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Aerosol effects on clouds and precipitation during the 1997 smoke episode in Indonesia

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Abstract

In 1997/98 a severe smoke episode due to extensive biomass burning, especially of peat, was observed over Indonesia. September 1997 was the month with the highest aerosol burden. This month was simulated using the limited area model REMOTE driven at its lateral boundaries by ERA40 reanalysis data. REMOTE was extended by a new convective cloud parameterization mimicking individual clouds competing for instability energy. This allows for the interaction of aerosols and convective clouds and precipitation. Results show that convective precipitation is diminished at all places with high aerosol loading, but at some areas with high background humidity precipitation from large-scale clouds may over-compensate the loss in convective rainfall. At individual time steps, very few cases were found when polluted convective clouds produced intensified rainfall via mixed phase microphysics. However, these cases are not unequivocal and opposite results were also simulated, indicating that other than aerosol-microphysics effects have important impact on the results. Overall, the introduction of the new cumulus parameterization and of aerosol-cloud interaction improved the simulation of precipitation patterns and total amount.

1 Introduction

Aerosols and clouds and their non-linear interaction are amongst the biggest challenges in current climate modeling and prediction. While there exists a number of studies considering aerosol effects on stratiform clouds (for a review see Lohmann and Feichter, 2005), only few studies exist that discuss effects on convective clouds (Rosenfeld and Woodley, 2001; Andreae et al., 2004; Graf, 2004; Langmann, 2007) and potential effects on global circulation (Nober et al., 2003) arising from changes in latent heat release due to diminished warm rain formation in the tropics. There aerosols from biomass burning are abundant and deep convection is the prevalent form of precipitation formation. No publications are known to the authors on the aerosol effects on

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warm and mixed phase convective precipitation in large-scale climate or atmospheric models. One reason for the situation is that in current climate models convective clouds are treated by mass flux parameterization excluding explicit cloud microphysical processes. This deficit to a certain degree can be overcome by using cloud-resolving models. However, such models are computationally demanding and this prevents their application in longer-term climate studies. Very recently Langmann (2007) presented results of aerosol-cloud interaction during the heavy smoke episode around Indonesia in 1997/1998, when the seasonal peat fires run out of control due to lack of rain during the El Nino episode. However, Langmann (2007) used the simplistic approach of Nober et al. (2003), without explicit cloud microphysics, of aerosol effects on warm rain only and ignored mixed phase processes. These, however, may lead to non-linear effects (as observed over Amazonia by Andreae et al., 2004 and discussed by Graf, 2004) resulting in a reduction of warm rain where the convective instability is moderate and increased precipitation due to formation of ice where convective instability is large. Over Indonesia, due to the small scale topography determined by a vast number of smaller and larger often steep volcanic islands in very warm waters, clearly high resolution models are necessary to simulate precipitation reasonably well.

Here we will introduce an alternative approach (Nober and Graf, 2005) to convective clouds in a limited area model. An individual cloud model including explicit cloud microphysics of the warm and of the mixed phase is run with several different initial radii and with internally much enhanced vertical resolution at every time step of the limited area model. We will apply this model to the month with most severe smoke concentrations over Indonesia and around, September 1997. This month is characterized by strong pollution from smoke but only weak to moderate atmospheric instability. While September is the month with least precipitation in Indonesia, there is still enough (order of 50 mm per month) to allow for the investigation of aerosol effects on clouds and precipitation. Results will show that, as observed in single cases over Amazonia (Andreae et al., 2004), the smoke aerosols lead to mostly decreased precipitation. Only in very few cases in areas of smoke contamination and concurrent strong atmospheric instability convective precipitation is increased.

