



**The Impacts of Biomass Burning Activities on Convective Systems in
the Maritime Continent**

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34 **Abstract**

35 Convective precipitation associated with Sumatra squall lines and diurnal rainfall
36 over Borneo is an important weather feature of Maritime Continent in Southeast Asia.
37 Over the past few decades, biomass burning activities have been widespread during
38 summertime over this region, producing massive fire aerosols. These additional aerosols
39 brought to the atmosphere, besides influencing local radiation budget through directly
40 scattering and absorbing sunlight, can also act as cloud condensation nuclei or ice nuclei
41 to alter convective clouds and precipitation in the Maritime Continent via the so-called
42 aerosol indirect effects. Based on four-month simulations with or without biomass
43 burning aerosols conducted using the Weather Research and Forecasting model with
44 chemistry package (WRF-Chem), we have investigated the aerosol-cloud interactions
45 associated with the biomass burning aerosols in the Maritime Continent. Results from
46 selected cases of convective events have shown significant impacts of fire aerosols on the
47 weak convections in hydrometeors and rainfall amount either in the Sumatra or Borneo
48 region. Statistical analysis over the fire season also suggests that fire aerosols have
49 substantial impacts on the nocturnal convections associated with the local anticyclonic
50 circulation in the western Borneo. In addition, near surface heating from absorbing
51 aerosols emitted from fires could weaken land breezes and thus the convergence of
52 anticyclonic circulation. Therefore, the rainfall intensity of the nocturnal convections has
53 been significantly decreased during the fire events.

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55



56 **1 Introduction**

57 Biomass burning in Southeast Asia has become a serious environmental and societal
58 issue in the past decade due to its impact on local economy, air quality, and public health
59 (Miettinen et al., 2011; Kunii et al., 2002; Frankenberg et al., 2005; Crippa et al., 2016;
60 Lee et al., 2018). Abundant aerosols emitted from such fires not only cause
61 environmental issues but also affect regional weather and climate through the direct and
62 indirect effects of biomass burning aerosols (Grandey et al., 2016; Hodzic and Duvel,
63 2017; Jeong and Wang, 2010; Ramanathan and Carmichael, 2008; Taylor, 2010; Tosca et
64 al., 2013). Carbonaceous compounds such as black carbon (BC) in biomass burning
65 aerosols can reduce sunlight through both absorption and scattering to warm the
66 atmosphere while cool the Earth's surface (Fujii et al., 2014; Andreae and Gelencsér,
67 2006; Satheesh and Ramanathan, 2000; Ramanathan et al., 2001). Besides these direct
68 effects, biomass burning aerosols can act as cloud condensation nuclei or ice nuclei to
69 alter cloud microphysical structures and thus cloud radiation. Such “indirect effects” of
70 these aerosols on the climate are even more complicated due to various cloud and
71 meteorological conditions (Sekiguchi et al., 2003; Lin et al., 2013; Wu et al., 2013;
72 Grandey et al., 2016; Ramanathan et al., 2001; Wang, 2004).

73 For the Maritime Continent in Southeast Asia, convective precipitation associated
74 with the so-called Sumatra squall lines (SSL) and diurnal rainfall over Borneo is an
75 important weather feature (Lo and Orton, 2016; Ichikawa and Yasunari, 2006; Koh and
76 Teo, 2009; Yi and Lim, 2006; Wu et al., 2009). Convections of SSL are initially formed
77 in the northwestern side of Sumatra by the prevailing sea breezes from Indian Ocean and
78 the Sumatran mountain range, then propagate over the Malacca Strait affecting the Malay



79 Peninsula. Lo and Orton (2016) analyzed 22-year (1988 to 2009) ground-based Doppler
80 radar data and identified a total of 1337 squall lines in Singapore. They found that these
81 events with the diurnal cycle of rainfall most occur during either the summer monsoon
82 season (June-September) or the inter-monsoon periods (April-May and October-
83 November). Singapore, for example, experiences typically about 6~7 squall lines per
84 month during these periods. Oki and Musiake (1994) analyzed the seasonal and diurnal
85 cycles of precipitation using rain gauge data and showed that large-scale low-level winds
86 are a critical modulating factor in the diurnal cycle the convective rainfall over Borneo
87 besides the general reason of land-sea contrast behind convective rainfall in the Maritime
88 Continent. Furthermore, Ichikawa and Yasunari (2006) used five years Tropical Rainfall
89 Measuring Mission (TRMM) precipitation radar (PR) data to investigate the role of the
90 low-level prevailing wind in modulating the diurnal cycle of rainfall over Borneo. They
91 found that the diurnal cycle is associated with intraseasonal variability in the large-scale
92 circulation pattern, with regimes associated with either low-level easterlies or westerlies
93 over the island.

94 Interestingly, frequent biomass burning activities coincide with vigorous convective
95 systems in the Maritime Continent, especially during the summer monsoon season (June-
96 September), and could thus produce aerosols to affect convections in the region.
97 Rosenfeld (1999) analyzed TRMM data and hypothesized that abundant biomass burning
98 aerosols could practically shut off warm rain processes in tropical convective clouds.
99 Compared to the adjacent tropical clouds in the cleaner air, clouds encountered with
100 smokes could grow to higher altitudes with rain suppressed, hypothetically due to the
101 reduction of coalescence efficiency of smaller cloud drops into raindrops. Recently,



102 using Weather Research and Forecasting model with Chemistry (WRF-Chem), Ge et al.
103 (2014) have studied the direct and semi-direct radiative effects of biomass burning
104 aerosols over the Maritime Continent and found the radiative effect of biomass burning
105 aerosols could alter planetary boundary layer (PBL) height, local winds (including sea
106 breeze), and cloud cover. However, relative coarse resolution (27 km) adopted in their
107 simulation would not be able to reveal more details about how biomass burning aerosols
108 affect convective clouds through modifying cloud microphysics processes. Whereas,
109 Hodzic and Duvel (2017) have conducted a 40-day simulation using WRF-Chem with a
110 convection-permitting scale (4 km) to study the fire aerosol-convection interaction during
111 boreal summer in 2009 near the central Borneo mountainous region. Their result
112 suggests that modifications of the cloud microphysics by biomass burning aerosols could
113 reduce shallow precipitation in the afternoon and lead to a warm PBL anomaly at sunset,
114 all lead to an enforcement of deep convection at night. However, they have also
115 indicated that the radiative processes of moderately absorbing aerosols tend to reduce
116 deep convection over most regions due to local surface cooling and atmosphere warming
117 that increase the static stability, hence suggesting the complexity of the interaction of
118 biomass burning aerosols and convective clouds in the Maritime Continent.

119 In this study, we aim to examine and quantify the impacts of biomass burning
120 aerosols on convective systems over two targeted regions for analyses: the northern
121 Sumatra and the western Borneo in the Maritime Continent. Our focus is on not only the
122 change of hydrometeors in the convective clouds but also the change of rainfall amount
123 and intensity in these regions. We firstly describe methodologies adopted in the study,
124 followed by the results and findings from our numerical simulations over the Maritime



125 Continent. We have selected three cases in each study region to perform detail analyses.
126 In addition, statistical analyses covering the entire modeled fire season for each of these
127 two regions have also been performed to provide more generalized pictures about the
128 effects of fire aerosol on convection. The last section summarizes and concludes our
129 work.

130 **2 Methodology**

131 **2.1 Model and emission inventories**

132 In order to simulate trace gases and particulates interactively with the meteorological
133 fields, the Weather Research and Forecasting model coupled with a chemistry module
134 (WRF-Chem, see Grell et al. (2005)) version 3.6.1 is used in this study. Within WRF-
135 Chem, the Regional Acid Deposition Model, version 2 (RADM2) photochemical
136 mechanism (Stockwell et al., 1997) coupled with the Modal Aerosol Dynamics Model for
137 Europe (MADE) as well as the Secondary Organic Aerosol Model (SORGAM)
138 (Ackermann et al., 1998; Schell et al., 2001) are included to simulate atmospheric
139 chemistry and anthropogenic aerosol evolutions. MADE/SORGAM uses a modal
140 approach to represent the aerosol size distribution and predicts mass and number
141 concentrations of three aerosol modes (Aiken, accumulation, and coarse).

