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A conceptual model for the link between Central American biomass burning aerosols and severe weather over the south central United States

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Abstract

Each spring, smoke particles from fires over the Yucatan Peninsula and south Mexico cross over the Gulf of Mexico into the United States (US) under the control of moist oceanic air flow from the southwestern branch of the subtropical (Bermuda) high. Smoke can be transported deep into the south central US, where dry lines and warm conveyor belts are frequently formed and cause deep convection and severe weather. Lyons *et al* (1998 *Science* **282** 77–80) and Murray *et al* (2000 *Geophys. Res. Lett.* **27** 2249–52) noticed a ∼50% increase of lightning along the smoke transport path over the south central US during the May 1998 Central American smoke episode. Here we present a conceptual model of coherent microphysical and meteorological mechanisms through which smoke may impact convective clouds and subsequently result in more severe weather over the south central US. The conceptual model depicts a chain of processes in which smoke particles are first activated as cloud condensation nuclei when they are entrained into the warm conveyor belt, a convective zone formed over the south central US as a result of the encounter between the mid-latitude trough and the subtropical Bermuda high. As the convection continues with deepening of the mid-latitude trough, the greater concentration of water cloud condensation nuclei delays the warm rain processes, enhances the development of ice clouds, and invigorates the updrafts, all of which contribute to the formation of severe weather such as hail and lightning. The conceptual model is based on the reasoning of physical mechanisms revealed in previous studies (over the tropical biomass region), and is supported here through the analysis of satellite data, ground observations, aerosol transport model results, and idealized cloud resolving simulations of a day in May 2003 when record tornado events occurred over the south central US. Further assessment of this conceptual model is discussed for future investigations.

Keywords: Central American smoke, aerosol and severe weather in the United States, aerosol-cloud interaction

1. Introduction

Smoke particles modulate atmospheric radiative energy and precipitation processes directly by absorbing and scattering radiation, and indirectly by their microphysical effects on cloud formation. As reviewed in the 2007 IPCC report, the indirect effect of aerosols on climate is the largest source of uncertainty in global climate models (GCMs), partially because different aerosol–cloud interaction mechanisms have been proposed with qualitative but not quantitative understanding (Andreae

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and Rosenfeld 2008). The indirect aerosol mechanisms pertinent to smoke particles include: (1) the first indirect effect, where the size of water cloud droplets decreases as smoke particles enhance the number of cloud condensation nuclei available for activation (Twomey 1974); (2) the semi-direct (choking) effect, where absorption of solar radiation by smoke particles increases atmospheric stability and consequently suppresses the low-level cloud formation (Koren *et al* 2004); (3) the second indirect effect, where the smaller cloud droplets arising from the first indirect effect of smoke particles result in longer cloud lifetimes and larger cloud fractions (Albrecht 1989, Kaufman *et al* 2005); and (4) the invigoration effect, where for strong convection storms the warm rain process is delayed by the smoke through its first and second indirect effects, which in turn allows for more cloud water to be transported vertically, a greater release of latent heat, and a subsequent invigoration of the updrafts, thus supporting the development of intense thunderstorms and large hail (Rosenfeld 1999, Andreae *et al* 2004, Lin *et al* 2006).

While the aforementioned studies have improved our understanding of smoke–cloud interaction, they (except Twomey 1974) are primarily built upon the analysis of isolated data collections or observations over the smoke source regions of South America, southern Africa, Indonesia, and their downwind oceans. Extending these studies and their proposed mechanisms of smoke indirect effects to other biomass burning regions is essential for an improved characterization of aerosol–cloud interaction in GCMs. This is a challenging task, as the mechanisms proposed for the aerosol indirect effects range from small-scale microphysical processes in clouds to the meteorological and thermodynamic environment regulated by mesoscale to synoptic-scale systems that vary with region and season. It has been argued that some aerosol–cloud interaction mechanisms may be facilitated in one region while being suppressed in another, depending on meteorological regimes and particle concentration (Feingold *et al* 2001).

Despite there being much smoke-precipitation research in tropical and southern hemisphere regions, considerably less has been conducted in northern hemispheric mid-latitudes such as the continental US. Based upon the analysis of data from the tropical rainfall measuring mission (TRMM), Bell *et al* (2008) recently showed the urban (*local*) air pollution effect on the weekly cycle of precipitation in the US. Here, we want to point out that the US actually hosts a natural and persistent laboratory for smoke–weather interaction, namely the typical springtime transport of Yucatan Peninsula smoke into Texas and the American Southeast. This feature of smoke transport presents a number of intriguing scientific questions which require exploration. Notably with limited observations in 1998 in this region, Lyons *et al* (1998) and Murray *et al* (2000) hypothesized that there is a link between biomass burning in Mexico and the occurrence of severe weather (hail and lightning) over the downwind US region, and attributed (with speculation) the cause to the microphysical effects of smoke particles on cloud. They did not, however, consider any meteorological or synoptic factors specific to this region that could potentially facilitate the cloud invigoration processes and minimize the smoke choking effect on cloud. The focus of this paper is to propose a conceptual model that provides a more detailed, coherent, and physical explanation for such a hypothesis. This conceptual model is described in section 2. In section 3, we present the physical reasoning and basis of this conceptual model through limited data and modeling analysis of a 2003 case that has features similar to the 1998 event studied by Lyons *et al* (1998) and Murray *et al* (2000). Finally, we summarize our analysis in section 4 and discuss the future quantitative assessments of this conceptual model.

