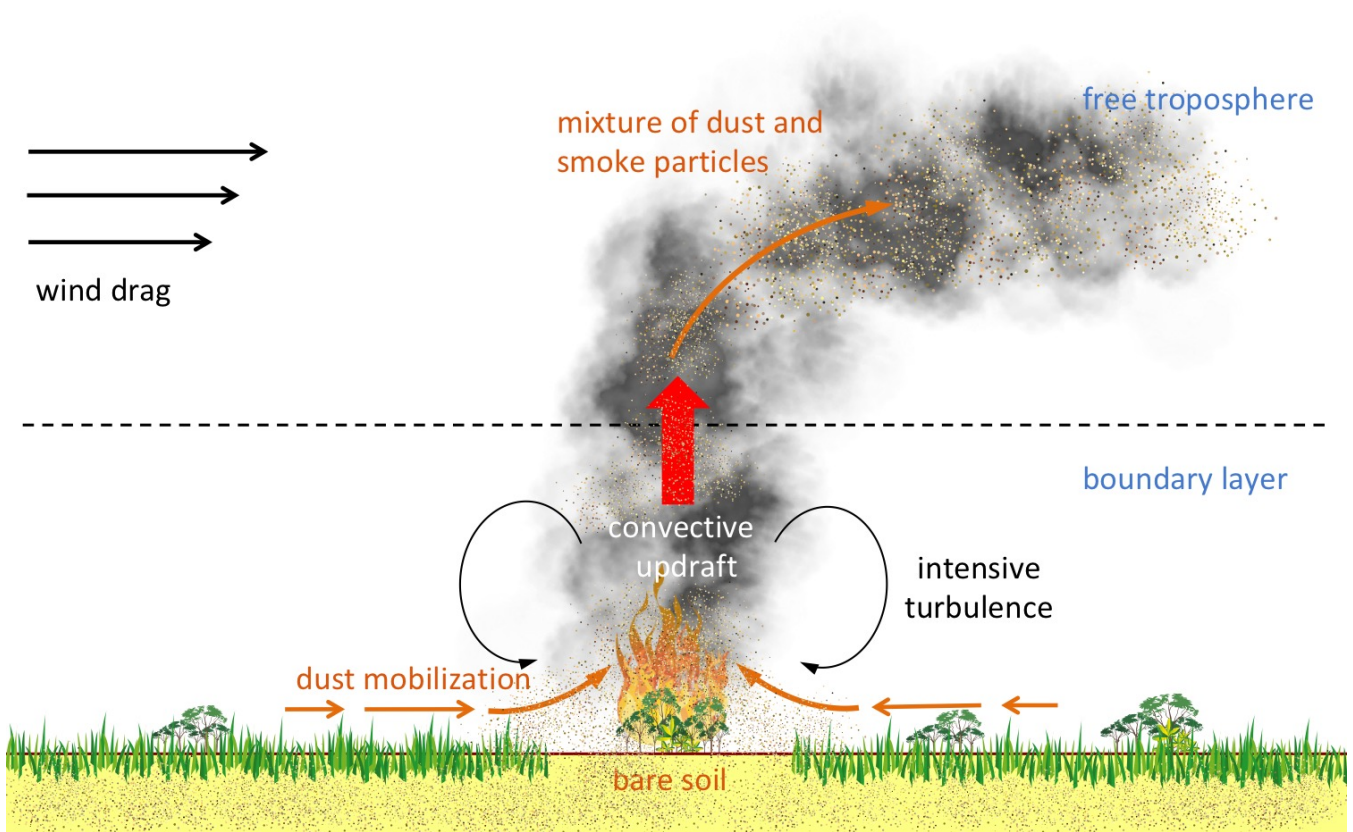


Figure 1. Schematic overview of the ~~processes related to dust~~ conceptual model of fire-driven emissions ~~during wildfires~~ of mineral dust.

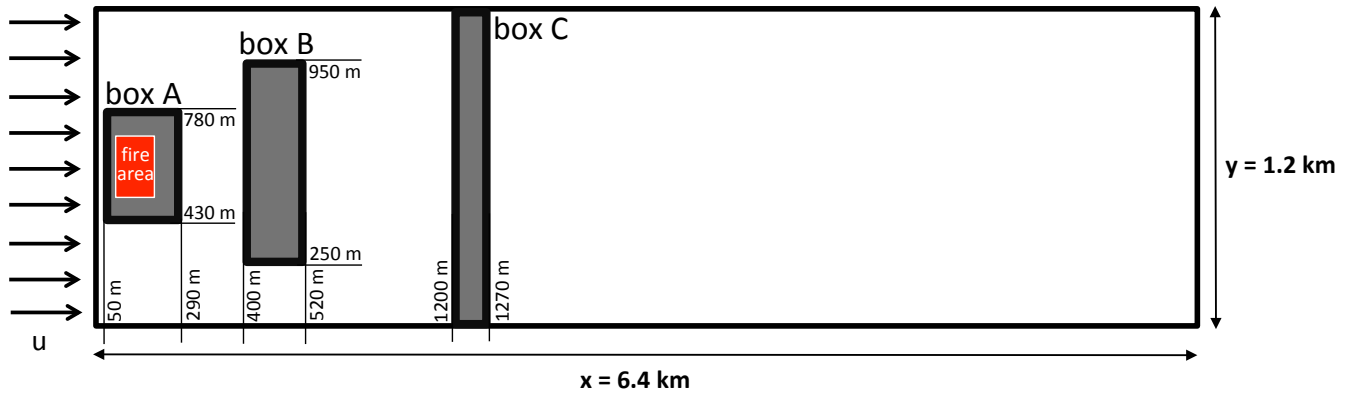



Figure 2. Schematic view of the *x-y*-plane of the model domain. Three areas with different distances to the fire area are marked (box A, B, C). Each box has a base size of $84,000\,\text{m}^2$ (Figure not true to scale).