142 To resolve the convective system in the Maritime Continent in our simulations, two
143 model domains with two-way nesting are designed. Here, Domain 1 (431×141 grid
144 cells) has a resolution of 25 km, while Domain 2 (561×591 grid cells) has a resolution
145 of 5 km (Fig. 1). Specifically, Domain 1 is positioned to include the tropical Indian
146 Ocean on its west half in order to capture the path of Madden-Julian Oscillation (MJO),



147 and in the meantime to have a northern boundary constrained within 23°N in latitude to
148 avoid potential numerical instability from the terrain of Tibetan Plateau. Domain 2 with
149 a finer resolution is positioned to cover the mainland Southeast Asia as well as the islands
150 of Sumatra and Borneo. The National Center for Environment Prediction FiNaL (NCEP-
151 FNL) reanalysis data (National Centers for Environmental Prediction, 2000) are used to
152 provide initial and boundary meteorological conditions, and to perform four-dimensional
153 data assimilation (FDDA) to nudge model temperature, water vapor, and zonal and
154 meridional wind speeds above the planetary boundary layer (PBL) for Domain 1. The
155 Mellor-Yamada-Nakanishi-Niino level 2.5 (MYNN) (Nakanishi and Niino, 2009) is
156 chosen as the scheme for planetary boundary layer in this study. Other physics schemes
157 adopted in the simulations include Morrison two-moment microphysics scheme
158 (Morrison et al., 2009), RRTMG longwave and shortwave radiation schemes (Mlawer et
159 al., 1997; Iacono et al., 2008), Unified Noah land-surface scheme (Tewari et al., 2004),
160 and Grell-Freitas ensemble cumulus scheme (Grell and Freitas, 2014) (for Domain 1
161 only).

162 WRF-Chem needs emissions for gaseous and particulate precursors to drive its
163 simulations. For this purpose, we have used the Regional Emission inventory in ASia
164 (REAS) version 2.1 (Kurokawa et al., 2013). REAS includes emissions of most primary
165 air pollutants and greenhouse gases, covering each month from 2000 to 2008. In
166 addition, the Fire INventory from U.S. National Center for Atmospheric Research
167 (NCAR) version 1.5 (FINNv1.5) (Wiedinmyer et al., 2011) is also used in the study to
168 provide biomass burning emissions. FINNv1.5 classifies burnings of extratropical forest,
169 tropical forest (including peatland), savanna, and grassland. Fire heat fluxes for four



different types of fire are prescribed in WRF-Chem to calculate the plume height (rf. Table 1 in Freitas et al. (2007)). For peatland fire, we have set its heat flux as 4.4 kW m^{-2} , which is the same as that of savanna burning and differs from that of the tropical forest burning in 30 kW m^{-2} . The modified the plume rise algorithm in WRF-Chem to specifically improve the representation of tropical peat fire has been described in Lee et al. (2017). It is worth indicating that the heat flux from biomass burning is not incorporated in thermodynamic equation of current WRF-Chem model.

The default chemical profiles of several species in the lateral boundary condition are higher than their background concentrations in our study region and thus equivalent to provide additional aerosol sources from boundaries. To prevent this, we have set NO , NO_2 , SO_2 , and all primary aerosol levels to zero at the lateral boundaries of Domain 1. We have also adjusted the ozone profile used for lateral boundary condition based on the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) station in Bukit Kototabang, Indonesia (Lee et al. (2019)).

2.2 Numerical experiment design

Two numerical simulations, both include fossil fuel emissions while either with and without the biomass burning emissions (labeled as FFBB and FF, respectively), have been conducted to investigate the impacts of biomass burning aerosols on convective systems in the Maritime Continent through both direct and indirect effects. Our study focuses on the fire season from June to September of 2008. Therefore, the simulations start from 1 May of 2008 and last for five months. The first month is used as a spin-up period. Among the years with available emission data, both emission amount of biomass burning and total precipitation in 2008 approximate their ensemble mean or represent an



193 average condition. Nevertheless, interannual variation of biomass burning emissions
194 alongside precipitation in the studies regions do exist (Lee et al., 2017; Lee et al., 2018),
195 and the influence of such variation on the effects of fire aerosol on convection should be
196 addressed in future studies.

197 **2.3 Analysis methods**

198 The primary target of this study is the convective systems associated with Sumatra
199 squall lines and diurnal rainfall over Borneo. Thus, our analyses mainly focus on the
200 convections over two specific regions: the Sumatra region (r1 in Fig. 1) and the Borneo
201 region (r2 in Fig. 1). The area coverage of the Sumatra region (r1) is from 97° to 103° E
202 in longitude and 0° to 6° N in latitude, while the area coverage of the Borneo region (r2)
203 is from 109° to 115° E in longitude and 1° S to 5° N in latitude.

204 To examine the impacts of fire aerosols on cloud formation and rainfall intensity as
205 well as amount, we have selected three convective systems each for the two focused
206 regions to perform an in-depth case study. We first trace the path of individual
207 convections and focus the analyses on the specific area of each of these convective
208 systems to identify the impacts of fire aerosols. Table 1 shows the selected cases in the
209 Sumatra region (r1) and the Borneo region (r2).

210 The consequent analyses are then focused on the fire-season-wise statistics of
211 convections for each study region. Table 2 shows the fire periods in the two study
212 regions. There are total of 54 convective systems simulated during the fire periods in the
213 Sumatra region (r1) and 35 convective systems in the Borneo region (r2).



The statistical quantities used in this study follows Wang (2005) to estimate the mean value over a specific region (e.g., r1 or r2). The cloud area mean quantities are defined as a function of output time step (t) by the following equation:

$$\bar{c}^{area}(t) = \frac{1}{N(t)} \sum_{\substack{q > q_{min} \\ n > n_{min}}} c(x, y, z, t). \quad (1)$$

Here c is a given quantity (e.g., cloud water mass). Eq. (1) only applies to the grid points where both the mass concentration q and number concentration n of a hydrometeor exceed their given minima. The total number of these grid points at a given output time step t is represented by $N(t)$. The cloud area mean quantities are used to present the average quantities of a given variable at a given output time step. Note that the cloud area mean quantities only apply to hydrometeors. For rainfall, the analyzed quantities are spatial averages over a specific area of the convective system for case study or over the entire study region for longer-term statistic estimate.

3 Results

3.1 Model evaluation

3.1.1 Precipitation

The satellite-retrieved precipitation of the Tropical Rainfall Measuring Mission (TRMM) 3B42 3hrly (V7) dataset (Huffman et al., 2007) is used in this study to evaluate simulated rainfall. Figure 2a and 2b show the Hovmöller plots of daily TRMM and FFBB precipitation from 1 June 2008 to 30 September 2008, respectively. Compared to the satellite-retrieved data, the model has captured all the major rainfall events in the two analysis regions (Fig. 3). In addition, because of its higher spatial resolution than



235 TRMM, the model produces more light rain events. Nevertheless, as indicated in our
236 previous study (Lee et al., 2017), a wet bias of the model is evident and mainly comes
237 from water vapor nudging in data assimilation (FDDA). As a result, the daily average
238 rainfall in FFBB over the Sumatra region (r1) is 11.05 ± 5.90 mm day⁻¹ from 1 June 2008
239 to 30 September 2008, higher than that of 7.21 ± 5.54 mm day⁻¹ derived from TRMM
240 retrieval. The wet bias also exists in the modeling results in the Borneo region (r2),
241 where daily average rainfall there is 15.40 ± 8.49 mm day⁻¹ in FFBB and only 9.56 ± 7.20
242 mm day⁻¹ in TRMM. For the simulated rainfall in FFBB, the temporal correlation with
243 TRMM is 0.44 in the Sumatra region (r1) and 0.64 in the Borneo region (r2).

244 3.1.2 Aerosol optical depth (AOD)

245 Because of limited ground-based observational data of aerosols, we use Aerosol
246 Optical Depth (AOD) from the level-3 Moderate Resolution Imaging Spectroradiometer
247 (MODIS) gridded atmosphere monthly global joint product (MOD08_M3;
248 http://dx.doi.org/10.5067/MODIS/MOD08_M3.061) to evaluate modeled aerosol spatial
249 distribution and relative concentration. Figure 4a shows MODIS monthly AOD in
250 Southeast Asia in September 2008. High AOD occurs in the southern part of Sumatra
251 and the southwestern part of Borneo. Compared to the MODIS retrieval, the modeled
252 AOD in FFBB has similar spatial distribution but a higher value (Fig. 4b). It is because a
253 high spatiotemporal resolution in our simulation enables the model to capture episodic
254 fire events better. In contrast, FF simulation produces much lower AOD values than
255 those of MODIS and FFBB, thus suggesting biomass burning aerosols make a substantial
256 fraction in atmospheric AOD during burning seasons.