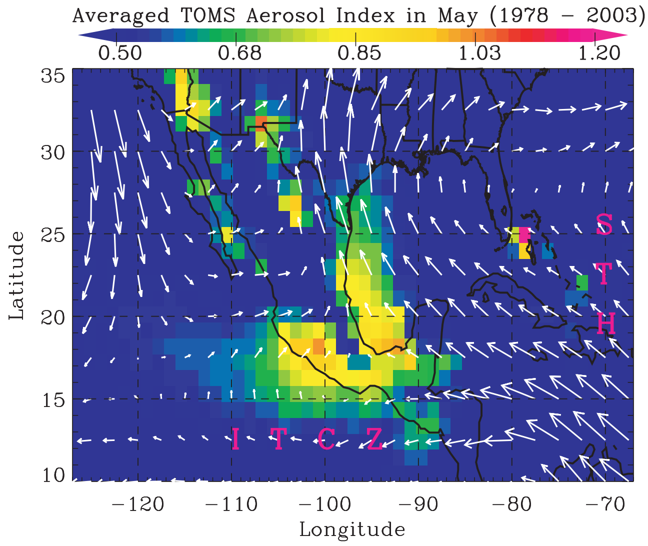

Figure 1. Total Ozone Mapping Spectrometer (TOMS) aerosol index (filled colors) and wind vector (white arrows) at 700 hPa in May averaged from 1978 to 2003. STH and ITCZ, respectively, denote the subtropical high pressure system (e.g., Bermuda high) and intertropical convergence zone. A larger TOMS aerosol index generally indicates high concentration of absorbing aerosols such as smoke particles. A similar figure but for shorter-time averages of TOMS index and wind vector is shown in Rogers and Bowman (2001). Wind data are adopted from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis; TOMS aerosol index data are obtained from National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC).

2. The conceptual model

Biomass burning in Central America is mainly used to clear land for agricultural practices (Kauffman *et al* 2003). Burning coincides with the March–May northern tropical dry season, and terminates in early June when the rainy season begins (Reid *et al* 2004, Wang *et al* 2006). As detailed below (in (a)–(b)), because of its synoptic systems and geographic layout (figure 1), the Central American smoke region (centered over the Yucatan Peninsula) provides a unique natural laboratory to study the hypothesis of the smoke invigoration effect on organized cloud systems. A number of dynamic and microphysical effects observed within this region (and described in the following (c)–(d)) also contribute to the proposed conceptual model.

(a) *Synoptic systems favorable for deep convection*. During spring, the major synoptic systems in the regions over and

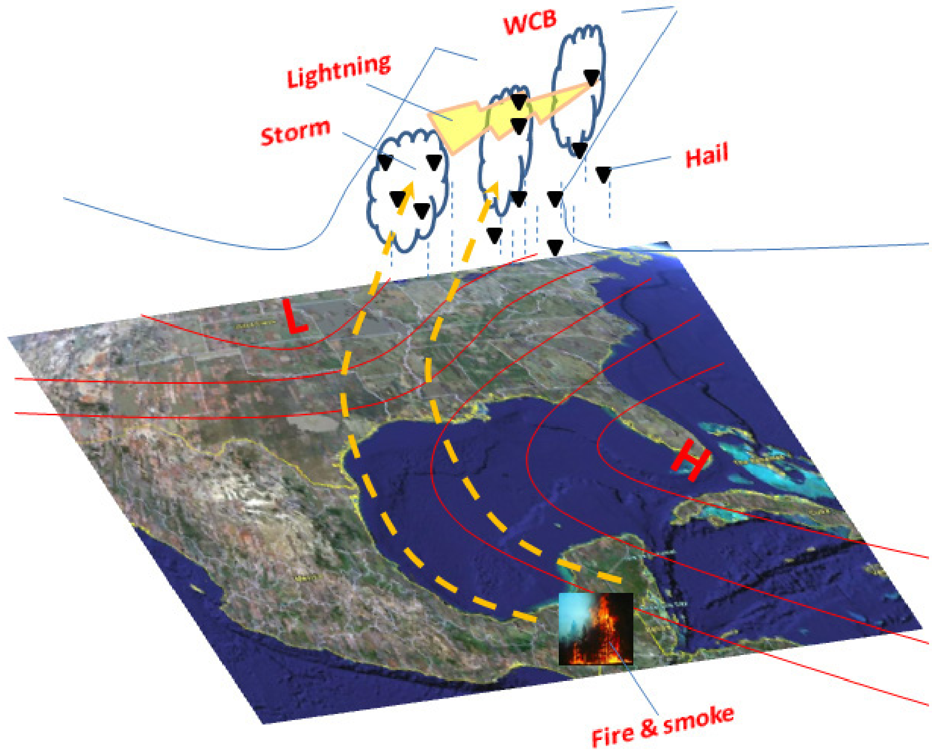

Figure 2. A conceptual model that illustrates the typical synoptic regimes for the interactions over the south central US between mid-latitude clouds and long-range transported smoke particles from the Yucatan Peninsula. Smoke particles interact with clouds in the warm conveyor belt (WCB), delay the onset of warm rain, and consequently invigorate the updrafts, causing intensive thunderstorms and large hail over the US. See the text in section 2 for details.

to the north of the Gulf of Mexico are the subtropical (Bermuda) high and the mid-latitude westerly waves. Dry lines frequently occur over the southern and central Great Plains (covering parts of Texas, Oklahoma, Kansas, Arkansas, etc) when the moist, warm southerly airflow (e.g., the low-level jet) from the Gulf of Mexico meets the dry, cold northwesterly flow from the Rocky Mountains, causing deep convection and severe weather (figure 2).

