Enhancement of Santa Ana Winds due to Wildfire Smoke

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1. Introduction

The Santa Ana winds are strong warm and dry down-slope airflows blowing from the Great Basin to the Pacific coast in late fall and winter (Sommers, 1978; Raphael, 2003; Conil and Hall, 2006). They are one of the dominant features of climate in southern California during this period. Santa Ana winds are driven by the air pressure gradient between the two regions located in the southern edge of an anti-cyclonic system over the western U.S. Both large mountains (Klemp and Lilly, 1975; Smith, 1985; Durran, 1990) and local topography features such as gaps (Gabersˇek and Durran, 2004) play important roles in their formation and variability. A summary of past studies and a recent analysis of the local and synoptic mechanisms for Santa Ana winds were provided by Hughes and Hall (2010).

Santa Ana winds have severe ecological and environmental consequences to southern California, including wildfires and heavy smoke plume. Santa Ana winds have long been linked to large wildfire occurrence (Minnich, 1983; Keeley et al., 1999; Moritz et al., 2010). Westerling et al. (2004) reported that wildfires periodically burned large areas of chaparral and adjacent woodlands in fall and winter in southern California and these fires often occurred in conjunction with Santa Ana weather events. Combustion emissions and strong Santa Ana winds were found to have pronounced effects on patterns and levels of ambient ozone in southern California during the extensive wildland fires of October 2007 (Bytnerowicz et al., 2010). The 8-h daytime average ozone concentration exceeded the federal standard.

Smoke particles from wildfires are one of the sources of atmospheric aerosols, which can generate disturbances in the atmospheric thermodynamics, circulation, and clouds and precipitation through their radiative forcing (Charlson et al., 1992; Hansen et al., 1997; Ackerman et al., 2000; Menon et al., 2002; Koren et al., 2004; Liu, 2005a and b). Liu (2005b) investigated the role of smoke particles in atmospheric circulation anomalies by examining the Yellowstone wildfires and the severe 1988 northern U.S. drought. The modeling results indicated that absorption of solar radiation by smoke particles weakens the North America trough in the middle latitudes. Rainfall in the Midwest is therefore reduced, suggesting that the Yellowstone wildfires might feedback the atmosphere by enhancing the drought condition. It can be assumed based on these studies that smoke plume from wildfires related to Santa Ana winds could modify the winds in the smoke area. This study is to provide evidence for this assumption through dynamical and modeling analyses.

2. Methods

An atmospheric dynamical model with smoke aerosol radiative forcing was constructed to obtain analytical evidence for atmospheric response to large-scale smoke aerosol radiative forcing and the associated physical processes. The model consists of a set of zonally symmetric equations for hydrostatic, nondivergent, and zonally geostrophic perturbation motions. The equation set is the same as the one used by Charney (1975) for the bio-geophysical self-feedback mechanism except the inclusion of vertical eddy heat transfer and aerosol radiative forcing. The radiative effects of smoke aerosols were taken into account in two ways, the absorption of solar radiation by aerosols, which directly heats the atmosphere, and the change in the surface radiative balance as a low boundary condition of the equations. The optical depth was specified based on in-situ measurement of a California fire (Hlavka et al., 2005). The single scattering albedo was specified based on and the Smoke, Clouds and Radiation-Brazil (SCAR-B) experiments (Kauffman et al., 1998).

The National Center for Atmospheric Research (NCAR) regional climate model (RegCM, Dickinson et al., 1989; Giorgi and Bates, 1989) was used to simulate the impacts of wildfire smoke on radiation and atmospheric circulation in the Pacific coastal area. The atmospheric and soil condition during January 1988 was simulated. The simulation domain is centered at 40°N and 99°W and contains 97 by 61 grid points with a horizontal resolution of 60 km. There are 14 vertical layers with the top model atmosphere at 80 hPa. The initial and horizontal lateral boundary conditions for the RegCM simulations of wind, temperature, water vapor, and surface pressure were interpolated from the analysis of the European Center for Medium-Range Weather Forecast (ECMWF), which has a resolution of 1.875° of latitude and longitude (roughly 200 by 175 km at mid-latitudes). The meteorological and SST data were obtained from archives of the NCAR Scientific Computing Division.