2 Model

A new convective cloud field model (CCFM) that is based on a concept from population dynamics (Nober and Graf, 2005; Graf and Yang, 2007) has been coupled with the regional atmospheric chemistry model with tracer extension REMOTE (Langmann, 2000). Originally CCFM was modified and coupled with REMO (the meteorology alone version of REMOTE) for a whole year test over the West Pacific warm pool area, which showed that a simplified CCFM can successfully be used in a limited area model (Graf and Yang, 2007). Our REMOTE-CCFM domain covers Indonesia and the northern part of Australia with a horizontal resolution of 0.5 degrees and 101 grid points in longitude and 55 grid points in latitude. The model was applied with 20 vertical layers of increasing thickness between the Earth's surface and the 10 hPa pressure level. ECMWF reanalysis data were used as lateral boundary conditions every 6 h. The constant time step is 5 min. For our current study the model just includes one tracer, the total particulate matter (TPM), which can be transported by horizontal and vertical advection, convective processes and vertical diffusion as well as be affected by wet and dry deposition. Due to the elevated sulfur content and hygroscopicity of Indonesian vegetation and peat fire aerosols (Langmann and Graf, 2003), particle deposition is calculated as for sulphate.

The emission estimate uses vegetation and peat maps, remotely sensed fire counts and reports on the total area burned to determine TPM emissions with 0.5 degrees horizontal resolution (Langmann and Heil, 2004). Up to 90% of the total smoke mass during the catastrophic 1997/1998 fires resulted from burning peat. These weekly data were used and the smoke released into the first model layer. While Freitas et al. (2006) emphasized the need to inject the smoke from Amazonian forest fires at higher elevation, in the case of Indonesian peat fires, dominated by smoke from relatively cool sources, the release near the surface is the better approach.

CCFM treats convective clouds as individuals competing for available instability energy. A simplified cloud model including explicit (yet simple) cloud microphysics is run at every time step with a number of different initial conditions representing cloud types of different size. The vertical resolution for the individual cloud model is increased considerably to 70–100 m. For the limited area model REMOTE we cannot apply a large number of different initial cloud types as requested in Nober and Graf (2005) for CCFM use in coarse grid models. Instead we use a simplified version of only three cloud types that are different in their initial cloud radius similar as in Graf and Yang (2007): small, medium and large. Thus, the initial set-up of the model is as in this study except that the maximum cloud radius at cloud base is set to 1/3 of the height of the PBL and a modified cloud microphysics scheme was used in order to be able to include effects of the aerosols on cloud microphysics. In contrast to a recent study by Langmann (2007), who used a modified Tiedtke scheme only including smoke effects on warm rain formation, switching from high to low autoconversion at a preset limit of CCN concentration, our microphysics scheme includes also mixed phase processes following the parameterizations of Ogura and Takahashi (1971) as described in Nober and Graf (2005). This potentially allows for an intensification of precipitation in polluted areas where convective instability is high (Andreae et al., 2004; Graf, 2004).

For the aerosol-cloud interaction studies the autoconversion formula of Berry (1968) was used in the convective cloud parameterization instead of the standard Kessler (1969) parameterization:

$$\frac{dq_r}{dt} = \frac{\rho \cdot 10^3 \cdot q_l^2}{60\left(5 + \frac{0.0366 \cdot N_b}{\rho \cdot 10^3 \cdot q_l^{\cdot} D_b}\right)} \tag{1}$$

where q_r and q_l are precipitation water and cloud liquid water mixing ratio (kg/kg) respectively, ρ is air density, N_b and D_b are droplet number density (i.e. CDNC in no cm^{-3}) and droplet relative dispersion at the cloud base. D_b is set to standard values: over sea it is 0.366 and over land it is 0.146.

For stratiform clouds a parameterization of the autoconversion rate by Beheng (1994) is used instead of the Sundquist (1978) scheme:

$$dq_r/dt = (\gamma_1 * 6 * 10^{28} n^{-1.7} N_l^{-3.3} (10^{-3} \rho q_l)^{4.7})/\rho \quad (2)$$

where N_l is the cloud droplet number concentration, as above ρ is air density and q_l is cloud water mixing ratio, γ_1(=15) is a tunable constant which determines the efficiency of rain formation, n (=10) is the width parameter of the initial cloud droplet spectrum described by a gamma function.