(b) *Unique smoke transport path into the continental US*. Smoke production is at a maximum during the springtime dry season in the Yucatan Peninsula (Reid *et al* 2004). As is apparent in figure 1, smoke crosses the subtropical Gulf of Mexico and can extend far northward into mid-latitude synoptic systems over the southern US. Hence, in contrast to the normal oceanic airflow, the southerly airflow from the Gulf of Mexico during spring brings larger concentrations of smoke particles to the south central regions of the US. These smoke particles not only affect air quality but may also influence cloud processes associated with convection often initiated by the dry lines over Texas and the Great Plains (Wang and Christopher 2006).

(c) *Microphysical properties*. Smoke particles serve as efficient cloud condensation nuclei (CCN) (Reid *et al* 2005). Given that severe storms naturally have strong updrafts and high supersaturations, the Twomey effect can become significant even for moderate aerosol loadings. For the cases of smoke interaction discussed here, clouds are likely to be 'CCN saturated'. Reid *et al* (1998) found for such storms that the impacts of smoke on cloud droplet concentration vary little between moderately polluted particle concentrations and massively polluted conditions. It should be noted that the hygroscopic growth of smoke particle in the moist air originating over the Gulf of Mexico also decreases absorption by the particles and thus minimizes the semi-direct (choking) effect on clouds, thereby favoring the Twomey effect on the warm rain process.

(d) *Smoke invigoration effect on clouds*. After smoke reaches the Great Plains, its continued transport to the northeast depends on the mid-latitude synoptic systems. Most often, the presence of a mid-latitude ridge (centered over the central US) tends to suppress the transport of smoke. In contrast, the presence of a trough associated with southward movement of a cold front facilitates the transport, as this trough together with the flow around the Bermuda high can act to enhance the warm conveyor belt, thus lifting the smoke particles from the boundary layer to the free troposphere and transporting them further downwind to the central and eastern US (figure 2). In convective processes initiated either by the dry line or the warm conveyor belt, smoke particles have been hypothesized to invigorate clouds (Rosenfeld 1999, Andreae *et al* 2004, Lin *et al* 2006), thereby supporting the hypothesis of the link between biomass burning in Mexico and severe weather (hail and lightning) in the downwind regions of the US (Lyons *et al* 1998, Murray *et al* 2000).