257 **3.1.3 Sounding profiles**

258 We have used multiple weather sounding profiles measured in Bintulu Airport,
259 Malaysia (113.03° E, 3.20° N), provided by University of Wyoming
260 (<http://weather.uwyo.edu/upperair/sounding.html>). An example for detailed summary is
261 a case at 12 UTC on 22 September 2008 (Fig. 5a). This sounding provides information
262 of atmospheric state (e.g., vertical distributions of pressure, temperature, wind speed,
263 wind direction, and humidity) coinciding with one of our selected case study (r2c3) of
264 diurnal convective rainfall in Borneo. Compared to the observed sounding data, the
265 FFBB simulation has produced similar temperature and wind profiles and well captured
266 the low-level and high-level wind speeds and wind directions (Fig. 5a versus 5b). It also
267 well predicts several key indexes of convection: temperature and pressure of the Lifted
268 Condensation Level (LCL) simulated in FFBB are 296.2 K and 955 hPa, respectively,
269 which are close to the values of 296.2 K in temperature and 960.7 hPa in pressure derived
270 from the observed sounding data. The model predicts 3049 J of Convective Available
271 Potential Energy (CAPE), while 2031 J of CAPE is estimated in the observed sounding
272 data. Besides this 22 September 2008 case, the model has also captured major features of
273 observed profiles for all the other cases selected in our analyses.

274 **3.1.4 Cloud vertical structure**

275 The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)
276 provides information of the vertical structure of clouds on its path around the globe
277 (https://www-calipso.larc.nasa.gov/products/lidar/browse_images/production/), including
278 that of one of our cases (r2c3) of diurnal convective rainfall in Borneo on September 22,



279 2008 (Fig. 6a). For this case, CALIPSO shows the vertical structure of a convective
280 system over Borneo along with high $\text{PM}_{2.5}$ concentration near the surface (yellowish
281 color near the surface), implying a potential impact of biomass burning aerosols on
282 convective clouds. It can be seen that the FFBB simulations well captures the vertical
283 structure of convective clouds as well as the near-surface aerosol layers, including their
284 vertical extension (Fig. 6c versus 6a). With the comparison of FF simulation, we are able
285 to identify the biomass burning origin of these aerosols near the surface.

286 **3.2 Analyses of selected cases in two study regions**

287 **3.2.1 The Sumatra region (r1)**

288 The three selected cases in r1 or the Sumatra region (r1c1, r1c2 and r1c3) all
289 occurred in the afternoon (2 PM or 5 PM local time) and lasted less than 24 hours (Table
290 1). Most fire aerosols in this study region were initially emitted from the central and
291 south Sumatra then transported along with southwesterly winds to encounter convections
292 in the northern Sumatra. Compared to the result of FF, $\text{PM}_{2.5}$ concentration in FFBB can
293 be 6~12 times higher in the Sumatra region (r1) in these selected cases (Fig. 7).

294 Aerosols from biomass burning in FFBB add 2~3 times more cloud droplet number
295 concentration and 8~20% higher cloud water mass compared to the results in FF (Table
296 2). The mean radius of cloud droplets in FFBB is about 6~7 μm , clearly smaller than that
297 in FF (10~11 μm). Smaller cloud droplet in FFBB reduces the efficiency of
298 autoconversion, and further decreases rain water mass and raindrop number
299 concentration. Hence, raindrop number concentration in FFBB is 40~50% lower than
300 that in FF among our selected cases in r1 (Table 3). However, besides autoconversion,



rain water mass is also affected by other microphysics processes. Larger raindrops combining smaller cloud droplets in FFBB can increase the efficiency of cloud droplet collection by rain and thus produce higher rain water mass but number, possibly compensating the decrease of rain water mass resulted from lowered autoconversion. Overall, rain water mass decreases 15% in the case of r1c2 and 10% in the case of r1c3, respectively. Compared to the cases of r1c2 and r1c3, the case of r1c1 is a relatively weak convective system. After introducing fire aerosols, the mass concentration of snow and graupel in this case increases 62% and 48%, respectively. Melting snow and graupel in the lower atmosphere results in a significant increase of rain water mass concentration by 49%. Thus, total hydrometeor mass is increased by 36% in FFBB from that in FF. Note that the “aerosol-aware” microphysics scheme in WRF-Chem only applies to the warm cloud process (Morrison et al., 2005; Morrison et al., 2009); therefore, ice nucleation is parameterized of ambient temperature only regardless of the aerosol concentration.

In the FF simulations, the convective system in the case of r1c2 and r1c3 is stronger than the system in the case of r1c1, and the average rainfall of r1c2 and r1c3 is also higher than the rainfall of r1c1 (Table 4). Adding fire aerosols in FFBB does not substantially change the average rainfall in r1c2 and r1c3 (+3% and -8%, respectively; Table 4). However, in the relatively weak convective system of r1c1, adding fire aerosols significantly increases the mean rainfall amount by 106% ($1.33 \pm 0.47 \text{ mm } 3\text{hr}^{-1}$ in FF versus $2.74 \pm 1.21 \text{ mm } 3\text{hr}^{-1}$ in FFBB).



3.2.2 The Borneo region (r2)

The three selected cases in r2 (r2c1, r2c2, and r2c3) also occurred during the summer monsoon season when active biomass burning events existed in the west Borneo. In these cases, fire aerosols were transported to the north and northeast by the southeasterly and southwesterly winds. Because of the proximity of fire emissions, the $PM_{2.5}$ concentration in FFBB can be 24 times higher than that in FF in the Borneo region (r2) in these selected cases (Fig. 7).

The modeled results demonstrate the substantial impacts of fire aerosols on both ambient aerosol concentration and cloud droplet number concentration. $PM_{2.5}$ concentration in FFBB is drastically higher than that in FF with the highest increase appears in the case of r2c1 at 4940%, more than doubled the values of r2c2 (2402%) and r2c3 (2422%). The increase in cloud droplet number concentration in the case of r2c1 (703%) is also substantially higher than those in r2c2 (337%) and r2c3 (409%) (Table 2). The mean radius of cloud droplets in FFBB is about 6~7 μm , which is substantially smaller than that in FF (10~11 μm). The mean cloud droplet radii in FF and FFBB in r2 are similar to the results in r1. On the other hand, the increase of cloud water mass due to fire aerosols is not so dramatic in all these cases, only about 8%~27% higher than that in the FF simulations (Table 3). As discussed above, rain number concentration in FFBB over the Borneo region (r2) is lower than that in FF, similar to the cases in r1, likely due to the low efficiency of autoconversion induced by the presence of a large quantity of smaller cloud droplets. Rain water mass of FFBB in the r2c1 case is decreased by about 6% due to fire aerosols, which is similar to the results in the r1c2 and r1c3 cases over the Sumatra region (Table 3). However, interestingly, rain water and snow mass are both



substantially increased in FFBB by 64% and 69% in r2c2 and by 19% and 60% in r2c3, respectively (Table 3). The cases of r2c2 and r2c3 are relatively weak convective systems, similar to the case of r1c1. Our results show that fire aerosols have substantial impacts on cold cloud processes in the weak convective systems. Overall, total hydrometeor mass concentration in FFBB have increased 47% in r2c2 and 13% in r2c3.

The changes of rainfall amount due to fire aerosols in r2 are similar to the cases in r1. For the strong convection case of r2c1, adding fire aerosols in the FFBB simulation decreases the total rainfall amount by 18%. However, in the weak convection cases of r2c2 and r2c3, adding fire aerosols would double the rainfall amount (Table 4). Compared to the results in FF, rainfall intensity is persistently higher in FFBB during the convection life cycle in those weak convection cases. Nighttime rainfall intensity in FFBB, especially, is much higher than the rainfall intensity in FF. Therefore, as shown by our results, fire aerosols appear to have more substantial impacts on the quantities of hydrometeors and rainfall of the weak convection cases in both Sumatra region (r1) and Borneo region (r2).

3.3 Fire-season statistics of convections in two study regions

Statistics covering the entire simulated fire season (~4 months) for each study region have been derived to provide trend/tendency information regarding several aspects of the impact of fire aerosols on convections. In our simulations, $PM_{2.5}$ concentration in FF during the fire periods, which can be regarded as the background value for FFBB simulation before adding fire aerosols, is $1.36 \pm 0.19 \mu g m^{-3}$ in r1 and $0.56 \pm 0.09 \mu g m^{-3}$ in r2. In comparison, $PM_{2.5}$ concentration in FFBB is $11.37 \pm 10.41 \mu g m^{-3}$ in r1 and



367 $10.07 \pm 7.73 \mu\text{g m}^{-3}$ in r2. Note that unlike in some other studies where the control
368 simulations use constant aerosol concentrations, fire aerosol concentrations in our
369 simulations can vary in responses to changes in fire emissions, or aerosol removal by rain
370 scavenging due to precipitation change caused by fire aerosols themselves. Hence, the
371 processes included in our simulations are closer to reality, and the results could better
372 reflect the nature of fire aerosol-convection interaction in the Maritime Continent.