From the above parameterizations we know that the formation of precipitation highly depends on cloud droplet concentration and liquid water content. However, the impact of CCN on the cloud droplet number concentration is not well known. There are two methods that have been used to relate changes in cloud droplet number concentration CDNC to changes in aerosol concentrations. These are basically diagnostic (empirical) (Jones et al., 1994; Boucher and Lohmann, 1995) and prognostic (mechanistic) parameterizations (Chuang and Penner, 1995; Abdul-Razzak and Ghan, 2000). In this paper we simply used the Boucher and Lohmann (1995) relationship, which is

$$\mathrm{CDNC} = 10^{2.21+0.41\,\log(\mathrm{mSO4})} \quad (3)$$

where mSO4 is the sulphate aerosol mass concentration ($\mu g\, SO_4\, m^{-3}$) and CDNC is in cm^{-3}. Distinct higher sulfur content was observed in Indonesian peat fire aerosols compared to other vegetation fire aerosols (Gras et al., 1999) and Langmann and Graf (2003) suggested this to be due to accumulated volcanic sulfur. Recent laboratory studies (Dusek et al., 2005) showed that young aerosols resulting from peat fires are very specific in that they form hollow spheres instead of conglomerates as known from other smoke sources. These spheres have limited capacity to act as cloud condensation nuclei. However, it is not yet known how these particles behave when aged. Hence, we conservatively assume that, concerning cloud microphysics, aged peat smoke aerosol acts like organic aerosol, i.e. comparably to sulphate particles, which are very effective cloud condensation nuclei. Thus, we assume for simplicity that M_{TPM}=M_{SO4}.

In our model region most grids are covered by sea, but the potentially large amount of sea salt aerosol source is only included in the current model by fix concentration differences. Following Roeckner (1995) we assume different background CDNC over land and sea: In the planetary boundary layer, up to 850 hPa, background CDNC=200 cm^{-3} over land, and CDNC=100 cm^{-3} over sea, in the upper model layers we use CDNC=50 cm^{-3}. We performed a control run with these background CDNCs and a test run with background CDNC plus TPM emissions as simulated interactively by REMOTE-CCFM. A more sophisticated treatment of sea salt aerosols would be beneficial since sea salt may produce giant cloud droplets, thus leading to enhanced drizzle and lower humidity remaining in the atmosphere. We are aware of the fact that our treatment of aerosol microphysics is rather crude compared to specialist models. However, it is much more sophisticated than in nearly all current atmosphere and climate models and it may be seen as a compromise. A more sophisticated treatment of the complexity of aerosols and their interaction with clouds would require a fully coupled chemistry-aerosol-cloud approach that is beyond the scope of this study. However, this study is a step towards that goal showing that the aerosols exert an important effect also on convective clouds. We concentrate here on September 1997, the month with the strongest smoke pollution observed during the whole 1997/1998 episode.

3 Results

In Fig. 1 we show total precipitation as analyzed for September 1997 by the Global Precipitation Climate Center, GPCC, including surface rain gauge results only. This data set probably has a negative bias (Langmann and Heil, 2004) and the observation density is very sparse. Even over land not in every grid box there is at least one gauge installed. In Fig. 2 total (top), large scale (middle) and convective (bottom) precipitation are shown for the control run (left column) and the test with added pollution (middle column) as well as the difference between the two model simulations (right column). Note that the differences are drawn at a smaller scale of mm/month!

The standard REMOTE model containing a mass-flux parameterization for convective clouds from Tiedtke (1989) severely over-estimates precipitation (see Graf and Yang, 2007), mainly over sea, while the introduction of CCFM (Fig. 2a) clearly improves the results as already discussed in Graf and Yang (2007). The main precipitation now is simulated over land north of the Equator as observed, but the model overall remains to be too wet. There is the potential of having too much rainfall at places (like over the high mountains of Irian Jaja), but these also appear in the original versions of REMO and REMOTE and, actually, there do not exist any observations. For a discussion of these effects see Graf and Yang (2007). The inclusion of TPM in the model simulation changes the microphysical structure of the clouds and this leads to a further improvement of the precipitation pattern (Fig. 2b) making it more similar to what the observations are. The increased precipitation at the westernmost boundary is due to boundary effects. So, overall, REMOTE with CCFM and including TPM provides a very reasonable distribution of precipitation at the height of the dry season over Indonesia and the West Pacific warm pool. The strongest change of precipitation (Fig. 2c) in the simulation including smoke is found over land (Borneo, North Sumatra, Peninsula Malaysia and West Irian Jaja), where the pollution is strongest. There at most places we see a reduction in total rainfall.