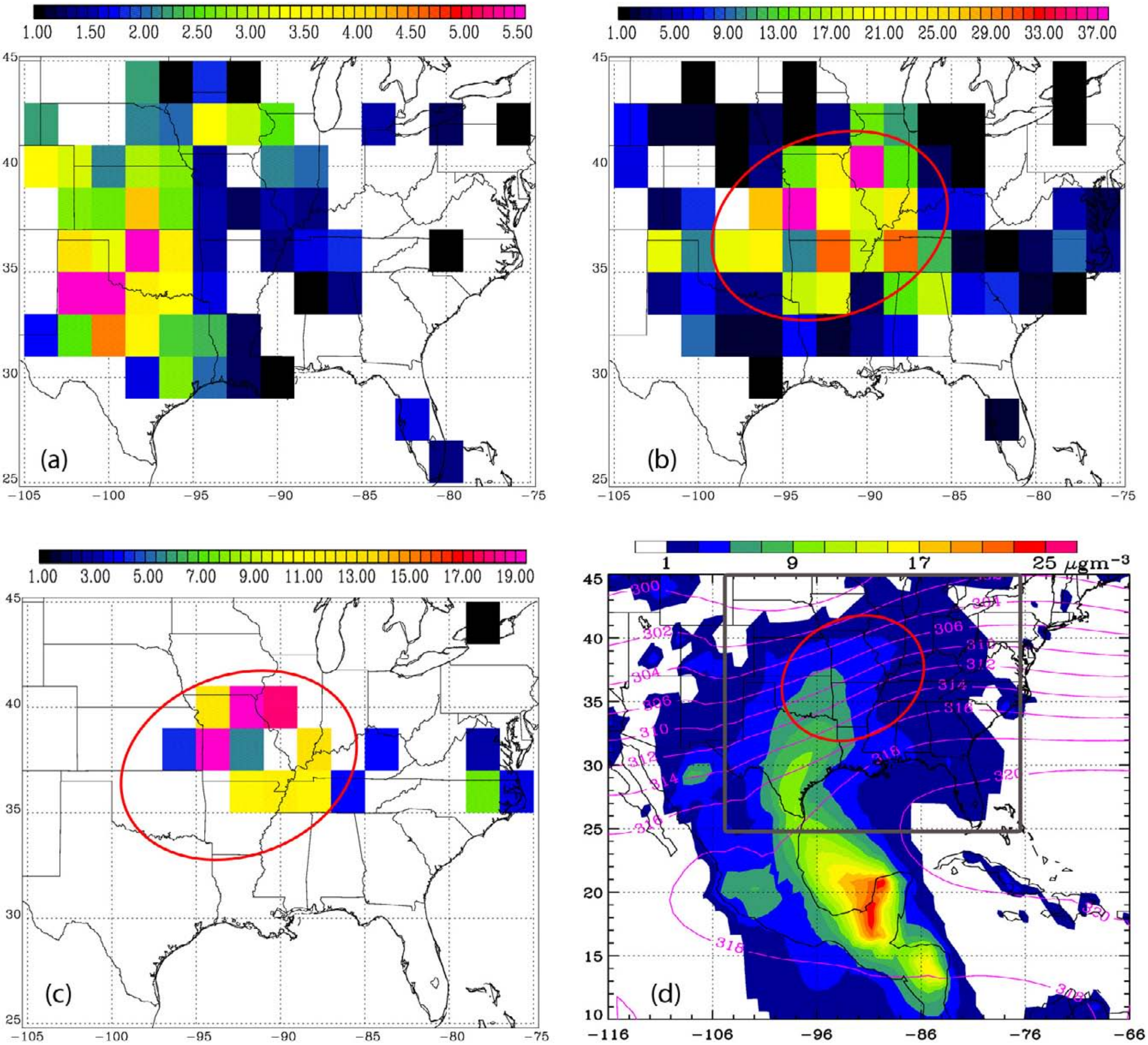

Figure 3. (a) Climatological mean in May of tornado number distribution computed at 2×2 grid resolution. The tornado data are obtained from the National Climate Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). (b) Tornado number distribution in May 2003. (c) The anomaly of tornado numbers in 3–5 May and 9–11 May 2003 relative to the climatological mean in May. Shown only are the anomalies that are beyond one standard deviation of the climatological mean. In this figure, the climatological mean is computed from data in 1979–2001, as defined by the NCEP North American regional analysis (http://www.cdc.noaa.gov/). (d) Averaged mass of smoke particles along the smoke transport path near the surface in May 2003. The smoke transport path is defined as the region where the model simulated smoke concentration is larger than 1.0 μg m^{-3} near the surface (Wang *et al* 2006). Also shown in pink lines are the averages of 700 mbar geopotential height (in units of 10 m) during days of smoke transport. The rectangle in gray in (d) denotes the area corresponding to panels (a)–(c). Ellipses in red in (b)–(d) highlight the region where larger numbers of tornadoes occurred in May 2003.

3. Observational and modeling support for the conceptual model

The description in section 2 suggests that cloud processes over the south central US in spring have a high likelihood of being affected by the smoke particles transported from the Yucatan Peninsula. Based upon previous studies of the smoke effect on deep convection (Rosenfeld 1999, Andreae *et al* 2004), we hypothesize that the formation of ice or mixed-phase clouds over the south and central US should be enhanced as a result of the smoke invigoration process, which in turn facilitates the formation of hail and lightning (Pruppacher and Klett 2003). Unfortunately, Central America (unlike southern Africa and South America) has never had a dedicated campaign for studying the climate effect of smoke aerosols. The data available for the 1998 case presented by Lyons *et al* (1998) and Murray *et al* (2000) are also limited for the study of cloud microphysical processes, although they revealed a 50% increase of cloud-to-ground lightning (as compared to the climatological mean) along the smoke transport path over the south central US. Hence, we lack sufficient data to quantitatively evaluate the conceptual model described in section 2. Rather, we qualitatively articulate this model based upon the physical reasoning and limited case studies for 2003 which showed some similar features to the 1998 case.

3.1. Limited observations supporting the conceptual model

While the transport of smoke from Central America to the US occurs every year, the strength of such transport varies. The largest transport in the 1990s was in May 1998 (Peppler *et al* 2000) and it was studied by Lyons *et al* (1998) and Murray *et al* (2000). The largest transport of Central American smoke in the last decade (since 1998) occurred during May 2003 (Wang *et al* 2006). This smoke event also coincided with anomalously severe weather. Weather observations during the smoke events in May 2003 were reported in 'State of the Climate in 2003' (Levinson and Waple 2004) as follows: 'May 2003 had a total of 546 tornadoes, the most reported in any month for the US, exceeding the previous month/year record by 145 tornadoes. Two outbreaks of severe weather, on 3–5 May and on 9–11 May, led to 25 F3–F5 tornadoes for the month'. Previous studies mandated by the US Congress have tried to use the weather research and forecasting (WRF) model to simulate and understand the cause of these severe weather events in May 2003, but the simulations were not successful (personal communication with Dr Julian Wang at NOAA Air Resources Laboratory).

The null results from traditional climatological analyses and modeling studies are certainly suggestive for several unaccounted factors. Could smoke particles that are not included in the WRF have played an important role in the severe storms that caused so many tornadoes in a short time period? Alternatively, is the correlation between smoke transport and severe weather confounded by other meteorological phenomena? The correlation between smoke concentration and severe storms is robust, at least on a regional scale (figure 3). Our analysis shows that the distribution of numbers of tornadoes in May 2003 reaches its maxima values in a southwest-to-northeast band centered at $-92°$ W (the ellipse in figure 3(b)), but in the climatological mean (from 1979 to 2001) the maximum occurs in a south–north band along $-100°$ W (figure 3(a)). While the tornado climatology can be biased by the observational systems including population density and road networks, this uncertainty is difficult to quantify. Nevertheless, the regions in which the tornado numbers in May 2003 increased by a factor of 3 or greater than the climatological mean plus one standard deviation (such as in the red ellipses of figure 3(b) and during the two tornado outbreaks in figure 3(c)) are found (and can only be found) along the smoke transport path (shown in figure 3(d)). Hence, the alignment between smoke transport path and the distribution of tornado number anomalies in May 2003 supports the proposed conceptual model described in figure 2.