373 Averaged through the entire modeled fire periods, cloud water mass (Q_c), cloud
374 droplet number concentration (Q_{nc}), and rain drop number concentration (Q_{nr}) in FFBB
375 differ substantially from those in FF, demonstrating the influence of fire aerosols. Figure
376 8 shows that adding fire aerosols in FFBB would increase Q_c by 14% and Q_{nc} by 226%
377 in r1, and Q_c by 18% and Q_{nc} by 349% in r2. Another pronounced change in response to
378 adding fire aerosols is a decrease in Q_{nr} by 44% in r1 and 47% in r2. Although an
379 increase in snow mass (Q_s) and graupel mass (Q_g) and a decrease in rain water mass (Q_r)
380 after adding fire aerosols, the uncertainty of these hydrometeor changes is large.

381 In Sect. 3.2, we have discussed the significant rainfall increase occurred in the weak
382 convective systems after adding fire aerosols. Here we use the fire-season statistics to
383 further this discussion. Regardless the strength of convective precipitation, the mean 3-
384 hourly rainfall during the fire periods is $1.06 \pm 0.85 \text{ mm } 3\text{hrs}^{-1}$ in FF and $1.09 \pm 0.86 \text{ mm } 3\text{hrs}^{-1}$
385 3hrs^{-1} in FFBB over the Sumatra region (r1), statistically does not change. The rainfall
386 difference in the Borneo region (r2) between FF and FFBB is also insignificant
387 ($1.32 \pm 1.20 \text{ mm } 3\text{hrs}^{-1}$ in FF versus $1.35 \pm 1.14 \text{ mm } 3\text{hrs}^{-1}$ in FFBB).

388 On the other hand, based on the diurnal rainfall pattern in two study regions, we
389 notice that daily maximum and minimum rainfall show apparent differences between the



FFBB and FF simulations in r2, while such differences are rather small in r1 (Fig. 9). The maximum or minimum rainfall intensity in the two simulations are closely aligned with the 1:1 line in Fig. 9a and 9b. However, when looking into each of the 54 convective events in r1, there are 30 events where the model predicted higher maximum and minimum rainfall intensity in FFBB than in FF. These are mostly weak convective events.

Additionally, and somewhat opposite to the rainfall statistics in r1, the intensity of maximum and minimum rainfall in r2 is higher in FF than in FFBB. The daily rainfall peak in r1 is mostly less than $3 \text{ mm } 3\text{hrs}^{-1}$; in comparison, one-third of convective events in r2 have daily maximum rainfall exceeding $3 \text{ mm } 3\text{hrs}^{-1}$. We have categorized the maximum rainfall based on its values in the afternoon and midnight. We find that those heavy maximum rainfalls in r2 tend to occur in the midnight (Fig. 9c) associated with the anticyclonic circulation formed in the western Borneo induced by southeasterly winds from the Southern latitude turn northeastward along the west coast of Borneo, owing to the terrain of Borneo Island and the sea breezes from the South China Sea. The vortex produced by such a circulation leads to strong updraft and then strong convection. Note that this anticyclonic circulation is different from the Borneo vortex, the latter appears as a persistent feature of the boreal winter climatology and is related to the northeasterly from the South China Sea and cold surge events (Chang et al., 1983; Chang et al., 2005).

The low-level wind pattern of Borneo convections is similar to the westerly regime, especially the weak westerly (WW) regime identified by Ichikawa and Yasunari (2006). According to their analysis, the WW regime tends to occur in boreal summer. Its composites include an anticyclonic feature with the weak wind field over the Borneo



413 Island. The deep convective storms developed in the WW regime tend to stay close to
414 the west coast associated with the lower-level convergence enhanced by the prevailing
415 wind and local circulations around there, resulting in localized rainfall over the offshore
416 region of the west coast. Based on our simulations, the onset of convection occurs in the
417 afternoon over the western mountain range of Borneo. These storms would consequently
418 evolve into widespread shallow storms in the evening over the western part of the island.
419 The maximum rainfall appears on the west coast because of a local westward propagating
420 rainfall system that develops around midnight or early morning.

421 The comparison of the maximum rainfall between FF and FFBB in Fig. 9 shows that
422 fire aerosols tend to reduce the maximum rainfall, especially for high-intensity rainfall
423 events. In other words, fire aerosols have substantial impacts on the nocturnal
424 convections, which are associated with the local anticyclonic circulation in the western
425 Borneo. This effect on nocturnal convections in the western Borneo by fire aerosols will
426 be discussed further in the next section.

427 **3.4 The impact of biomass burning activities on nocturnal** 428 **convections in the Borneo region**

429 To further analyze the effects of fire aerosols on nocturnal convections, we have
430 categorized convective events into nocturnal convections (NC) and non-nocturnal
431 convections (non-NC), based on whether the maximum rainfall occurs from midnight to
432 early morning or in the time frame from late afternoon to evening. Figure 10 shows the
433 diurnal time series of precipitation averaged over the Borneo region ($r2$) in FF and FFBB.



434 Again, 3-hour-mean rainfalls of nocturnal convections are higher than those of non-
435 nocturnal convections in both simulations.

436 Nocturnal convections tend to stay close to the west coast associated with a lower-
437 level convergence enhanced by the prevailing wind and local circulations mainly related
438 to the land breezes from inland of the western Borneo. The strong convergence near the
439 surface over the offshore region of the west coast causes the weak westerly monsoon
440 windflaws and local land breezes to merge during the nighttime. However, during the
441 fire periods, the daytime absorption of fire aerosols (e.g., black carbon) can cause an
442 atmospheric warming (even without fire generated heating flux being incorporated in the
443 model). This could increase near surface air temperature, weaken land breezes and thus
444 surface convergence. As a result, the nocturnal convections in FFBB cannot develop as
445 strong as those in FF. On the other hand, both nocturnal and non-nocturnal convections
446 are initiated over the western mountain range under a prevailing wind of the sea breezes
447 from the South China Sea. The increases of near surface temperature owing to the fire
448 aerosols can enhance this prevailing wind from the ocean and thus lead to a higher
449 convective rainfall in FFBB during the onset stage of the nocturnal convections as well as
450 non-nocturnal convections.

451 Diurnal evolution of vertical profiles clearly indicates that mass mixing ratio of total
452 hydrometeors, temperature, and vertical velocity differ in both daytime and nighttime
453 between FF and FFBB for those nocturnal convections (Fig. 11). The differences of near
454 surface temperature between FF and FFBB are more pronounced during the period after
455 sunset (Fig. 11d). The differences of near surface temperature mainly happen over land,



456 and the higher near surface temperature in FFBB weakens the land breezes and near
457 surface convergence along the coast. Starting from late afternoon, (about 5 PM local
458 time), vertical velocity increases with time until sunrise next day in both simulations (Fig.
459 11e) due to the convergence of the monsoon windflaws and local land breezes during the
460 nighttime, and this matches very well with that of mass mixing ratio of total
461 hydrometeors (Fig. 11a and 11e). Noticeably, the main differences in vertical velocity
462 and hydrometeor mass mixing ratio between FFBB and FF also start to become evident
463 after entering the evening. Because of the weaker convergence near the surface in FFBB,
464 the differences in vertical velocity at the higher altitude between FFBB and FF peaks in
465 the nighttime.

466 It should be indicated that if the heat flux generated by fires was incorporated in the
467 model, the warming effects from biomass burning would be even stronger and could
468 persist in nocturnal timeframe as demonstrated in Zhang et al. (2019). However, this
469 would likely be more effective for open fire regime. For most of peat fires, burning is
470 largely proceeded underground. Based on our significantly reduced heat flux for the peat
471 fires as discussed in Sect. 2.1, if the heat flux was incorporated in the model, such fires
472 would not increase surface temperature by 4-5 °C as suggested for the tropical (open) fire
473 cases in Zhang et al. (2019).

474 As a summary, the schematics shown in Fig. 12 illustrate the impact of biomass
475 burning activities on nocturnal convections in the Borneo region. In the daytime, under
476 the prevailing wind of sea breezes from the South China Sea, convections develop over
477 the western mountain range. Because near surface heating from the absorption of



478 sunlight by fire aerosols could enhance the prevailing wind from the ocean, convective
479 rainfall becomes higher at the onset stage of the nocturnal convections (still in daytime)
480 due to biomass burning activities (Fig. 12b). In the nighttime, convection moves to the
481 offshore region of the western Borneo. The strong convergences near the surface merge
482 the weak westerly monsoon windflaws with local nighttime land breezes to form an
483 anticyclonic circulation (Fig. 12c). During the fire periods, the daytime near surface
484 warming by fire aerosols could also further weaken land breezes and surface
485 convergence. Hence, the nocturnal convections during fire events would not develop as
486 strong as in days without fires (Fig. 12d versus 12c).