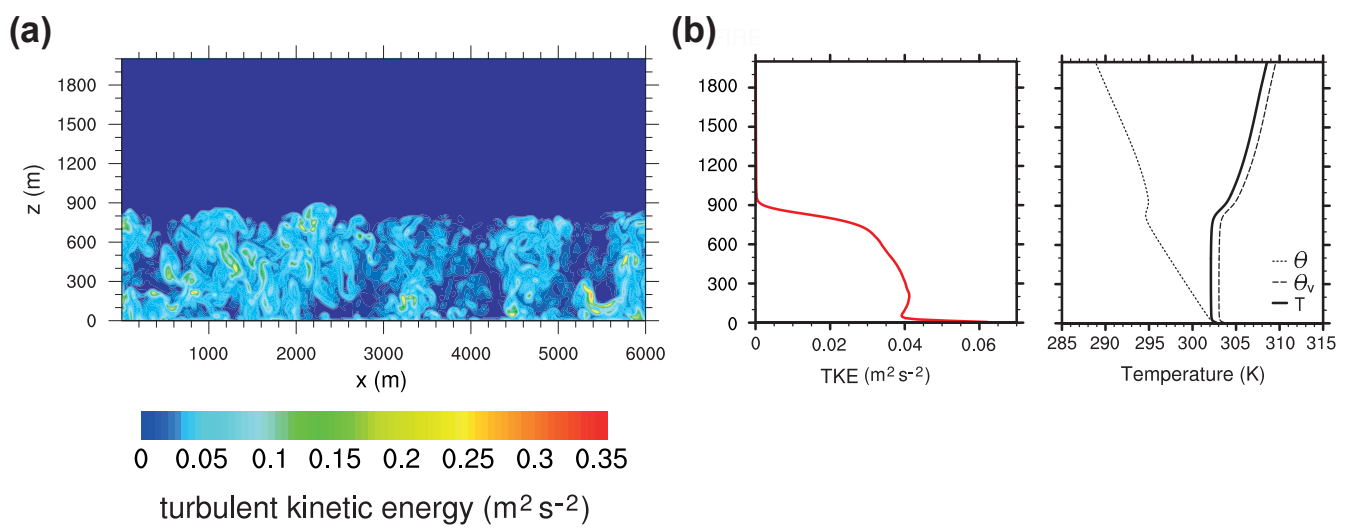



Figure 3. (a) Vertical cross section of the TKE for the NO-FIRE simulation after 2 h spin-up time, (b) averaged vertical profiles of the TKE (left panel), the absolute temperature T, potential temperature θ, and virtual potential temperature θ_v (right panel) for the NO-FIRE simulation.

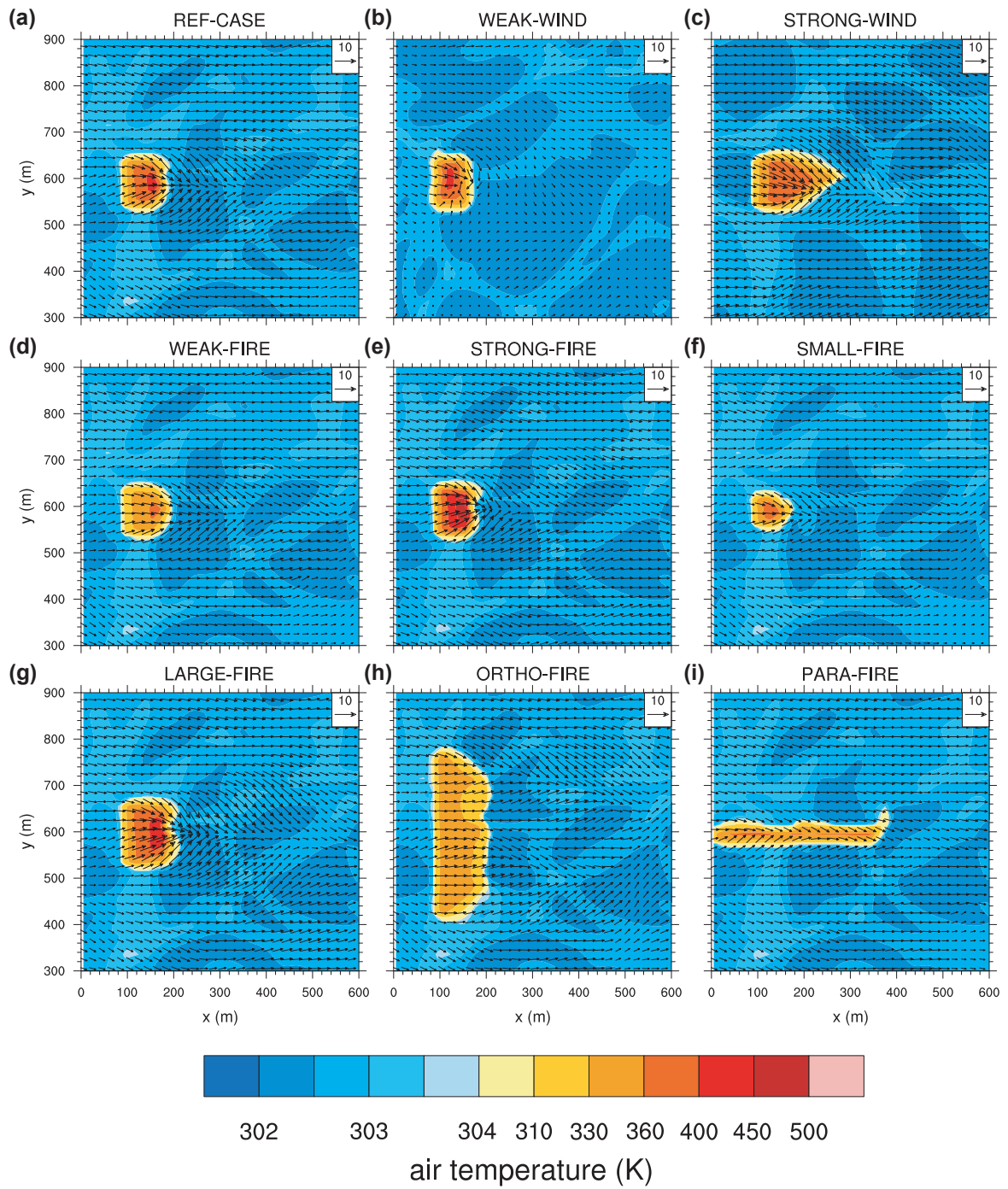



Figure 4. Horizontal cross sections of the wind vector and air temperature fields 20 minutes after fire ignition in the lowest model level of $z = 5$ m.

