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The direct radiative effect of wildfire smoke on a severe thunderstorm event in the Baltic Sea region

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ABSTRACT

On August 8, 2010, a severe derecho type thunderstorm in the Baltic Sea region coincided with smoke from wildfires in Russia. Remarkable smoke aerosol concentrations, with a maximum aerosol optical depth of more than 2 at 550 nm, were observed near the thunderstorm. The impact of the wildfire smoke on the thunderstorm through direct radiative effects was investigated using the Hirlam Aladin Research for Mesoscale Operational Numerical Weather Prediction in Euromed (HARMONIE) model. HARMONIE was successfully able to resolve the dynamics of the thunderstorm, and simulations that considered the influence of the smoke-related aerosols were compared to simulation without aerosols. As simulated by the HARMONIE model, the smoke reduced the shortwave radiation flux at the surface by as much as 300 W/m^2 and decreased the near-surface temperature by as much as 3 °C in the vicinity of the thunderstorm and respectively 100 W/m^2 and 1 °C in the thunderstorm region. Atmospheric instability decreased through the direct radiative effect of aerosols, and several dynamic features of the simulated thunderstorm appeared slightly weaker.

1. Introduction

The aerosol direct radiative effect results from the scattering and absorption of radiation. The global direct radiative effect of both natural and anthropogenic aerosols is an important component of the radiative balance of the Earth and the direct radiative effect of aerosols has been estimated in numerous modelling and observational studies (e.g. Jacobson, 2001; Remer et al., 2008; Haywood and Boucher, 2000). The aerosols from biomass burning may have either a warming or cooling effect on climate as the optical properties of smoke depend on the geographical source region, the season and the type of biomass burning (Carslaw et al., 2010; Forster et al., 2007). The amount of scattering and absorption is dependent on the ratio of black carbon and organic matter and is highly variable among different fire conditions (Reid et al., 2005a,b).

In addition to the effect on climate, biomass burning can have a considerable influence on short-term weather conditions (e.g. Robock, 1991; Stone et al., 2011). Stone et al. (2011) studied the effect of smoke aerosols on the surface radiation budget during a fire in Colorado, USA. They estimated that the shortwave radiative forcing was between −65 and −194 W/m^2 per unit aerosol optical depth (AOD) (at 500 nm) and that the longwave radiative forcing was an average of 10 W/m^2 per unit AOD (at 500 nm) during the daytime for the studied case.

Aerosol from biomass burning can cause significant change in vertical profiles of temperature and moisture through the direct radiative effect and thus can have important impact on numerical weather prediction (NWP) results (Grell et al., 2011). Both the direct radiative effect and indirect effect of aerosols are important for the development of deep convection (Fan et al., 2008, 2013). Depending on the aerosol optical properties, the direct radiative effect of aerosols from biomass burning can cause cooling near the ground and heating at higher altitudes, which may decrease atmospheric instability and therefore weaken convection (Fan et al., 2008). Jiang and

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Feingold (2006) found that aerosol direct radiative effect led to reduction in surface latent and sensible heat fluxes and weakened convection. Mallet et al. (2009) simulated aerosol direct radiative effect of dust with MesoNH model and found considerable decrease in convectively available potential energy (CAPE) over West Africa. However, sometimes stronger deep convection and more pronounced convective storms form due to the direct radiative effect (Grell et al., 2011). Different types of aerosols may have different direct radiative effects: Ge et al. (2013) investigated the sensitivity of smoke aerosol radiative forcing to the ratio of black carbon and organic matter to determine the effective amount of scattering and absorption. More black carbon (more absorption) led to greater warming in the atmosphere (Ge et al., 2013).

In addition to the direct radiative effect, aerosols have an indirect effect on weather through the modification of cloud properties by acting as cloud condensation nuclei (CCN) (Twomey, 1977; Rosenfeld, 2000). High smoke concentrations lead to high number of CCN, which impact clouds and microphysics (Grell et al., 2011). The convective invigoration effect is described by Rosenfeld et al. (2008). In polluted air there are smaller drops that do not precipitate prior to reaching supercooled levels. Supercooled drops freeze and release latent heat at supercooled levels. Ice precipitation falls and melts at lower levels consuming heat. Latent heating higher up and heat consumption through melting at lower altitude lead to invigoration of convective clouds and greater amount of precipitation (Rosenfeld et al., 2008). Fan et al. (2013) explained that smaller and longer lasting ice particles are of great importance on cloud properties in addition to the convective invigoration through additional latent heat release from freezing of greater amount of cloud water. Studies about aerosol indirect effect on convective storms give different results. E.g. Ntelekos et al. (2009) studied the influence of aerosols on intense convective precipitation with online-coupled WRF-CHEM model and found that aerosol can both decrease and increase the precipitation amount depending on the meteorological environment. Li et al. (2009) simulated squall line with WRF model with different aerosol concentration scenarios and found that convection was enhanced in the polluted environment.