487 **4 Summary**

488 By comparing WRF-Chem modeling results include or exclude biomass burning
489 emissions (FFBB versus FF), we have identified certain detailed impacts of fire aerosols
490 on convective events within two study regions in the Maritime Continent during a four-
491 month period (June 2008 ~ September 2008). In total, 54 convective systems in the
492 Sumatra region and 35 convective systems in the Borneo region have been simulated.
493 Three convective events of each study region have been selected for in-depth
494 investigation. In addition, statistical analyses have been performed throughout the entire
495 simulation period for each region. We have focused our analyses on two rainfall
496 features: 1) convective precipitation associated with Sumatra squall lines, and 2) diurnal
497 rainfall over the western Borneo.

498 We find that fire aerosols lead to the increase of cloud water mass and cloud droplet
499 number concentration among all analyzed cases while a substantial reduction of rain drop
500 number concentration. Influences of fire aerosols on other hydrometeors vary from case



501 to case. Specifically, our results show that fire aerosols can significantly change the
502 quantities of hydrometeors, particularly those involved in cold cloud processes and
503 rainfall of weak convections in either the Sumatra region or the Borneo region. Rainfall
504 intensity is higher in FFBB during the entire convection life cycle in those weak
505 convection cases, and the nighttime rainfall intensity in FFBB is significantly higher than
506 that in FF.

507 Statistics performed throughout the entire modeled fire season shows that the fire
508 aerosols only cause a nearly negligible change (2-3%) to the total rainfall of convective
509 systems in both study regions. On the other hand, we notice that fire aerosols can still
510 alter daily maximum and minimum rainfall in some cases, for example, fire aerosols lead
511 to the increase of maximum and minimum rainfall intensity in 30 weak convective events
512 in the Sumatra region.

513 In the Borneo region, biomass burning activities mainly affect the rainfall intensity
514 of nocturnal convection. Because near surface heating from the absorption of fire
515 aerosols can enhance the prevailing wind from the ocean (sea breeze) during the daytime,
516 the convective rainfall over the western mountain range is higher during the onset stage
517 of the nocturnal convections. In the nighttime, the consequence of the above
518 thermodynamic perturbation by absorbing fire aerosols can further weaken land breeze
519 and surface convergence. Hence, the rainfall intensity of nocturnal convections under the
520 influence of fire aerosols would become weaker.

521 This study has demonstrated how biomass burning activities could affect convective
522 systems in the Maritime Continent by altering cloud microphysics and dynamics. We
523 find the biomass burning activities significantly change the diurnal rainfall intensity,



524 especially those low-level wind patterns associated with the weak westerly (WW) regime
525 as suggested by Ichikawa and Yasunari (2006). Our results show that neither a single
526 case study nor a simple statistical summary applied to overall model simulation period
527 without in-depth analyses could reveal the impact of biomass burning aerosols on
528 convections under different windflow regimes.

529 **Data availability**

530 FINNv1.5 emission data are publicly available from
531 <http://bai.acom.uar.edu/Data/fire/>. REAS emission data can be downloaded from
532 <https://www.nies.go.jp/REAS/>. TRMM data can be obtained from
533 <https://pmm.nasa.gov/data-access/downloads/trmm>. AOD from MODIS can be
534 obtained from http://dx.doi.org/10.5067/MODIS/MOD08_M3.061. Sounding profiles
535 are publicly available on <http://weather.uwyo.edu/upperair/sounding.html>. WRF-Chem
536 simulated data are available upon request from Hsiang-He Lee (lee1061@llnl.gov).

537 **Author contribution**

538 H.-H. L. and C. W. designed the experiments and H.-H. L. carried them out. H.-H.
539 L. configured the simulations and analyzed the results. H.-H. L. and C. W. wrote the
540 manuscript.

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739 Table 1. The case period of the selected cases in the Sumatra region (r1) and the Borneo
 740 region (r2)

Case name	Case period
r1c1	2008/08/10 0900 UTC ~ 2008/08/11 0300 UTC
r1c2	2008/08/19 0600 UTC ~ 2008/08/20 0000 UTC
r1c3	2008/09/23 0900 UTC ~ 2008/09/24 0000 UTC
r2c1	2008/08/05 0900 UTC ~ 2008/08/06 0300 UTC
r2c2	2008/09/17 0600 UTC ~ 2008/09/17 2100 UTC
r2c3	2008/09/22 0300 UTC ~ 2008/09/23 0000 UTC

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Table 2. The fire periods in the two study regions

The Sumatra region (r1)	The Borneo region (r2)
6/10/2008 ~ 6/20/2008	6/21/2008 ~ 6/27/2008
6/25/2008 ~ 6/28/2008	8/1/2008 ~ 8/8/2008
7/4/2008 ~ 7/7/2008	9/10/2008 ~ 9/30/2008
7/27/2008 ~ 8/20/2008	
9/17/2008 ~ 9/27/2008	

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Table 3. The mean differences in percentage of FFBB to FF (i.e. $(FFBB-FF)/FF \times 100\%$) for each selected case over the main convection area in the Sumatra region (r1) and the Borneo region (r2). Qc, Qi, Qr, Qs and Qg represents cloud, ice, rain, snow, and graupel mass concentration respectively. Qnc, Qni, Qnr, Qns and Qng means number concentration for each hydrometeor.

Case	Qc	Qi	Qr	Qs	Qg	Qnc	Qni	Qnr	Qns	Qng
r1c1	8%	27%	49%	62%	48%	248%	55%	-41%	33%	39%
r1c2	20%	-6%	-15%	-25%	1%	349%	-1%	-45%	-11%	-6%
r1c3	18%	10%	-10%	3%	5%	311%	4%	-50%	11%	-6%
r2c1	27%	1%	-6%	-5%	-4%	703%	3%	-59%	4%	-5%
r2c2	22%	10%	64%	69%	58%	337%	24%	-32%	17%	57%
r3c3	8%	10%	19%	60%	-2%	409%	-5%	-66%	8%	-12%



753 Table 4. The averaged precipitation (mm 3hrs⁻¹) of FFBB and FF for each selected case
 754 over the main convection area in the Sumatra region (r1) and the Borneo region (r2).
 755 Parentheses in the third column show the difference in percentage of FFBB to FF (i.e.
 756 (FFBB-FF)/FF × 100%).
 757

Case	FF	FFBB
r1c1	1.33±0.47	2.74±1.21 (+106%)
r1c2	2.97±1.42	3.05±1.49 (+3%)
r1c3	4.32±1.84	3.98±2.18 (-8%)
r2c1	3.73±2.64	3.07±1.21 (-18%)
r2c2	1.88±0.53	3.97±1.47 (+111%)
r3c3	0.54±0.53	1.10±1.02 (+103%)

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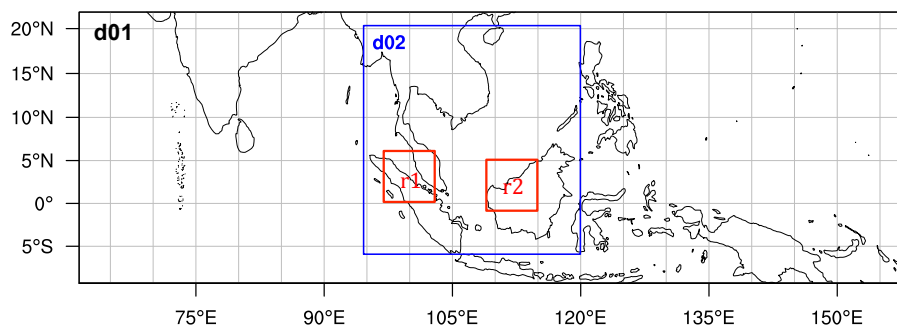


Figure 1. Domain configuration for WRF-Chem simulations. Domain 1 (d01) has a resolution of 25 km, while Domain 2 (d02) has a resolution of 5 km. Two red boxes indicate the two study regions: the Sumatra region (r1) and the Borneo region (r2).