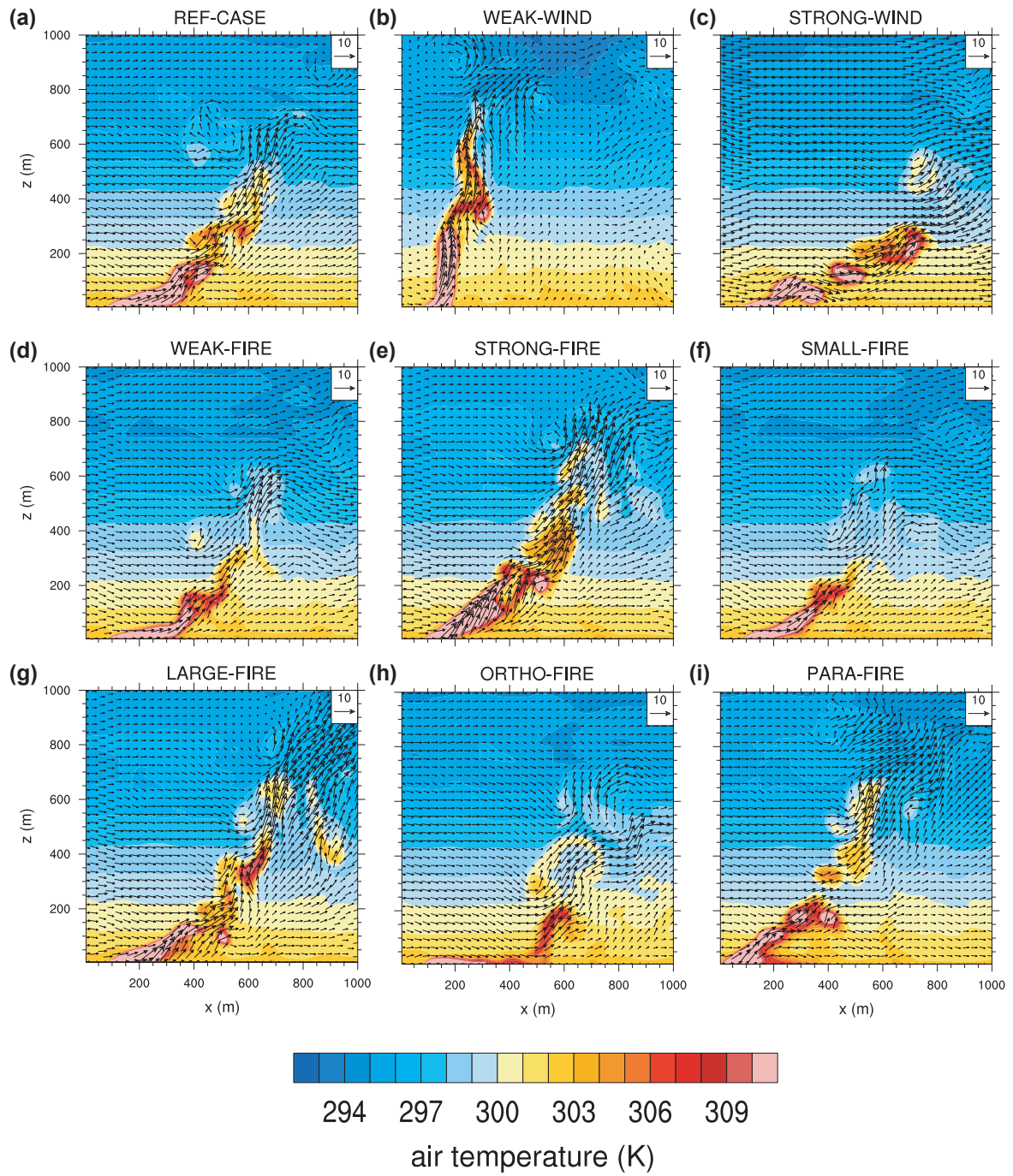
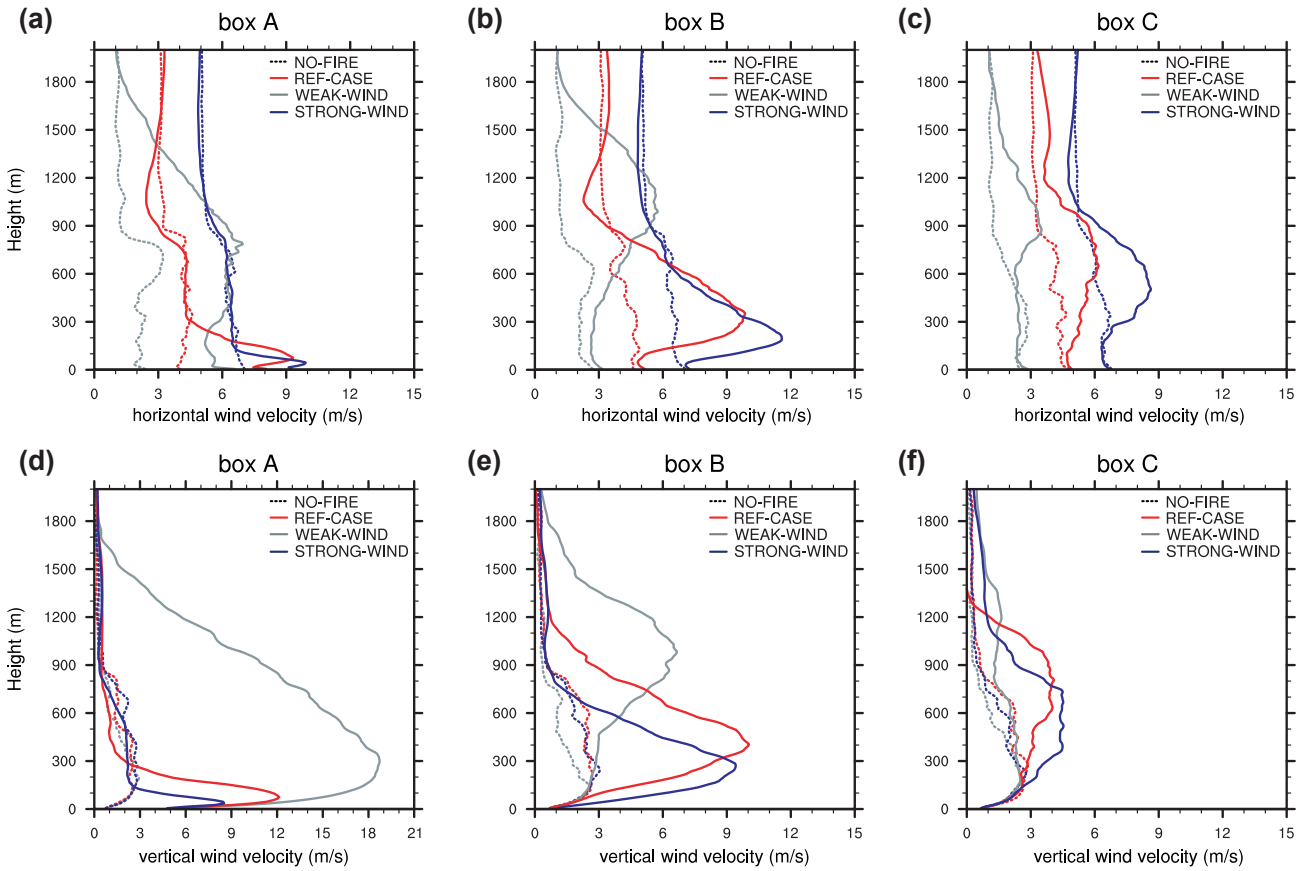