The mean aerosol column concentration (TPM) for September 1997 as it results from the interaction of smoke emission, transport and wet and dry deposition is rather similar to the one Langmann (2007) presented (not shown here). There are clearly maxima adjacent to the burning peat areas over South Sumatra, South Borneo and parts of Irian Jaja. Application of Eq. (3) to the aerosol concentration at all model levels for the control and for the test runs reveals the differences in column cloud droplet number, Fig. 3a. These differences, as expected, are largest where the aerosol concentration is biggest. The pattern of the cloud droplet column concentration very well matches the aerosol concentration. However, as seen from Fig. 3b, the strongest anomalies in liquid water path are not matching either the aerosol concentration or cloud droplet concentrations. Over Borneo the strongest positive anomaly in liquid water path is found to the North of the highly polluted area and similar it is over Sumatra. In general, over the whole model domain we see an increase in liquid water path except at some randomly scattered places.

Over most of the model area the particle column concentration is slightly increased when the pollution effects are included in the convective cloud microphysics (Fig. 3c). Rainout is depressed due to the suppression of warm rain formation in the most polluted areas. Only at some places, most prominent in the Northwest of Borneo, fewer particles are found in the air. There, while convective precipitation is decreased, total precipitation is increased significantly by enhanced large-scale rainfall (Fig. 2f) leading to more effective rainout of the aerosols.

Overall, while our model still seems to be too moist, the precipitation pattern simulated including smoke particle effects is much closer to surface observations. Total precipitation is reduced (Fig. 2b) compared with the run where only background CDNC were used (Fig. 2a) at most places where the aerosol load is large, but there are some extended areas next to these areas of reduced total precipitation where rainfall is substantially increased. These we find mainly over northwest Borneo and the Strait of Malacca and to the west of the northern tip of Sumatra as well as near the northern coast of Irian Jaja, always to the North of the most polluted areas, downwind from the highest pollution. As Fig. 2f indicates, these areas of increased total precipitation are due to heavier large-scale rainfall over-compensating for reduced convective rainfall (Fig. 2i). One reason for this behavior is that in the model, when convective precipitation is diminished, the remaining water vapor is added to the humidity used for the calculation of large-scale precipitation. This, in the moistest areas, may lead to excessive large-scale rain. These are areas of increased aerosol load as well and so it is of interest what kind of clouds produced these differences. Over land clearly convective precipitation is decreased everywhere where heavy pollution occurs (Fig. 2i), while over sea some slight increase in convective precipitation is seen also in polluted areas, e.g. Strait of Malacca and northern Sumatra Strait. However, these clouds rarely reach altitudes where freezing takes part in the formation of rainfall. Where rainfall is most depressed, on the other hand, it are the biggest clouds whose height is reduced, while smaller ones, mainly over Sumatra are higher than in the reference experiment.