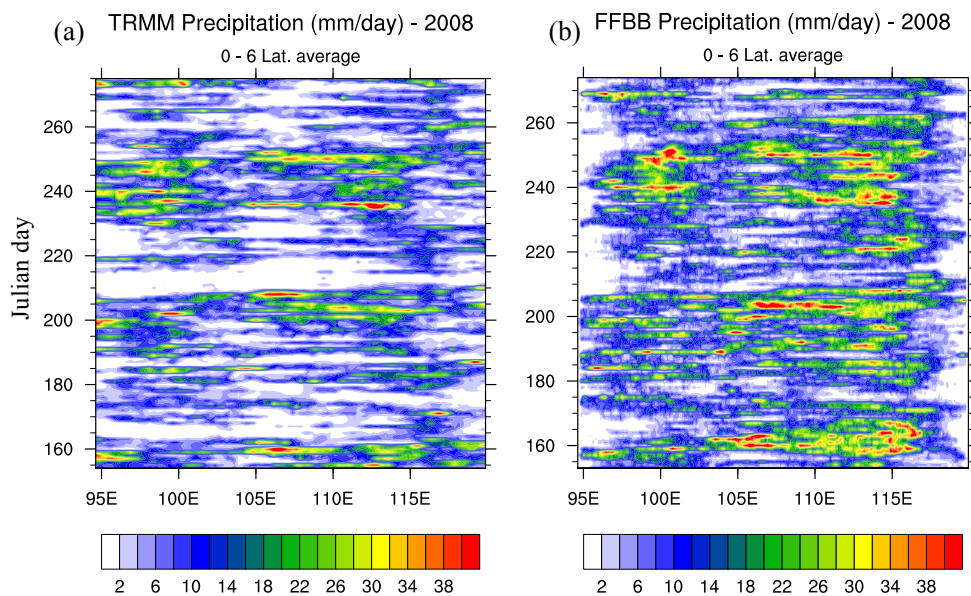
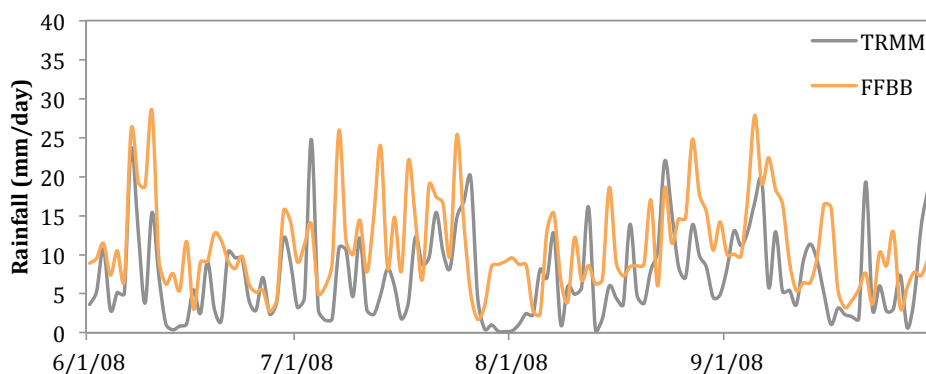


Figure 2. Hovmöller (time versus longitude) plot of daily precipitation (mm day^{-1}) from 1 June 2008 to 30 September 2008 from: (a) Tropical Rainfall Measuring Mission (TRMM) and (b) FFBB. Latitude average is from 0° to 6°N .

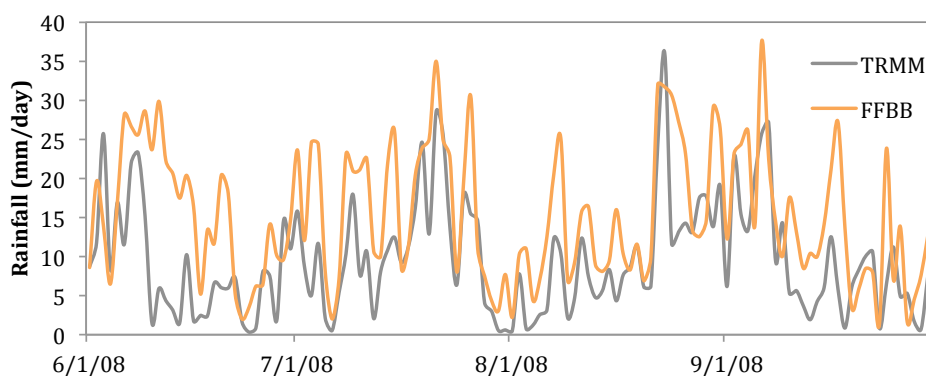


(a) Rainfall comparison - r1



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(b) Rainfall comparison - r2



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Figure 3. Time series of area-averaged daily rainfall (mm day^{-1}) from Tropical Rainfall Measuring Mission (TRMM) and FFBB over (a) the Sumatra region (r1) and (b) the Borneo region (r2).

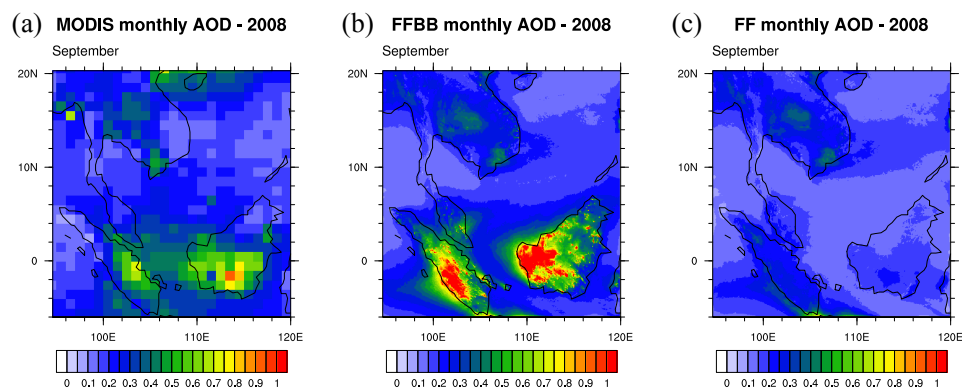


Figure 4. Monthly aerosol optical depth (AOD) in September 2008 from (a) Moderate Resolution Imaging Spectroradiometer (MODIS), (b) FFBB, and (c) FF.

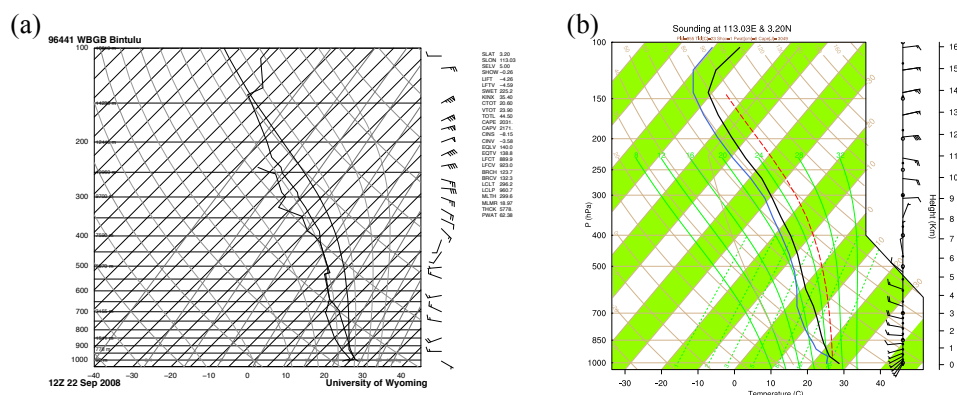
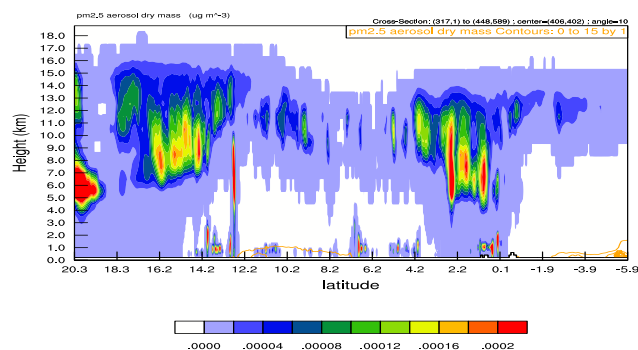
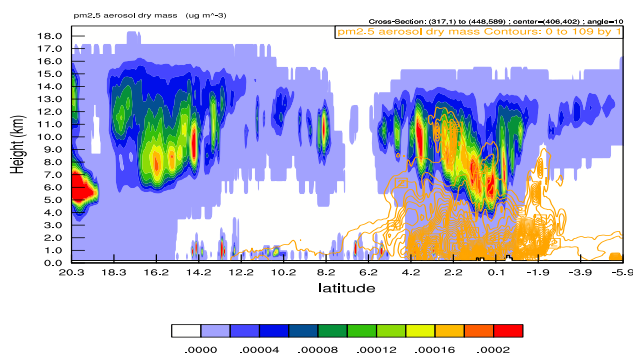
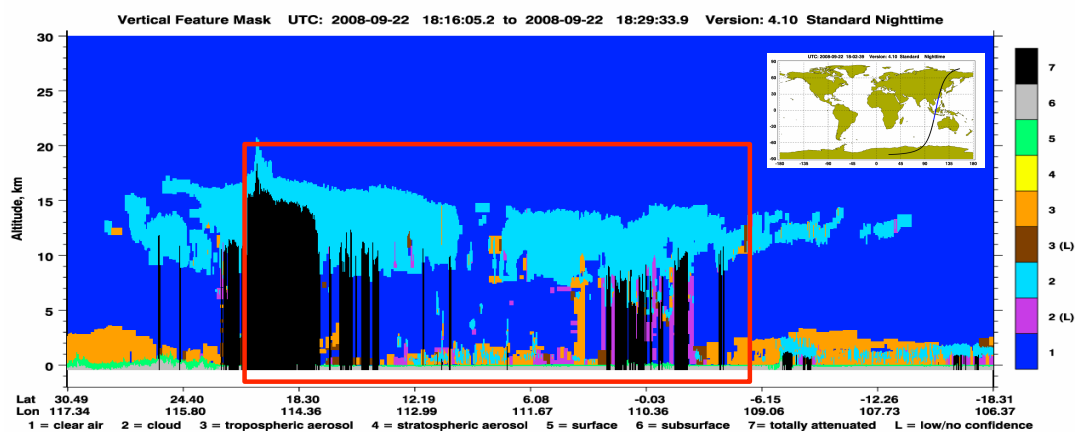