Figure 5. Vertical cross sections of the wind vector and air temperature fields ~~trough~~ through the fire center ($y = 600$ m) 20 minutes after fire ignition.

~~Vertical~~ profiles of the horizontal (upper row) and vertical (lower row) wind velocity for the ~~case~~ simulations ~~1-3~~ with a different ambient wind velocity (WEAK-WIND, REF-CASE, and STRONG-WIND) and different distances to the fire (box A, B, C in Fig. 2). Shown are the atmospheric profiles after fire ignition (solid line) with the profile in the undisturbed non-fire ~~PBL~~ situations (dashed line). Plotted are means of the maximum values per time step.

~~Vertical~~ profiles of the horizontal (upper row) and vertical (lower row) wind velocity for the ~~case~~ simulations ~~1-3~~ with a different ambient wind velocity (WEAK-WIND, REF-CASE, and STRONG-WIND) and different distances to the fire (box A, B, C in Fig. 2). Shown are the atmospheric profiles after fire ignition (solid line) with the profile in the undisturbed non-fire ~~PBL~~ situations (dashed line). Plotted are means of the maximum values per time step.

Figure 6. Vertical ~~cross sections of the turbulent kinetic energy (TKE) trough the fire center (y=600m) for all case simulations including the non-fire simulation (case 0) 20 minutes after fire ignition.~~

~~Vertical~~ profiles of the horizontal (upper row) and vertical (lower row) wind velocity for the ~~case~~ simulations ~~1-3~~ with a different ambient wind velocity (WEAK-WIND, REF-CASE, and STRONG-WIND) and different distances to the fire (box A, B, C in Fig. 2). Shown are the atmospheric profiles after fire ignition (solid line) with the profile in the undisturbed non-fire ~~PBL~~ situations (dashed line). Plotted are means of the maximum values per time step.