3. Results

The solutions of the dynamical model are illustrated in Figure 1. Temperature perturbations are symmetric to the center of the smoke area at 35°N. A cooling layer of about 1.5 km deep occurs in the lower atmosphere with the largest magnitude of about 0.5°C on the ground. Above it is a warming layer with the largest magnitude at the top. Temperature perturbations are determined by the relative importance of two mechanisms with opposite contributions. The eddy transfer of the surface sensible heat flux, which is reduced because of the negative radiative forcing of smoke, as indicated below from the numerical modeling, leads to temperature decrease, while aerosol absorption of solar radiation leads to temperature increase. The magnitude of the former impact is greater in the lower layer and, therefore, the temperature perturbations are negative. It is opposite in the upper layer.

Similar to temperature, perturbations in vertical motions are also symmetric to the center of the smoke area. Descending (negative) and ascending (positive values) motions correspond to cooling and warming, respectively. The magnitude of vertical motion perturbations in the lower layer is about 5×10^{-3} m/s, larger than that of the upper layer. This is different from temperature perturbations.

The zonal wind perturbations are asymmetric to the center of the smoke area. They are negative and positive in the southern and northern portions of the smoke area, respectively. This means easterly and westerly wind perturbations. The wind perturbation sign of each portion is the same throughout the vertical layers. The maximum magnitude is about 3 m/s. .

Similar to zonal wind, the meridional wind perturbations are asymmetric to the center of the smoke area. But they are positive and negative in the southern and northern portions of the smoke area, respectively. The perturbations occur mainly in the lower layer with a magnitude of 0.5 m/s. The combined zonal and meridinal wind perturbations suggest the trend of anti-cyclonic circulation motion in the low-layer atmospheric perturbations.