Figure 5. (a) Sounding profile observed at Bintulu Airport, Malaysia (113.03° E, 3.20° N) at 12 UTC on 22 September 2008. (b) Modeled sounding profile in FFBB at the same location and time as (a).





791 Figure 6 (a) The vertical structure of cloud retrieved from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
792 (CALIPSO) on September 22, 2008. (b)-(c) The sum of simulated hydrometeor mixing ratio (shaded; kg kg^{-1}) and $\text{PM}_{2.5}$ concentration
793 (contour; $\mu\text{g m}^{-3}$) in FFBB and FF, respectively. The profile domain of (b) and (c) is corresponding to the red rectangle in (a).
794

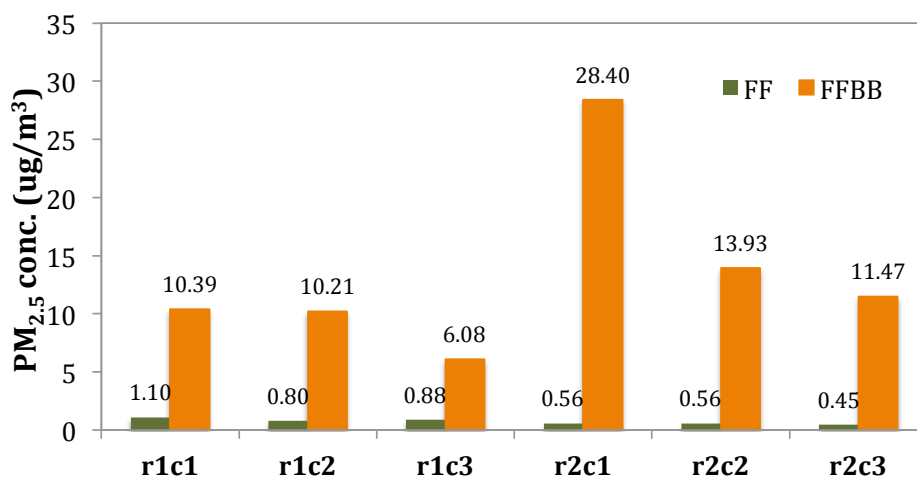
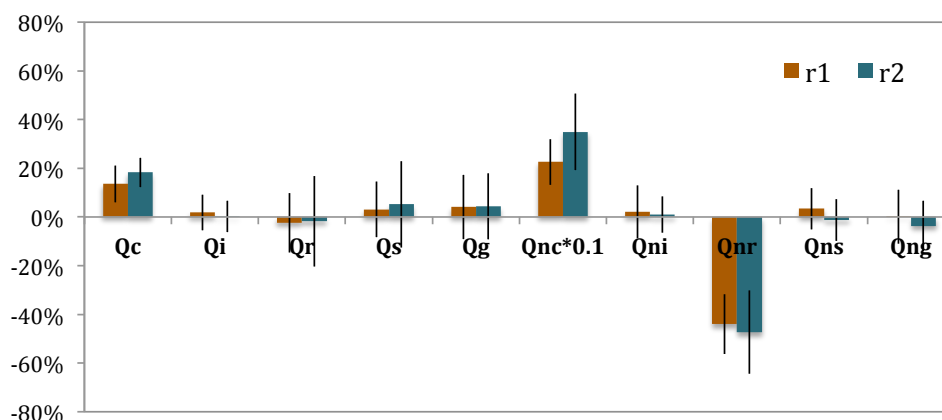


Figure 7. The mean PM_{2.5} concentration ($\mu\text{g m}^{-3}$) in FF and FFBB for selected cases in the Sumatra region (r1) and the Borneo region (r2).



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801
 802 Figure 8. The mean differences in percentage of FFBB to FF (i.e. $(FFBB-FF)/FF \times 100\%$)
 803 over all convective cases during the fire periods in the Sumatra region (r1) and the Borneo
 804 region (r2). Qc, Qi, Qr, Qs and Qg represents cloud, ice, rain, snow, and graupel mass
 805 concentration, respectively. Qnc, Qni, Qnr, Qns and Qng means number concentration for
 806 each hydrometeor. The error bars represent one standard deviation.
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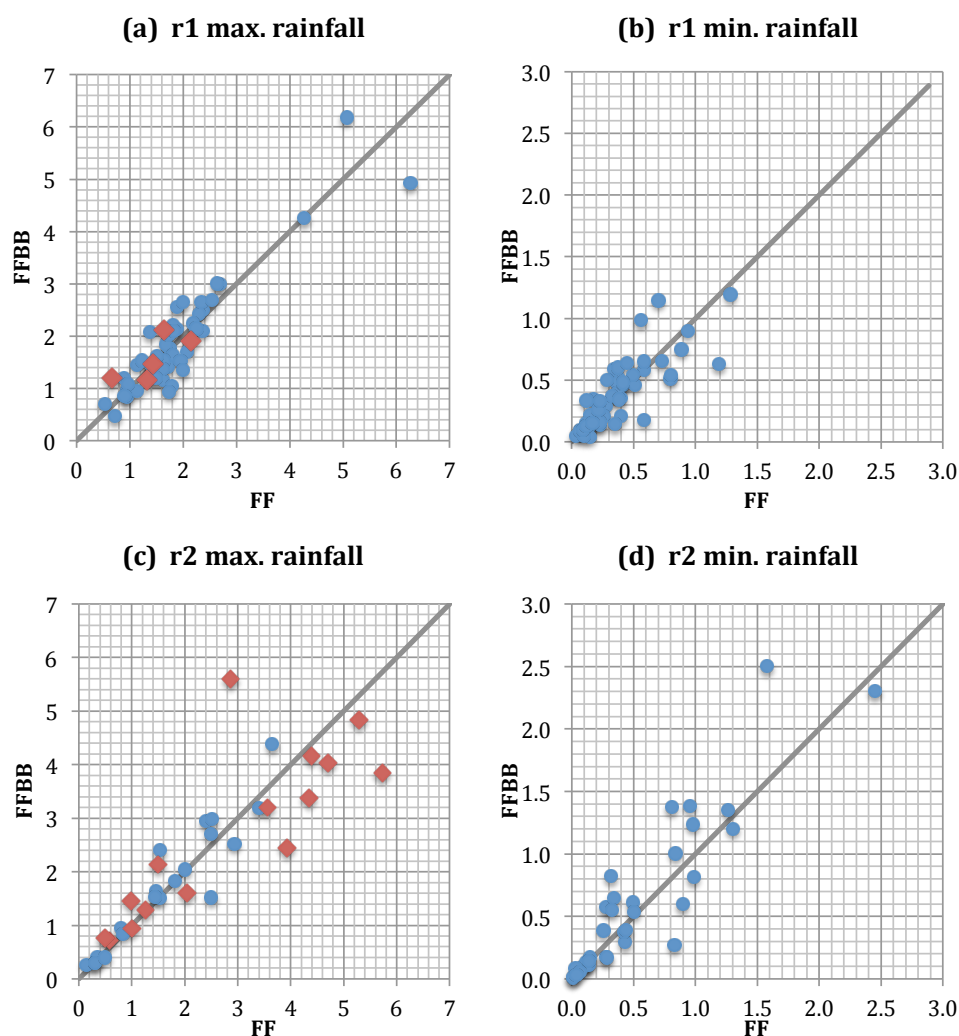
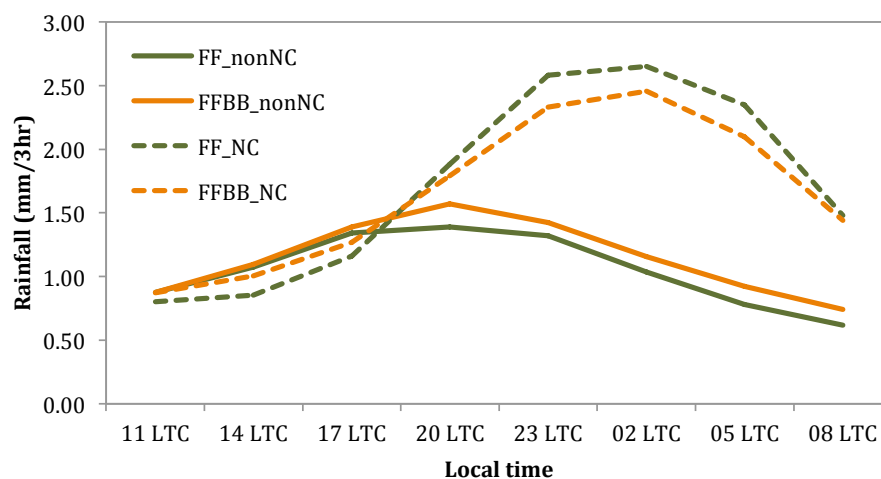