Figure 4 shows that during 3–5 May 2003 (one of the two tornado outbreak time periods mentioned in Levinson and Waple 2004), most tornadoes occurred after a mid-latitude trough replaced the ridge over the south central US late on 3 May (figures 4(a) and (b)), which subsequently transported the Central American smoke to the Great Plains (figure 4(e)). During nearly the same time period, the subtropical high pressure system moved northward, enhancing the smoke transport and leading to the formation of a warm conveyor belt (red box in figures 4(b), (e), and (h)). True color images from the Moderate Resolution Imaging Spectroradiometer (MODIS), together with Environmental Protection Agency (EPA) ground observation network data, and the output from an aerosol transport model (Wang *et al* 2006) *consistently* show that high concentrations of smoke particles were co-located underneath the convective clouds, both of which are driven by the warm conveyor belt (figures 4(b) and (e)). Wang *et al* (2006) further showed that the poor air quality observed by the EPA network (dots in figures 4(d)–(f)) was mainly due to the transport of smoke; the spatiotemporal variation of $PM_{2.5}$ (particulate matter with diameter less than 2.5 μm) and carbon concentration in May 2003 over the southeastern US was well captured by the modeled smoke distribution.

During the late evening of 4 May and on the afternoon of 5 May, the strength of the warm conveyor belt intensified as the trough was deepening, which caused the transport of smoke plumes further northward. After that, the warm conveyor belt then moved southeastward (red boxes in figures 4(c), (f), and (i)) and subsequently brought more smoke to the southeastern *middle* tropospheric layer, thus allowing for the interaction with convective clouds (figure 4(i)). In the process, smoke particles potentially invigorated convection. A combination of figures 4(a)–(c) and figures 4(g)–(i) with the figures 4(d)–(f) clearly showed that the formation of tornadoes (green dots in figures 4(a)–(c)) and hail (yellow diamonds in figure 4(g)–(i)) followed the movement of smoke transport path over the southeastern US. Most places experiencing tornadoes and hail were under the influence of the transported smoke particles (e.g., region B in figure 4(i)); while those regions experiencing similar synoptic conditions associated with the same trough but not reached by the smoke did not report any tornado or hail events (e.g., region A in figure 4(i)). Hence, the synoptic regimes and the processes shown in figure 4 support the conceptual model in figure 3, at least qualitatively.

The synoptic regimes during 9–11 May were similar to that in 3–5 May, and the following analysis focuses on 9 May. On that day, the distribution of fallen hail was aligned with a warm conveyor belt (region C in figure 5(a)) over the southeastern US. In this warm conveyor belt, a combination of the MODIS retrievals of *water* cloud effective radius (figure 5(b)) and optical thickness (figure 5(c)), as well as the modeled smoke mass concentration near the surface (figure 5(d)), show that the clouds have smaller effective radii and greater optical thicknesses along the smoke transport path (such as in the rectangle A) than in other regions less affected by smoke (such as in the rectangle B).

A quantitative analysis of aerosol–cloud interaction in the warm conveyor belt (shown as the region C in figure 5) was conducted by first combining the MODIS 1 km cloud optical properties with corresponding low-level smoke concentrations simulated in the model, and then calculating the statistics of cloud effective radius and cloud optical thickness for each smoke mass concentration bin (of 2 $\mu g\ m^{-3}$). The results