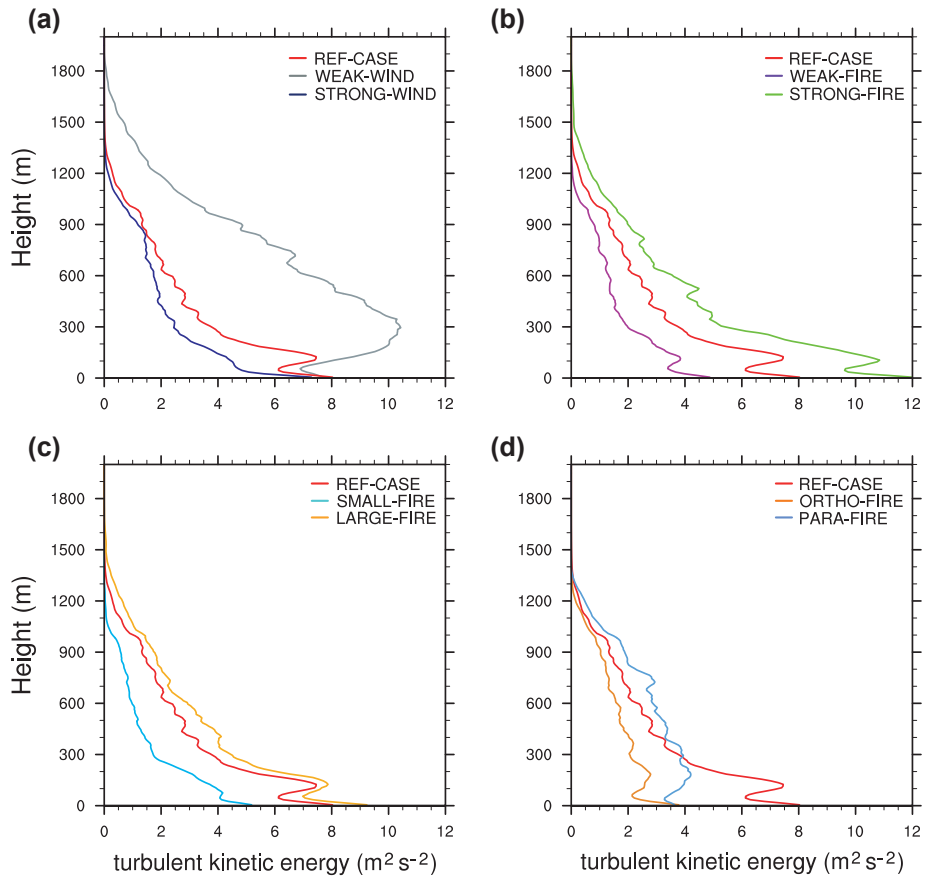



Figure 7. Vertical profiles of the turbulent kinetic energy (TKE) for the different case simulations. Compared are the impacts of (a) different ambient wind velocities, (b) fire intensities, (c) fire sizes, and (d) fire shapes/orientations. Plotted are means of the maximum values per time step.

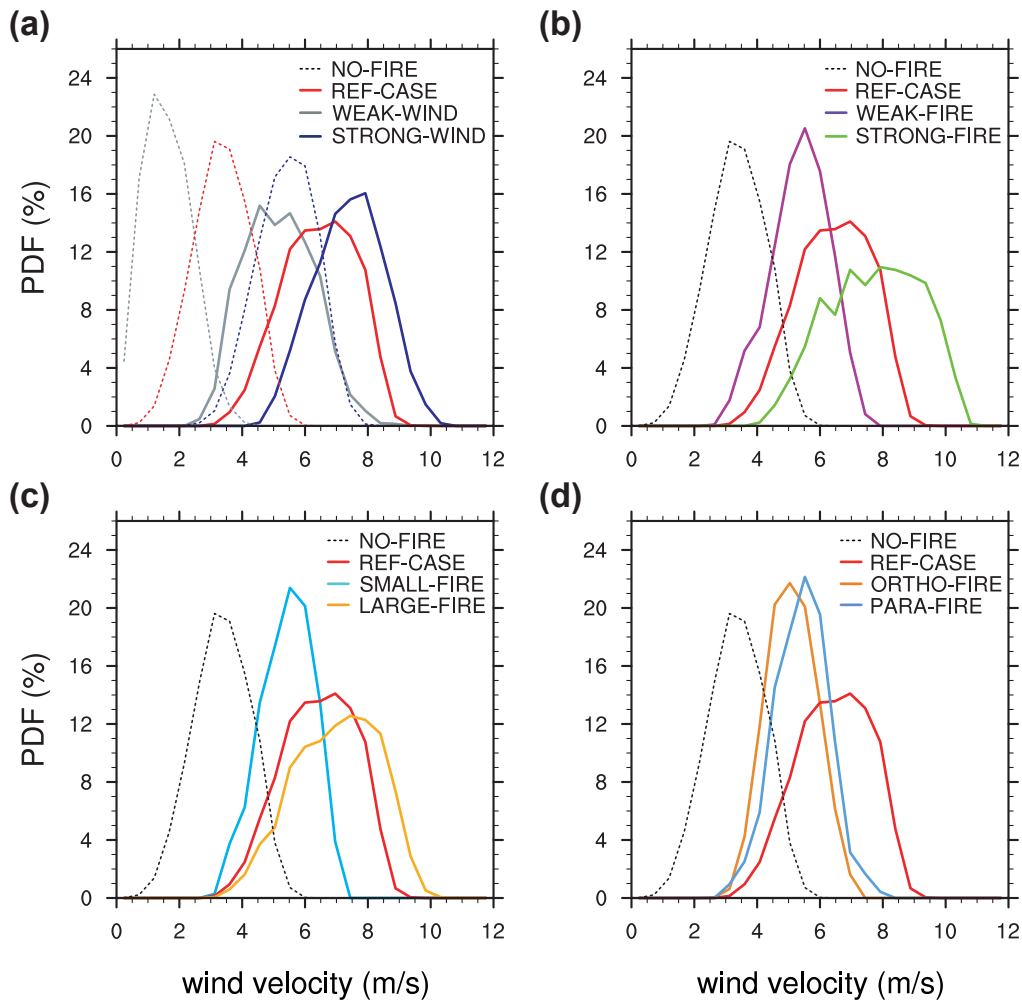



Figure 8. PDFs of the near-surface wind velocity ~~around~~ within the fire area ~~(box A)~~ for the different case simulations (solid lines) with respect to the PDFs of the non-fire ~~PBL~~ situations (dashed lines). ~~(a) compares~~ Shown are the impacts of different (a) ambient wind ~~velocity~~velocities, (b) ~~the impacts of the~~ fire ~~intensity~~intensities, (c) ~~the impacts of~~ fire ~~size~~sizes, and (d) ~~the impacts of the~~ fire ~~shape shapes and orientation~~ - always with respect to the ~~reference case 2.~~REF-CASE simulation.