While monthly mean cloud heights generally are not impressively increased (few 100 m only), this is different when we look into more detail. A comparison of time step data of atmospheric instability as measured by Convective Available Potential Energy (CAPE), cloud top temperature of the biggest cloud type, and convective precipitation for the runs including TPM plus background CDNC and only background CDNC revealed the following results at two distinct areas, one in the Sumatra Strait, where total precipitation is slightly enhanced and another over South Kalimantan where precipitation is strongly reduced. September is at the high of the dry season in Indonesia, so CAPE is generally small most of the time with just few extreme events. Even though the limited area model is forced every six hours by lateral boundary conditions from ECMWF reanalysis ERA40, weather as measured by CAPE may be very different around similar time steps in the polluted and non-polluted cases. This shows, amongst others, the modulating effect of the additional aerosol on atmospheric stability and weather. Hence it is not easy to make direct comparisons. CAPE in the mean is slightly higher and more variable over land than over sea. The cloud top temperatures nearly always remain above the freezing level of cloud droplets (-15°C) and as expected are more variable and lower over land. Rainfall from convective clouds is rare over land and even more so over sea. There is just one prominent case in the polluted atmosphere over the Sumatra Strait when CAPE leads to a much enhanced cloud height with cloud top temperature well below freezing and heavier convective precipitation than in the clean case. This is the only case over sea when CAPE is strongly increased in the polluted case. Over land we find another case in the polluted environment where CAPE is enhanced and convective precipitation is stronger, but here without reaching the freezing level. There are two cases at the beginning of the month when the opposite happens, i.e. CAPE is enhanced in the clean simulation and so are cloud height and precipitation. In another case, with enhanced CAPE in the polluted simulation and cloud top temperature well below freezing, the model simulates no convective precipitation at all. These individual results indicate that there is no regular and simple effect based on a combination of strong CAPE, low cloud top temperature and aerosol-microphysics effects alone that might produce regularly enhanced convective precipitation if the mixed phase state of the polluted convective cloud is reached.

If there exists a statistical effect linking CAPE or cloud top height to aerosol effects on precipitation, extensive analysis under different conditions would have to be performed. This would also include a multi-dimensional statistical analysis including the probability density functions of precipitation intensity under varying parameters such as CAPE, TPM (including certain thresholds), cloud top temperature, cloud size etc. Such study requires better representation of cloud microphysics. At least a two-moment scheme is required to simulate the aerosol effects on CDNC. Freezing temperatures would have to depend on droplet chemistry and size, and some information would be necessary on activation of ice nuclei. All this remains to be a future project.

The cloud radiative forcing at the top of the atmosphere (Fig. 5) is dominated by shortwave forcing and is generally negative due to the brightening of the clouds. The long wave forcing is in general positive, but smaller. The total negative forcing is damped where the clouds are significantly higher leading to less outgoing longwave radiation. The area mean of radiative forcing is positive but small and remains in the order of $0.7\,W/m^2$. At some places, like over the seas adjacent to northern Sumatra, over West Borneo and just to the north of Irian Jaja positive local values of 10 to $15\,W/m^2$ are reached.

4 Concluding discussion

We have applied a limited area model including internal explicit convective cloud treatment to a case study of much enhanced smoke pollution from mostly peat fires in Indonesia, September 1997. This specific episode is of interest due to the extreme pollution and occasional precipitation, which suggests that aerosol-microphysics effects should be relevant. Aerosols and clouds, both convective and large scale, were treated interactively and, for the first time, microphysical processes were included for warm and mixed phase rainfall formation not only in large scale but also in convective clouds. Our results show that, while the monthly mean rainfall is depressed over most of the heavily polluted area, there are clearly coherent areas, also polluted, where the opposite is the case. These areas basically are situated downwind of those with suppressed convective precipitation and occur, at least in the majority, over or in proximity to the sea, where moisture supply is high. Langmann (2007) also found individual 6h intervals in her simulation of the same case during which precipitation was enhanced over generally polluted areas. However, only considering the warm phase rainfall, she produced an overall reduction of rain in the monthly mean over the whole model domain. While, in principle, it would be possible that the increased rainfall is produced in our model due to moisture that is detrained from the clouds that had suppressed rainfall in the last time step, this process would generate a highly noisy pattern in space and time. With the clear patterns simulated by the model, however, we may rule out this model-internal shift of precipitation between time steps. Rather we observe a shift from convective to large-scale rainfall where the moisture level of the atmosphere is already high in the background simulations. Our results show that it is feasible to include a parameterization of explicit convective clouds including aerosol-microphysics effects in the style of CCFM (Nober and Graf, 2005) also in a limited area model. The resulting monthly precipitation pattern is closer to the (limited) observations when aerosol effects on convective clouds are considered than without. So far it is clear that warm convective rain is suppressed in polluted air masses and that part of this deficit can be made up by large-scale precipitation, sometimes even be over-compensated. Since mixed phase microphysics might be important for the non-linear switch from depressed to increased rainfall, it is very important to also include information on ice nuclei in aerosol-cloud models. In addition, higher moment microphysics will be necessary to better simulate aerosol effects on droplet formation and growth. Only then the right height (initial freezing temperature) of the switch will be detectable. This poses another big challenge to aerosol modelers that has not yet been met. Since there is no simple connection between aerosols and precipitation at ground, complex statistical studies are required of changes in PDF of rainfall intensity depending on pollution level and vertical profiles of temperature, winds and moisture. More case studies of observed precipitation and pollution will be necessary and our model still needs tuning to avoid it being too moist. However, the results obtained so far encourage us to further studies including the above mentioned process parameterizations and to also include the convective transport of chemical species (soluble and insoluble) in the near future.