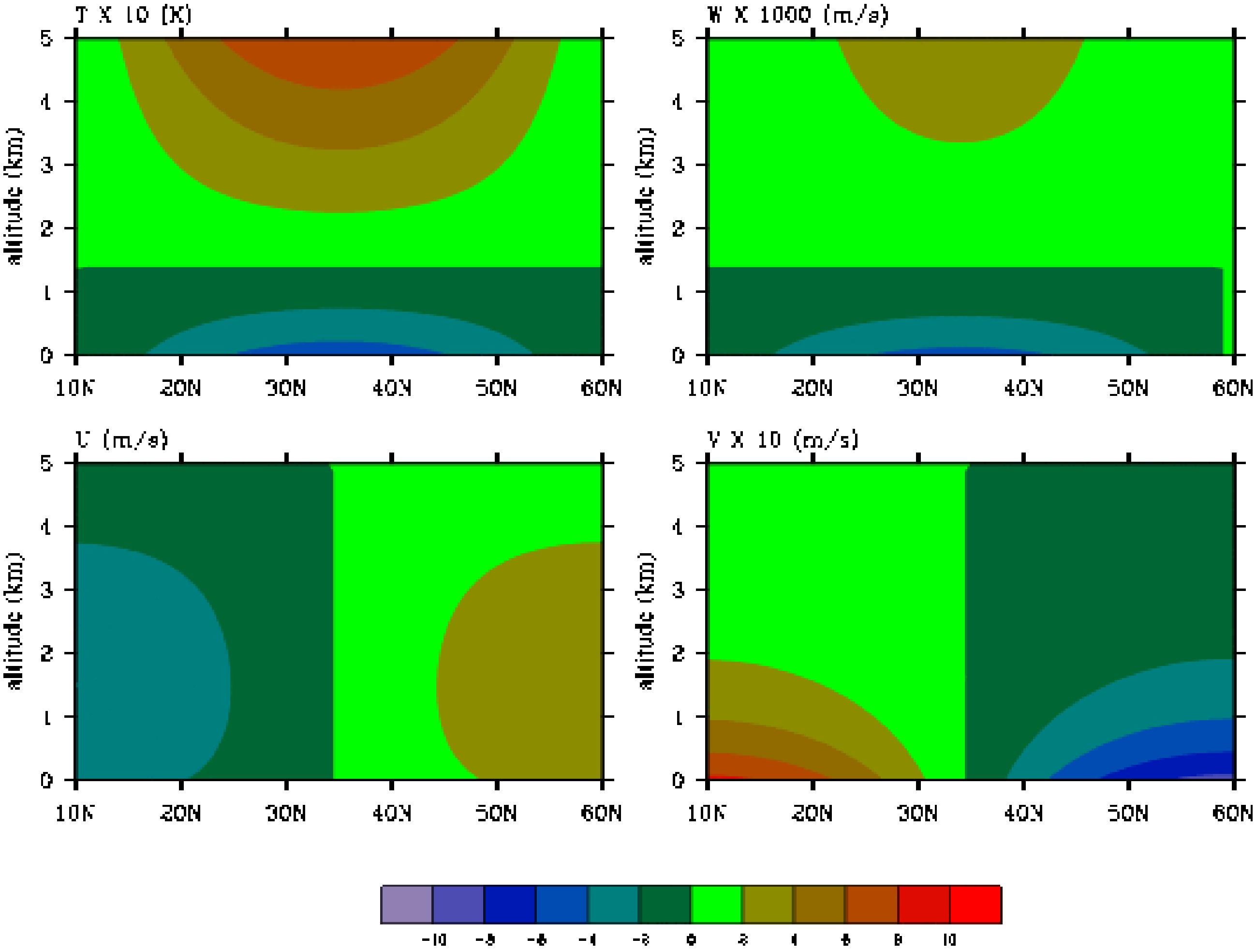

Figure 1 Illustrations of analytical solutions of the dynamical model for atmospheric perturbations. Temperature and vertical velocity are on top and zonal and meridional winds are in bottom. The horizontal axis is latitude and vertical axis is height.

The simulated and perturbed airflows from RegCM modeling is shown in Figure 2 for January 9, 1988. Perturbations for most of other days during the simulation month are similar, but the simulated wind field of this specific day has a typical anti-cyclonic circulation. Easterly winds can be found in southern California in the simulated airflows. But the speed is less than 10 m/s, lower than the typical magnitude of Santa Ana winds. Thus, this experiment is more about producing response of the circulation pattern related to Santa Ana winds. Easterly winds are found in the airflow perturbations. The largest magnitude of about 3 m/s appears in the offshore area.

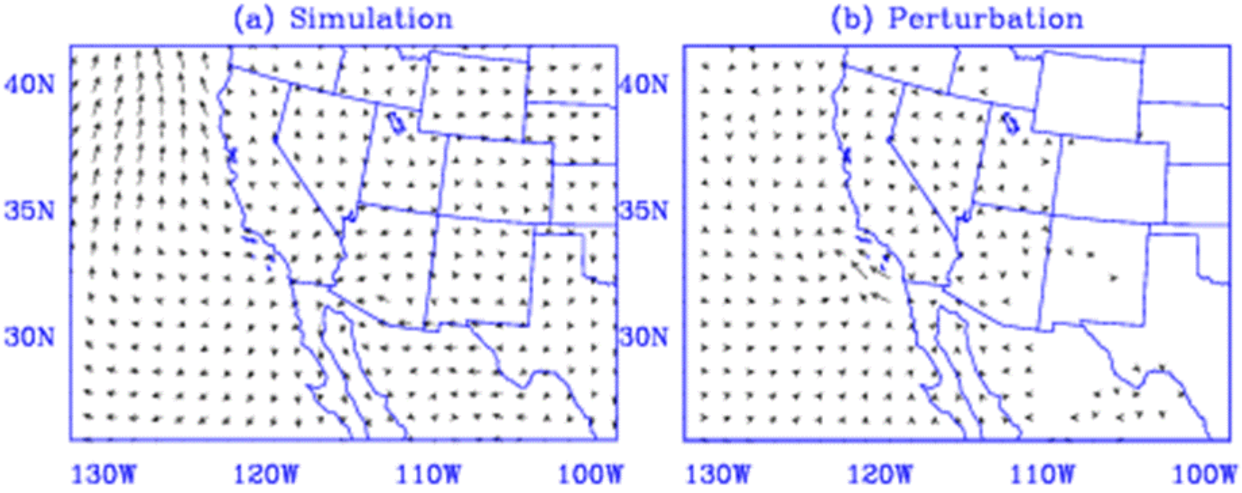

Figure 2 Simulation and perturbation in ground airflow on January 9, 1988 obtained from the NCAR regional climate model

Figure 3 shows the corresponding perturbations in other variables. Smoke particles lead to reduction in solar radiation on the ground in southern California and the adjacent ocean area. The largest reduction is about –20 Wm^{-2}, comparable to the magnitude of smoke radiative forcing from biomass burning in Amazon (Liu, 2005a). Sensible heat flux is therefore reduced in the land area. Air temperature is decreased by more than 1^{o}C. The vertical motion perturbations near the ground are positive, meaning subsidence.