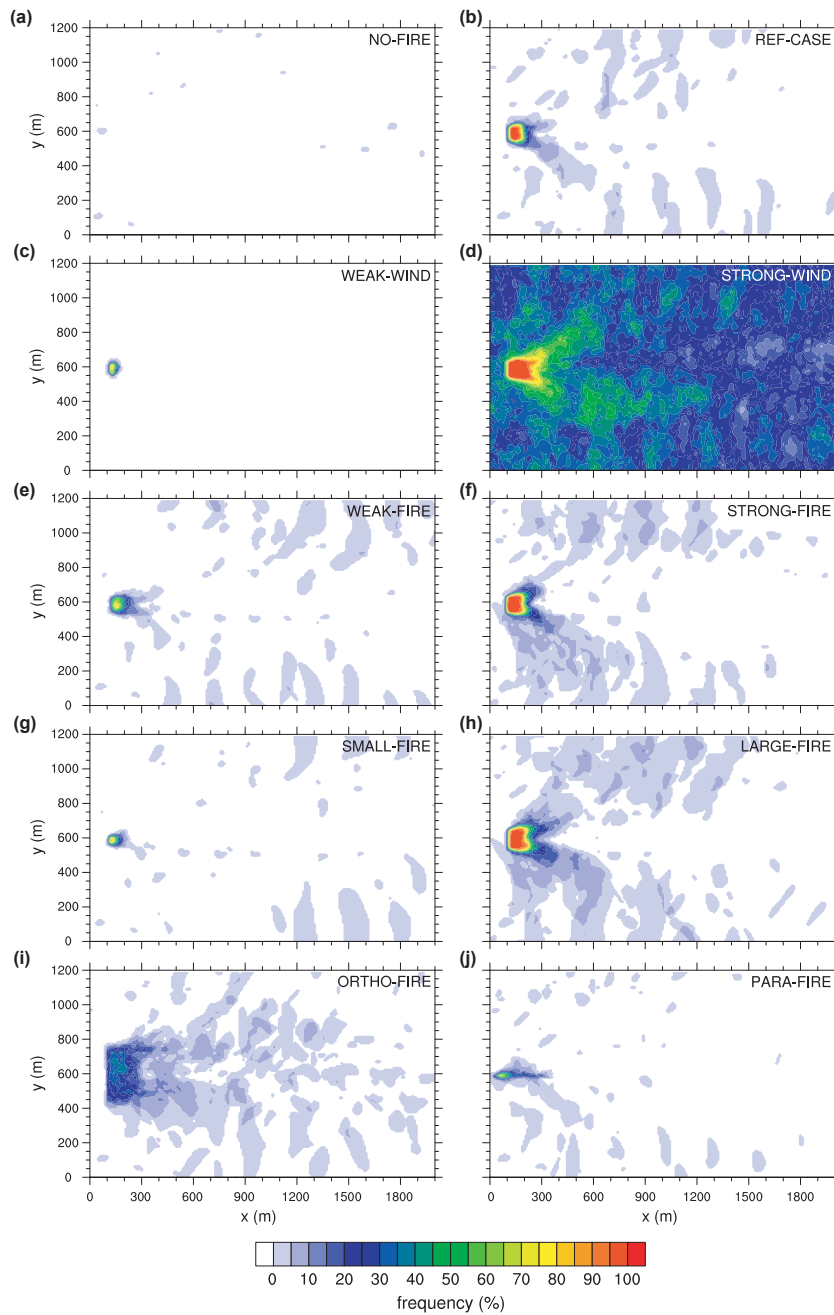



Figure 9. Spatial distribution of areas where a typical threshold velocity v_{tres} of ~~6.5~~6 m s^{-1} is ~~exceed~~ exceeded in the lowest model level. Shown is the frequency of occurrence of such wind velocities per grid cell.