Figure 9. The scatterplots of daily maximum and minimum convective rainfall ($\text{mm } 3\text{hr}^{-1}$) during the fire periods in in the Sumatra region (r1) and the Borneo region (r2). Red diamonds in (a) and (c) indicate that the maximum convective rainfall conducts in the midnight or early morning.



816
 817 Figure 10. The diurnal time series of precipitation averaged over the Borneo region (r2) for
 818 nocturnal convections (NC) and non- nocturnal convections (non-NC) during fire periods in
 819 FF and FFBB.
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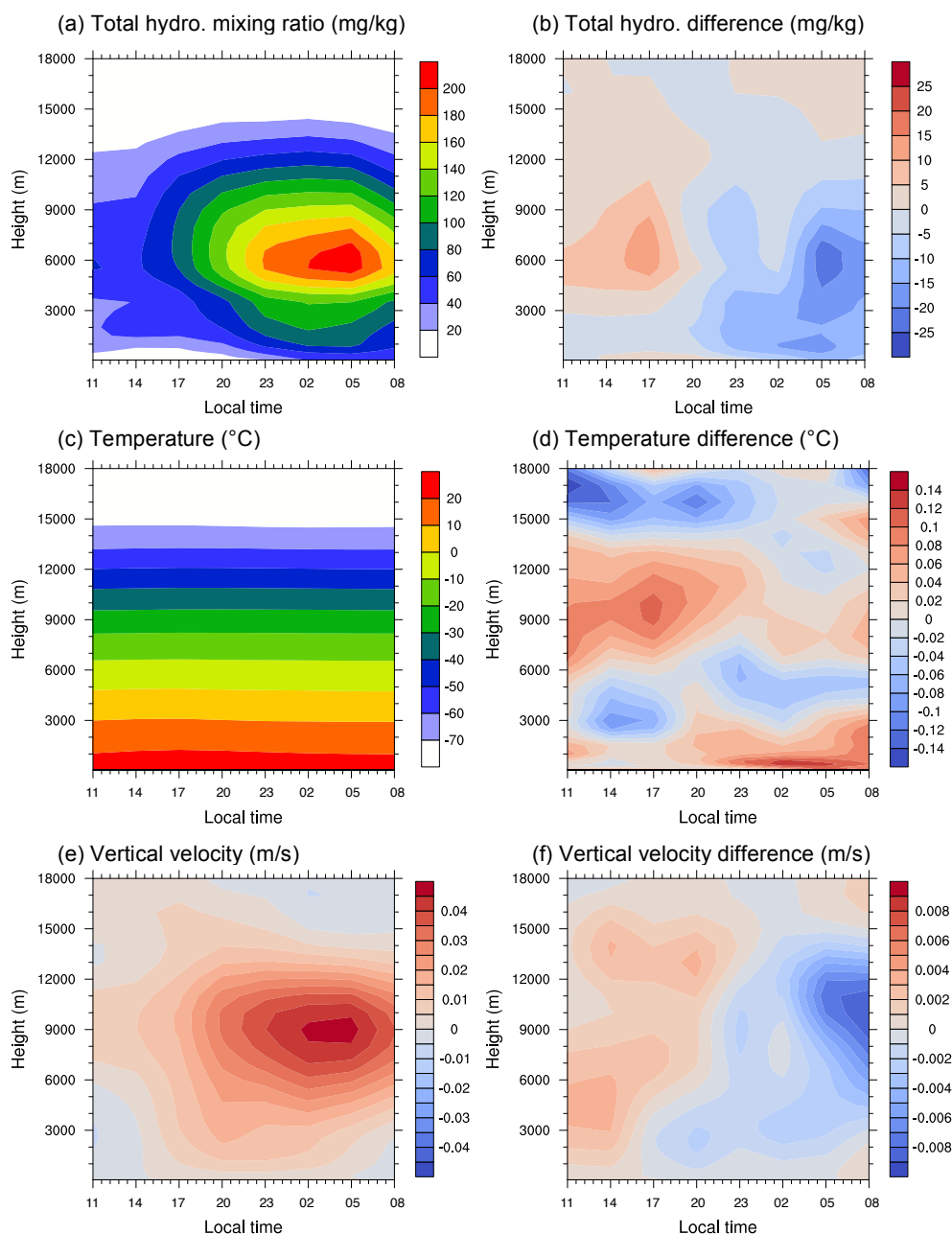
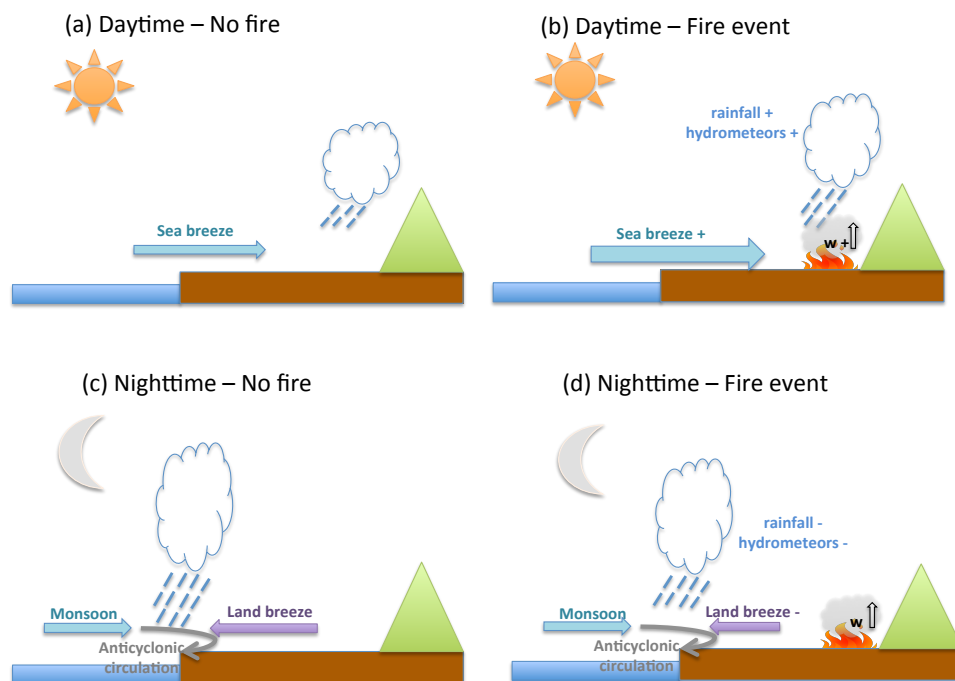


Figure 11. Diurnal evolution of vertical profiles over the Borneo region (r2) in FF for (a) total hydrometeor mixing ratio (mg kg^{-1}), (c) temperature ($^{\circ}\text{C}$), and (e) vertical velocity (m s^{-1}). Data are averaged all the nocturnal convections. (b), (d), and (f) is the differences between FF and FFBB (FFBB-FF) for each parameter.



832
 833 Figure 12. Schematics of diurnal rainfall/convection activity over the western Borneo. (a)
 834 and (b) illustrate the formation of convection during the daytime without and with fire event,
 835 respectively. (c) and (d) are the same as (a) and (b) but in the nighttime.
 836