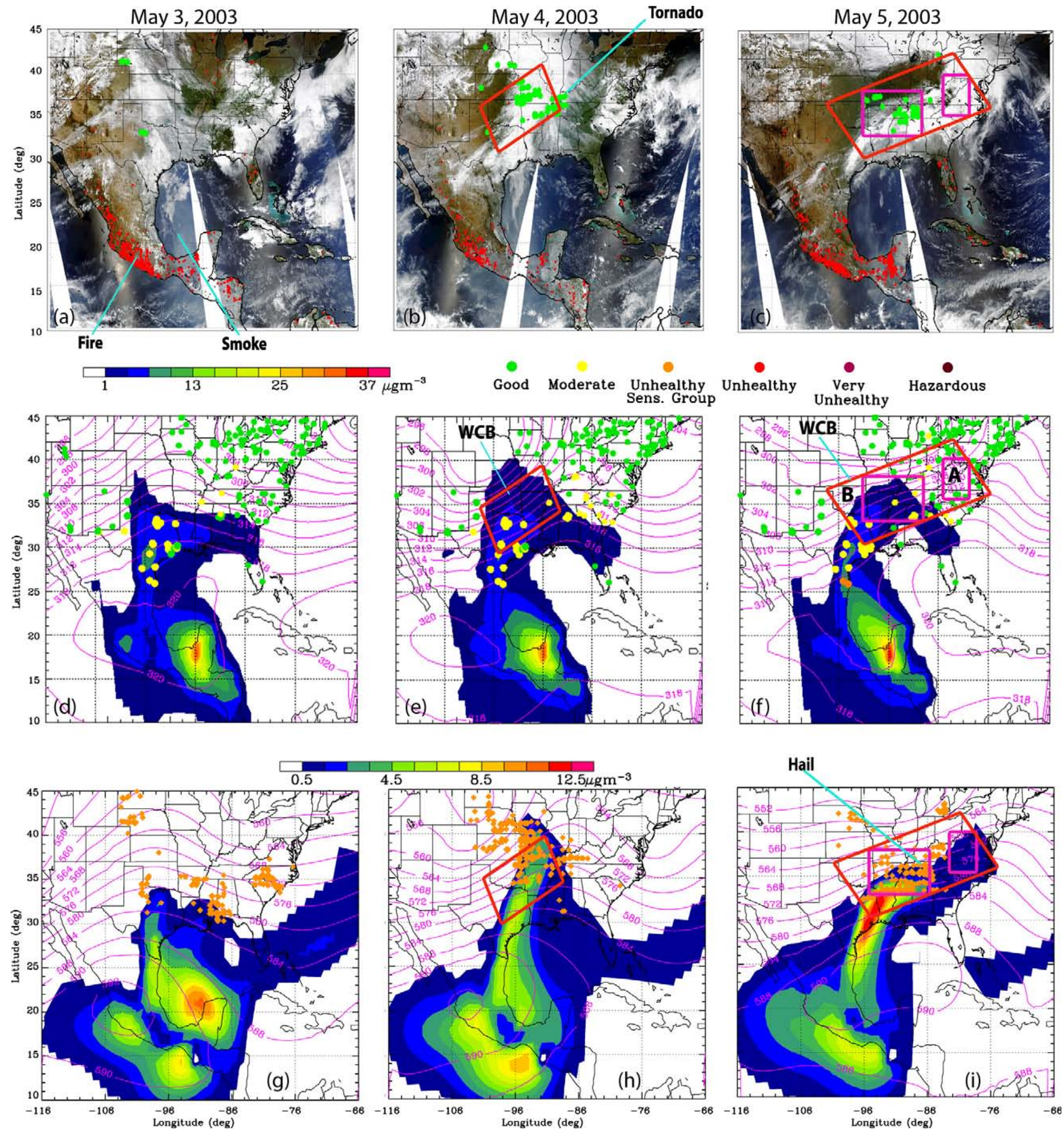

Figure 4. Top row: MODIS true color images from (a) Aqua satellite on 3 May, (b) from Terra satellite on 4 May, and (c) from Aqua satellite on 5 May; red and green dots respectively denote fire pixels detected by MODIS and the location of tornadoes reported by NOAA. Middle row: model simulated smoke concentration (filled color contour) near the surface at 12:00 CDT on (d) 3 May, (e) 4 May, and (f) 5 May. Dots are EPA $PM_{2.5}$ (particulate matter with diameter less than 2.5 μm) monitoring locations and are color-coded based upon the air quality category measured on that day. For example, $PM_{2.5}$ mass (in μg m^{-3}) of 15.4, 40.4, 65.4, 150.4, 250.4, and 500.4 are upper limits for the categories of good, moderate, unhealthy for special groups (e.g., elderly and children), unhealthy, very unhealthy, and hazardous, respectively. Pink solid lines are 700 mbar geopotential height (in 10 m). Bottom row: model simulated smoke concentration (filled color contour) in the 10th model layer (roughly 3000 m above surface) at 12:00 CDT on (g) 3 May, (h) 4 May, and (i) 5 May. Pink solid lines are 500 mbar geopotential height (in 10 m), and yellow diamonds are the locations of fallen hail reported by NOAA. Warm conveyor belt (WCB) is shown as red boxes on (b), (e) and (h) for 4 May and on (c), (f), and (i) for 5 May. Pink-color boxes A and B shown in (f) respectively indicate regions with high and low loading of smoke particles; these two boxes are also correspondingly marked in (c) and (i).

in figure 5(e) indicate a significant and generally steady increase of cloud optical thickness (from less than 8 to more than 30) and decrease of cloud effective radius (from 14 to 8 μm) as the smoke mass concentration increases (from 5 to 23 μg m^{-3}). These results are consistent with the findings of Rosenfeld (1999) and Andreae *et al* (2004) in which a two-step mechanism was found: (a) smaller-size water cloud droplets due to the high concentration of CCN