The above results from both analytical analysis and numerical modeling indicate the trends in easterly winds in southern California and the nearby ocean area in the atmospheric response to smoke particles. This therefore provides evidence for the assumption that smoke from wildfires driven by Santa Ana winds can feedback these winds by increasing their magnitude. The modeling results showed most significant wind perturbations in offshore area, in spite of much more significant perturbations in temperature and vertical motions in the land area.

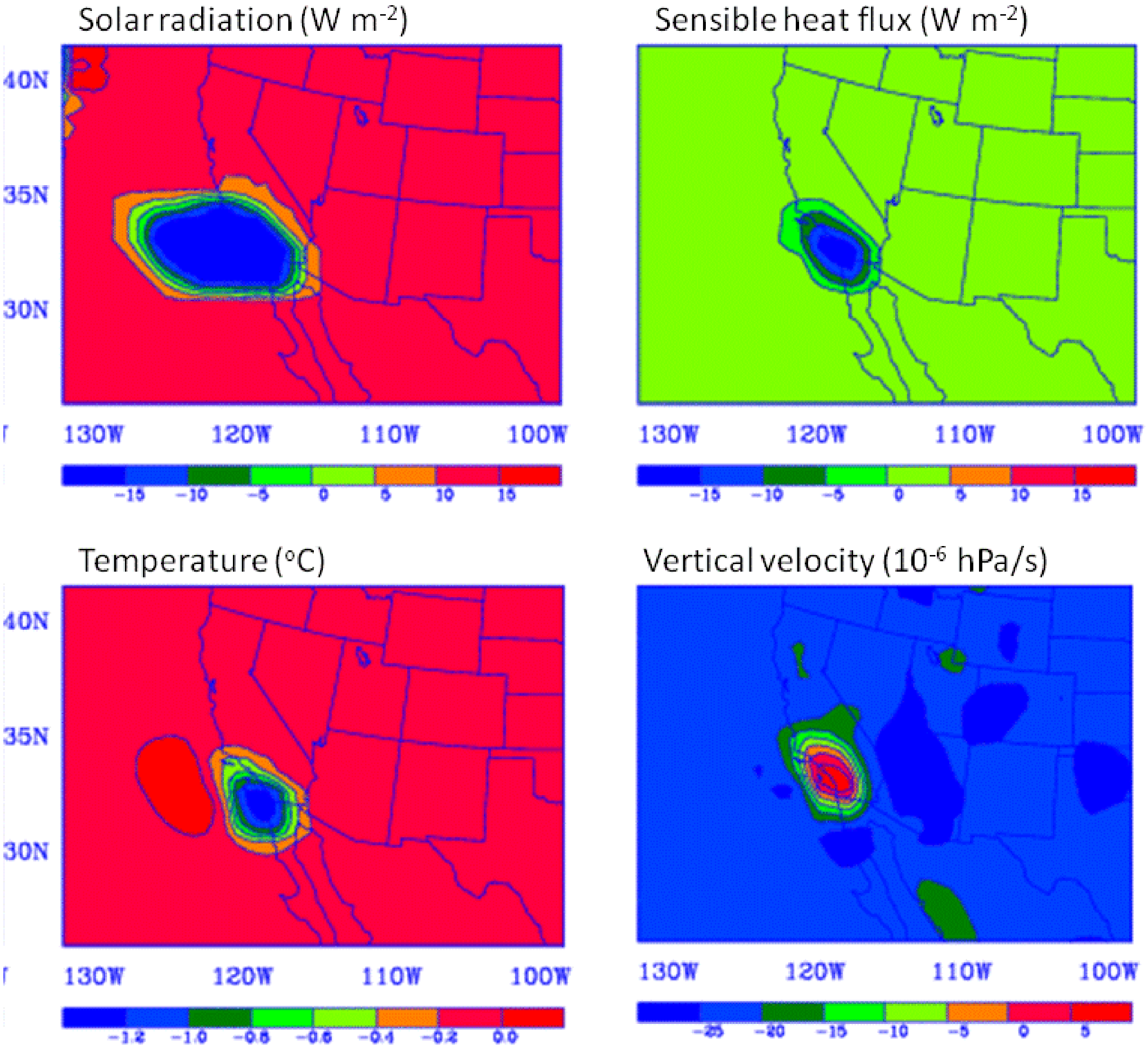

Figure 3 Perturbations in ground fluxes and variables on January 9, 1988 simulated with the NCAR regional climate model.

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