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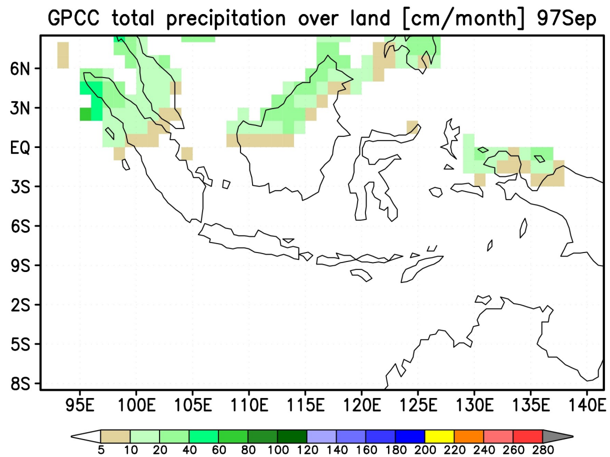

Fig. 1. Precipitation in September 1997 measured by ground-based rain gauges (GPCC: http://www.dwd.de).

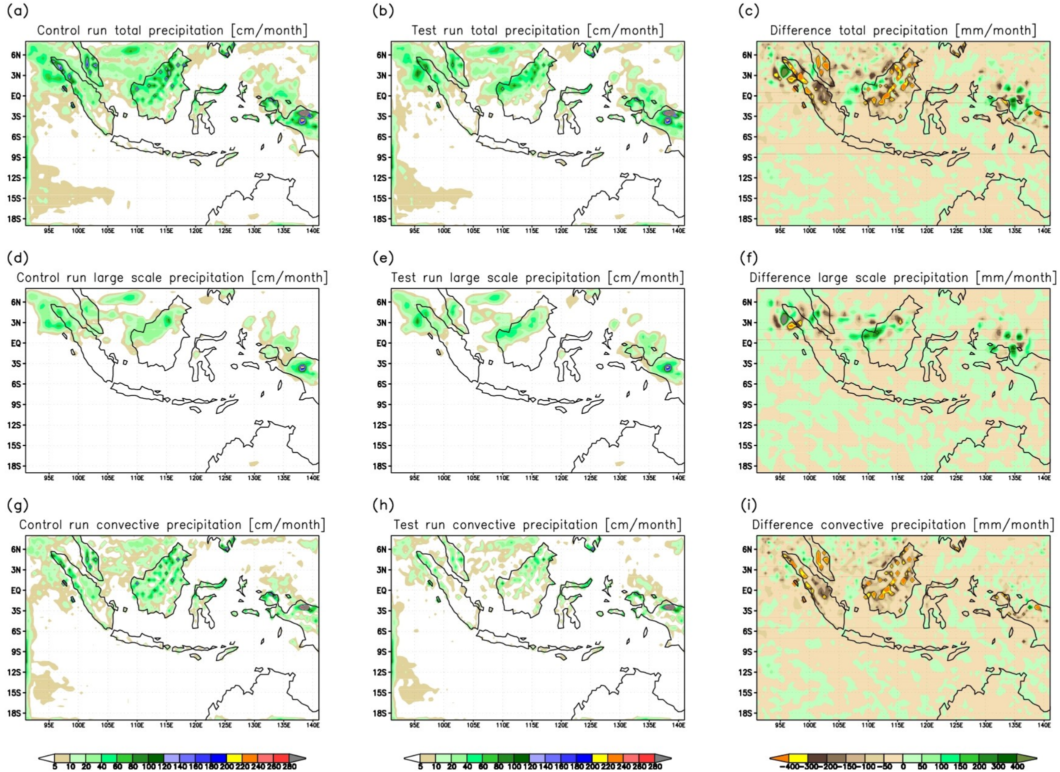

Fig. 2. Precipitation as simulated by REMOTE-CCFM simulated by REMOTE-CCFM and background CDNC (left column, total, large scale and convective rain from top to bottom), simulated by REMOTE- CCFM and background standard CDNC plus TPM (middle column) and precipitation anomalies between the two simulations (right column). Note that the colors for the differences (right column) are set to mm/month, while the absolute rainfall is in cm/month.