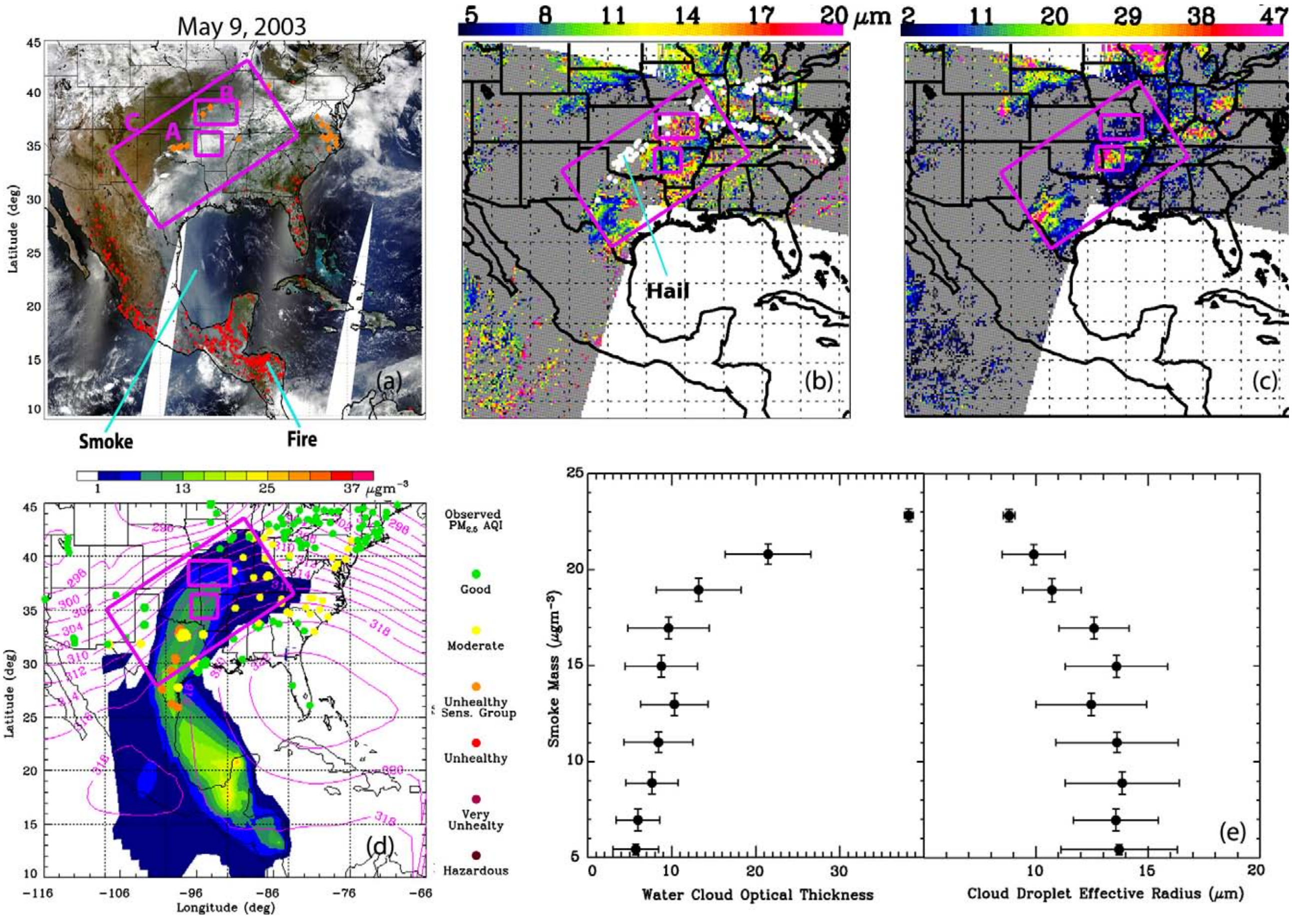

Figure 5. (a) MODIS true color image from Terra on 9 May 2003. Yellow diamonds are the locations of tornadoes reported by NOAA on that day. (b) and (c) respectively show the corresponding retrieval of *water* cloud effective radius and optical thickness. White dots on (b) are locations of hail reported by NOAA on that day. (d) Model simulated smoke concentration (filled color contour) near the surface at 12:00 CDT, 9 May 2003. Dots are EPA $PM_{2.5}$ monitoring locations and are color-coded based upon the air quality category measured on that day (see the explanations of air quality categories in the caption of figure 4 for details). Pink solid lines are 700 mbar geopotential height (in 10 m). Also in panels (a)–(d) are two smaller rectangles (indicated as A and B in (a)) respectively denoting regions with high and low concentration of smoke particles. (e) Change of MODIS-retrieved water cloud droplet optical depth and effective radius (y-axis) as a function of modeled smoke concentration near the surface in the warm conveyor belt (denoted as the big pink-color box C in panel (a) and consistently marked in (b)–(d)). The vertical bars in (e) show the ± 1 standard deviation of binned smoke concentration; the horizontal bars show the ± 1 standard deviation of water cloud optical thickness (left plot) and cloud effective radius (right plot) for the corresponding smoke bins.

suppress the warm rain process and thus make water clouds optically thicker in the early stage of deep convection (similar to figure 5(e)); (b) as strong convection continues, more smaller cloud droplets would be uplifted to higher altitudes, thus enhancing the ice processes and facilitating the formation of hail (figure 5(b)). Recent modeling studies of the aerosol impacts on deep convection have also found enhanced hail formation in the presence of increased aerosol concentrations, and further demonstrated that the associated variations in hail size can enhance the updraft strength and low-level vorticity of deep convective storms (van den Heever and Cotton 2004, van den Heever *et al* 2006).

3.2. Modeling analysis

van den Heever and Cotton (2007) modeled the impacts of urban-enhanced aerosols on the characteristics of downwind convection. They found that in the early stage of convective storm development, higher CCN concentrations lead to a smaller droplet size but a higher concentration of cloud droplets (and presumably also higher cloud optical thicknesses that are consistent with figure 5(e)). The higher concentration of smaller cloud droplets is then vertically transported, resulting in the generation of greater ice mixing ratios and hence conditions favorable for the enhancement of lightning (van den Heever and Cotton 2007). However, this catalytic effect of aerosols on ice clouds and lightning cannot be realized without favorable meteorological conditions (e.g., strong low-level convergence downwind of urban regions). Hence, these previous modeling studies support our conceptual model in that the unique synoptic regimes (warm conveyor belt) and geographical layout over the Gulf of Mexico and the south central US facilitate the smoke–cloud interaction, in particular the smoke-induced cloud invigoration.