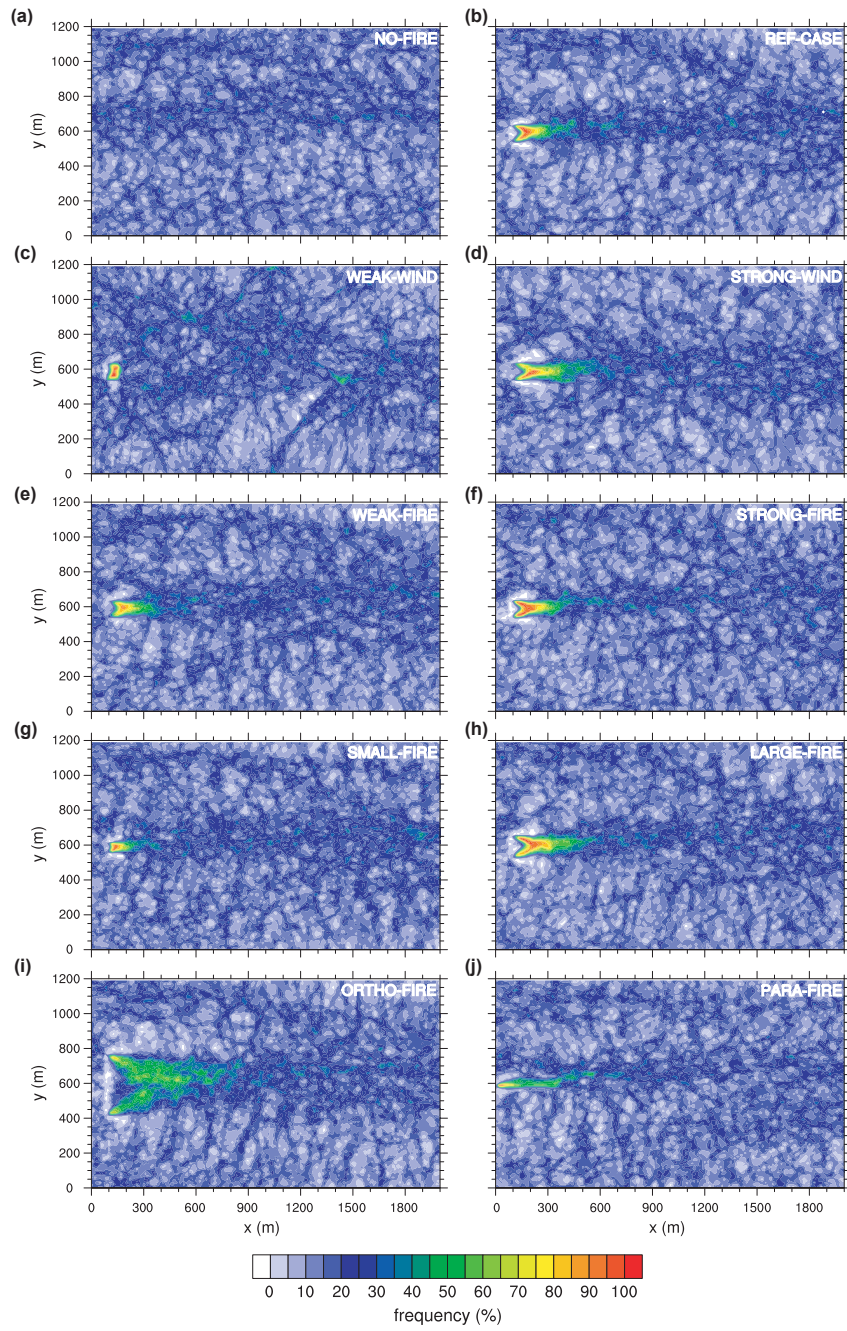



Figure 10. Spatial distribution of areas where the vertical wind velocity w_4 in the lowest model level is greater than $0.27\,\mathrm{m\,s^{-1}}$. Shown is the frequency of occurrence of such updraft velocities per grid cell.

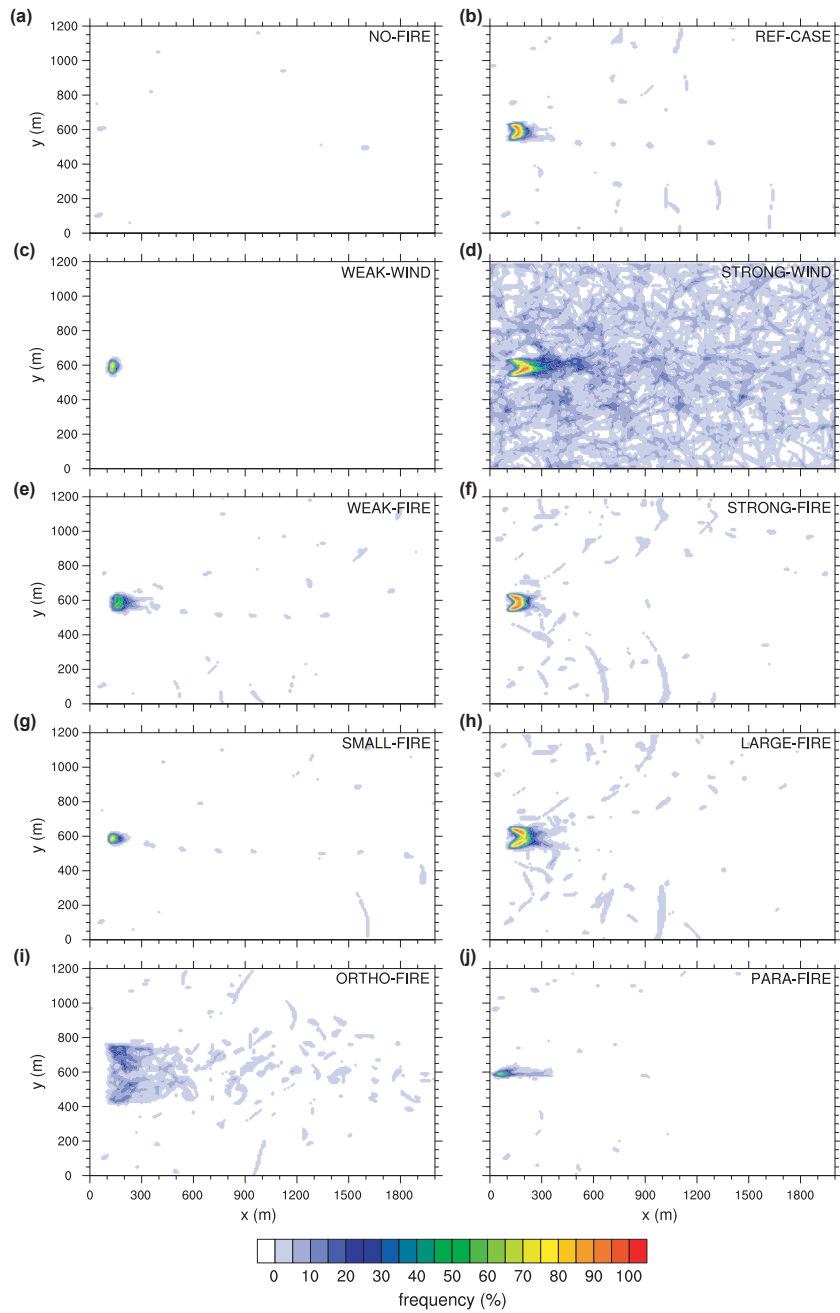



Figure 11. Spatial distribution of areas where both the horizontal threshold velocity $v_{\mathrm{tres}} = 6.5$ $v_{\mathrm{tres}} = 6$ m s^{-1} (cf. $\cancel{10}$Fig. 9) and a vertical wind velocity w_4 greater than 0.27 m s^{-1} (cf. $\cancel{11}$Fig. 10) are exceeded at the same time. Shown is the frequency of occurrence of such events per grid cell.

Vertical cross sections of the vertical wind velocity w trough the fire center (y=600m) for all case simulations including the non-fire simulation (case 0) 20 minutes after fire ignition.

Table 1. Overview of the case studies.