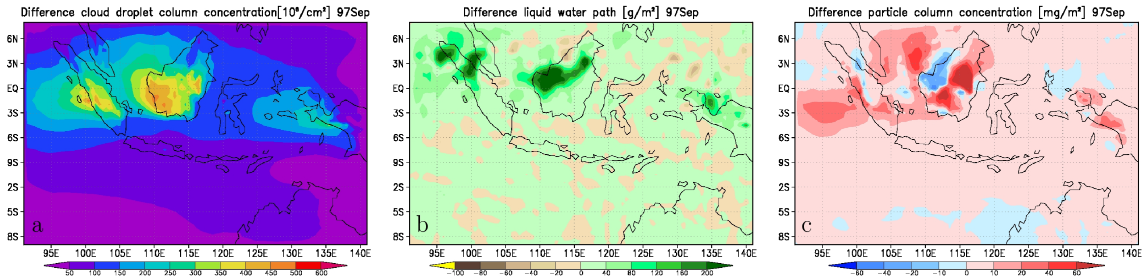

Fig. 3. Differences between REMOTE-CCFM simulations with additional smoke aerosols and without. **(a)** cloud droplet concentration, **(b)** liquid water path, **(c)** particle column concentration.

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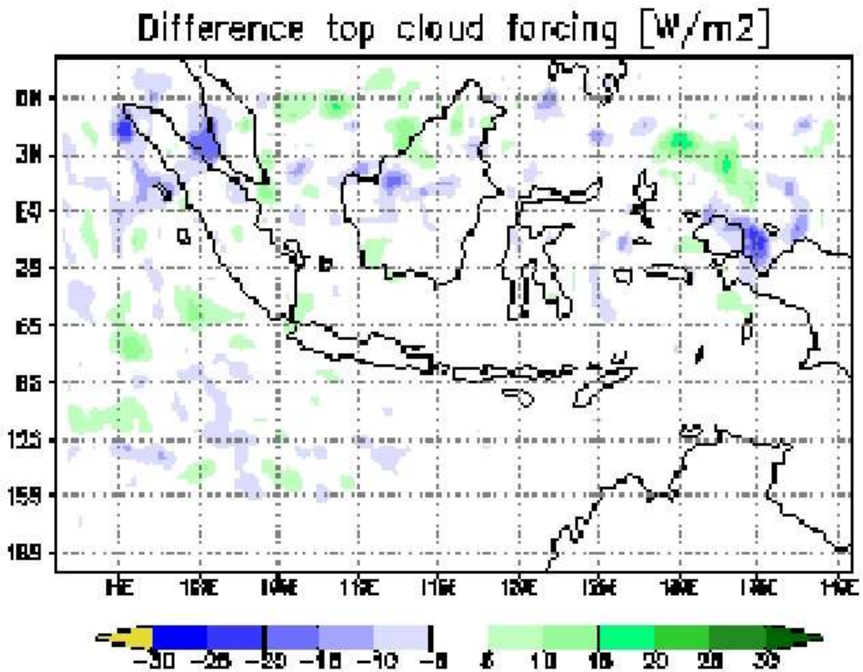

Fig. 4. Monthly mean top of the atmosphere total cloud radiative forcing difference between the runs with and without inclusion of TPM.

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