An idealized, single-grid cloud resolving model simulation using the regional atmospheric modeling system (RAMS) (Cotton *et al* 2003) was carried out to study the difference in cloud processes between clean (non-smoke) and smoky conditions. The simulations focus on a severe weather event that occurred on 9 May 2003 over the Great Plains (region A in figure 5(a)). The model is initiated with 1200 UTC sounding data from a regional aerosol transport model for 9 May 2003 (Wang *et al* 2006) for both the smoky and non-smoky simulations. The background aerosol concentration over the Great Plains was set to 200 cm^{-3} in the simulations. The smoke particle concentrations were derived from smoke mass concentrations simulated in the regional model (Wang *et al* 2006). In the derivation, smoke particles are assumed to have a mass density of 1.2 g cm^{-3} and a lognormal size distribution with a volume mean diameter of 0.3 μm and standard deviation of 1.8 μm, which makes 1 μg m^{-3} of smoke mass concentration equivalent to $\sim$36 smoke particles cm^{-3} (Wang and Christopher 2006). All of the smoke particles were assumed to be candidates for CCN, given than smoke particles have been previously found to be efficient CCN (Reid *et al* 1998). The horizontal grid spacing was 1 km, with a 200 $\times$ 200 $\times$ 50 grid domain, and variable grid spacing was used in the vertical direction. A time step for numerical integration of 5 s was utilized, and the simulations were run for 2 h. Convection was initiated through the use of a warm bubble.

Figure 6 shows that the smoky case produces more ice than the non-smoky case, and as the clouds continue to develop, 20%–40% enhancement of ice crystals by smoke particles are extended from the center of clouds to both cloud base and top. Since greater ice mixing ratios in deep convection generally prompt the occurrence of lightning (Pruppacher and Klett 2003), these model results are supportive of our conceptual model, although their quantitative assessment is difficult due to the lack of microphysical observations for this event, and is therefore out of the scope of this study.

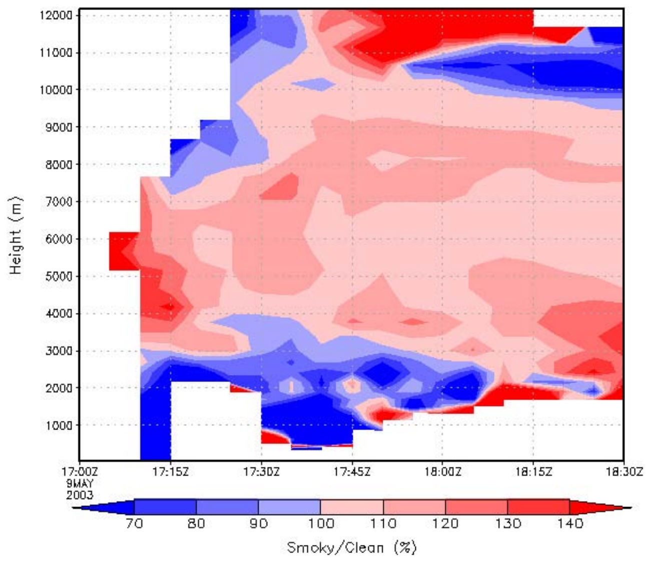

Figure 6. Time–height contour plot of the ratio of the horizontally averaged (over the whole model domain) ice mixing ratio between smoky and non-smoky simulations for cloud development in box A on figure 5(a). Note that the rapid variation of ratios around the cloud edges (top, side, bottom) should be treated with caution because the actual values of the ice mixing ratio are very small in cloud edges, and thus their absolute differences between smoky and non-smoky simulations are much smaller in the cloud edges than in the cloud centers. See the text in section 3.2 for details.

4. Discussion and summary

A conceptual model is proposed to describe the following three processes that link the transport of smoke from Central America with the enhancement of severe weather events (hail, lightning, and strong updrafts) over the south and central US. (1) Smoke particles are transported to the southern US under the control of moist oceanic air flow from the southwestern branch of the subtropical Bermuda high. (2) The concentration of background aerosols is relatively low over the Great Plains (Wang *et al* 2006). The transported smoke particles thus significantly enhance the concentrations of CCN and the resultant Twomey effect, thereby leading to smaller-size cloud droplets. (3) When a mid-latitude trough and the associated cold front move over the Great Plains and form dry lines (and the warm conveyor belt) with the airflow from Gulf of Mexico, the smoke particles are entrained into the deep convection, which can enhance updrafts, hail formation and lightning. We also expect that the smoke semi-direct effect is minimized in the process because the smoke particles are hydrated in the transport and thus are less absorptive.

The physical reasoning of the conceptual model is supported by the physics of the smoke invigoration effect on cloud revealed in previous studies (notably in South America) and by the observational and modeling analyses of the record tornado event in May 2003 that were conducted in this study. One caveat in studying smoke–cloud interactions is the covariance between the smoke transport and meteorological factors. Overcoming this caveat with observations alone is difficult because (a) it is nearly impossible that the exact same meteorological regimes respectively with and without smoke contamination will occur in the real world, and (b) the majority of current satellite and ground observations lack the capability to monitor the life cycle of microphysical development in a cloud. In contrast, numerical modeling is an excellent tool for studying the aerosol–cloud interaction because it allows for the investigation of experiments in which the synoptic conditions can be kept the same while the smoke concentration is varied. But such model experiments need to be calibrated with *in situ* observations for deep convective clouds. With these caveats in mind, this paper should be viewed as a starting point to systematically describe the major processes likely to cause the smoke–cloud interaction over the south central US. More continuous observations with innovative modeling approaches and statistical analysis are needed to quantitatively understand each process proposed in this conceptual model, in particular the relative roles played by the smoke microphysical effects and meteorological factors.

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