~~case~~ simulation name	~~$\lvert v_{10m}\rvert$~~ $\lvert u_g\rvert$ (m s^{-1})	F_{fire} (kW m^{-2})	~~T_{fire} (°C)~~ A_{fire} (m^2)	fire shape	description
~~0~~ NO-FIRE	3	-	-	-	~~–~~control run (no fire)
~~1~~ REF-CASE	~~1~~3	150	~~1000~~$7,000 = 70 \times 100$	~~7000 = 70x100~~ rectangular	weak ~~wind conditi~~ (moderate ambient w... properties)
~~2~~ WEAK-WIND	~~3~~1	150	~~1000~~$7,000 = 70 \times 100$	~~7000 = 70x100~~ rectangular	moderate wind condi... wind velocity
~~3~~ STRONG-WIND	5	150	~~1000~~$7,000 = 70 \times 100$	~~7000 = 70x100~~ rectangular	strong ~~wind conditi~~... velocity
~~4~~ WEAK-FIRE	3	75	~~800~~$7,000 = 70 \times 100$	~~7000 = 70x100~~ rectangular	weaker fire
~~5~~ STRONG-FIRE	3	270	~~1200~~$7,000 = 70 \times 100$	~~7000 = 70x100~~ rectangular	stronger fire
~~6~~ SMALL-FIRE	3	150	~~1000~~$1,800 = 40 \times 60$	~~1800 = 40x60~~ rectangular	smaller fire
~~7~~ LARGE-FIRE	3	150	~~1000~~$11,700 = 90 \times 130$	~~11700 = 90x130~~ rectangular	larger fire
~~8~~ ORTHO-FIRE	3	150	~~1000~~$7,000 = 20 \times 350$	~~7000 = 20x350~~ "line" (|)	line fire ~~(perpendicula...~~ direction
~~9~~ PARA-FIRE	3	150	~~1000~~$7,000 = 350 \times 20$	~~7000 = 350x20~~ "line" (–)	line fire ~~(parallel)~~ para...

Table 2. Fraction of the wind velocities larger than the non-fire limit for the direct fire area and the three boxes A, B, and C with different distances to the fire area (cf. Fig. 2). For the majority of the ~~cases~~ simulations with an ambient wind velocity of $3\,\mathrm{m\,s^{-1}}$, this upper non-fire threshold lies at $6\,\mathrm{m\,s^{-1}}$ (frequency of occurrence > 99.99 %). For ~~both setups with a weaker (case 1)~~ the WEAK-WIND and ~~a higher (case 3) ambient wind velocity~~ STRONG-WIND simulations, different threshold values of ~~4.5~~ 4 and 8 $\mathrm{m\,s^{-1}}$ are used. Additionally, the fractions concerning the $6\,\mathrm{m\,s^{-1}}$-limit are here indicated in brackets, too.

~~case~~ simulation	~~description~~ fire area	box A	box B	box C
	%	%	%	%
~~0~~ NO-FIRE	~~control run (no fire)~~ 0.05	0.03	0	0
~~1~~ REF-CASE	~~weak wind conditions~~ 63.3	~~7.4 (~~13.3	1.1	0.3
WEAK-WIND	85.8 (27.3)	9.8 (2.6)	~~0.04~~ 0.1 (0)	0 (0)
~~2~~ STRONG-WIND	~~moderate wind conditions~~ 31.0 (88.4)	~~13.3 1.1 0.3 3 strong wind conditions~~ 11.8 (56.0)	0.8 (42.4)	0 (28.3)
~~4~~ WEAK-FIRE	~~weaker fire~~ 24.7	6.6	0.4	1.1
~~5~~ STRONG-FIRE	~~stronger fire~~ 85.0	21.0	2.3	1.9
~~6~~ SMALL-FIRE	~~smaller fire~~ 25.0	3.2	0.05	1.5
~~7~~ LARGE-FIRE	~~larger fire~~ 74.4	25.7	4.0	1.6
~~8~~ ORTHO-FIRE	~~line fire (perpendicular)~~ 10.8	18.3	5.4	1.2
~~9~~ PARA-FIRE	~~line fire (parallel)~~ 25.8	4.6	0.5	0

Table 3. Relative fraction of the ~~excess~~ exceedance of a horizontal wind velocity of ~~6.5~~6 m s^{-1}, and relative fraction of a simultaneous ~~excess~~ exceedance of different vertical velocities of ~~$w_1 > 0.00014$~~$w_1 > 0.00014$ m s^{-1}, ~~$w_2 > 0.009$~~$w_2 > 0.009$ m s^{-1}, ~~$w_3 > 0.08$~~$w_3 > 0.08$ m s^{-1}, ~~$w_4 > 0.27$~~$w_4 > 0.27$ m s^{-1}, and ~~$w_5 > 5.1$~~$w_5 > 5.1$ m s^{-1}; each within the lowest model level at $z = 5$ m. The values concern ~~to~~ the model domain of ~~2 x 1.2~~2×1.2 km^2 shown in Fig. ~~10~~~~??~~11. Additionally, the peak values of the horizontal near-surface wind velocity and the total updraft velocity are provided.

~~case~~ simulation	~~description~~ f(v_{tres})	$|v_{\mathrm{max,srf}}|$	f(w_1)	
	%	(m s^{-1})	%	
~~0~~ NO-FIRE	~~control run (no fire)~~ 0.008	6.7	0.007	
~~1~~ REF-CASE	~~weak wind conditions~~ 0.9	9.3	0.4	
WEAK-WIND	0.09	9.9	0.09	
~~2~~ STRONG-WIND	~~moderate wind conditions 0.9 9.3 0.42 0.41 0.35 0.27 0.006 23.3 3 strong wind conditions~~ 30.8	10.6	~~12.93~~ 12.9	12
~~4~~ WEAK-FIRE	~~weaker fire~~ 0.6	~~0.61~~ 7.8	0.3	
~~5~~ STRONG-FIRE	~~stronger fire~~ 1.6	~~1.63~~ 10.9	0.7	
~~6~~ SMALL-FIRE	~~smaller fire~~ 0.3	~~0.32~~ 7.7	~~0.16~~ 0.2	
~~7~~ LARGE-FIRE	~~larger fire~~ 2.2	~~2.18~~ 10.5	~~0.91~~ 0.9	
~~8~~ ORTHO-FIRE	~~line fire (perpendicular)~~ 1.8	~~1.84~~ 8.7	~~0.89~~ 0.9	
~~9~~ PARA-FIRE	~~line fire (parallel)~~ 0.3	~~0.34~~ 8.0	~~0.15~~ 0.2	