In the summer of 2010, a high-pressure area situated in Russia blocked the westerly flow for a very long time. This resulted in hot (35 °C–41 °C) and dry (relative humidity 9–25%) atmospheric conditions that were suitable for wildfires, which occurred in western Russia from mid-June to mid-August 2010 (Witte et al., 2011). A smoke plume travelled clockwise around Moscow from August 5 to 9 (Sitnov et al., 2012). On August 8, the smoke plume was situated on the western border of Russia, and the presence of the smoke aerosols coincided with the thunderstorm event (Toll et al., 2014; Törmä et al., 2013) investigated in this paper.

The wildfires in the summer of 2010 in Russia have been thoroughly studied from the perspective of atmospheric chemical composition and aerosol loading (e.g. Huijnen et al., 2012; Witte et al., 2011; Sitnov et al., 2012; Konovalov et al., 2011; Van Donkelaar et al., 2011). The radiative forcing and optical properties of smoke are described by, e.g., Sitnov et al. (2012) and Chubarova et al. (2012). Péré et al. (2014) have studied the direct radiative effect of these fires on meteorological conditions using the CHIMERE chemistry-transport model for aerosol distributions and optical properties calculations with the Weather Research and Forecasting (WRF) model for meteorological simulations.

The direct radiative effect of the smoke aerosols at the surface from the 2010 summer wildfires in Russia (a decrease in the diurnal average shortwave radiation up to 100 W/m^2 occurred), as described by Péré et al. (2014), suggests that the smoke might have had a considerable influence on the derecho situation that occurred on the western side of the smoke plume path on August 8, 2010. This derecho has been previously modelled with convection allowing Hirlam Aladin Research for Mesoscale Operational Numerical Weather Prediction in Euromed (HARMONIE) model by Toll et al. (2014) but without consideration of the influence of the smoke on the storm. The HARMONIE model was successfully able to resolve the dynamics of the storm. Such a concurrence of smoke aerosols and a severe thunderstorm provided us an opportunity to investigate the aerosol effects on severe convection.

The main goal of the paper is to study the influence of aerosols from biomass burning on a severe thunderstorm event through the direct radiative effect. A short overview of the calculations for aerosol input data are presented in the model and methods section (Section 2.1). An overview of the HARMONIE model is given in Section 2.2, and an overview of the radiation scheme is given in Section 2.3. The experiment designs are described in Section 2.4, and the modelling results are presented in Section 3. The simulated storm dynamics with the direct radiative effect of aerosols are compared to the results presented by Toll et al. (2014), which were computed using a climatological aerosol distribution. Section 4 discusses the modelling results and potential deficiencies in the simulations.

2. Model and methods

2.1. Description of calculations for the aerosol input data

The aerosol input data for our study was provided by Dr. Vincent Huijnen and is documented in Huijnen et al. (2012). The aerosol input data for the present study originates from the aerosol modelling system based on the European Centre for Medium-Range Weather Forecasts (ECMWF) global model Integrated Forecasting System (IFS) coupled to a chemistry transport model (CTM-IFS) (Flemming et al., 2009). The aerosol modelling system based on CTM-IFS (Flemming et al., 2009) is described by Morcrette et al. (2009). This system forecasts and reanalyses the distribution of various aerosol species. The available aerosol species are sea salt, dust, organic and black carbon, and sulphate. The aerosols are advected by the model dynamics, and they interact with the model physics. Several aerosol physical processes are represented in the IFS: vertical diffusion and convection, sedimentation and deposition. In addition, the AOD from satellite measurements is assimilated in the IFS through the assimilation of aerosol-sensitive radiances (Benedetti et al., 2009).

Huijnen et al. (2012) assimilated daily fire emission estimates using fire radiative power observations from the Moderate Resolution Imaging Spectroradiometer (MODIS); this fire emission assimilation system is called the Global Fire Assimilation System (GFAS) (Kaiser et al., 2012). The fire emission rate was held constant during the entire day, because