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An online coupled meteorological and air quality modeling study of the effect of complex terrain on the regional transport and transformation of air pollutants over the Western United States

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Abstract

One of the most prominent of characteristics of the western United States that affects its meteorology is the complexity of its mountainous terrain. The meteorological Mesoscale Model, version 5 with Chemistry (MM5-Chem), an online-coupled atmospheric chemistry model, was used to investigate the effect of this terrain on a high air pollution event in the free troposphere. The simulations were evaluated by comparisons with data from the North American Regional Reanalysis (NARR). Complex terrain was shown to have an important influence on the vertical transport of air pollutants on the regional scale; emissions from ground level were vertically mixed as high as 5 km above sea surface level for the wintertime conditions simulated. The simulations showed that the vertical transport of emissions from the Earth's surface could have a more significant effect on mid and upper level chemical concentrations than chemical production. The vertical transport was caused predominately by terrain forced flow over the mountains' ridge-line and the terrain forced flow was affected by the mountain peak height and the complexity of the terrain downwind.

Keywords: Meteorology; Air pollution; Vertical transport; Regional transport; Complex terrain; Online coupled models

1. Introduction

Wind flow is strongly influenced by mountainous terrain (Cohn, 2004; Papadopoulos et al., 1992; Astling, 1984) and the resulting wind flows are known to affect the transport of air pollutants (Lange, 1989; Berman et al., 1995; Liu and Carroll, 1996; Venkatesan et al., 1989; Cionco et al., 1999; Green, 1999; Spangler and Keating, 1990). Wind flows over mountainous terrain may transport air pollutants to higher altitudes (Whiteman, 2000; Lea, 1968; Hanna, 1991).

Investigations of the effects of mountainous terrain on the vertical transport have been published especially for European locations. For example, Carnuth and Trickl (2000) used LIDAR to observe that the structure of atmosphere above 4 km was highly inhomogeneous and that it affected the transport of air pollutants. Nyeki et al. (2002) also

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used LIDAR to measure the vertical mixing and proposed that daytime convective boundary layer processes were responsible.

There are several factors that may affect the vertical mixing of air pollutant emissions from the ground layer into the free troposphere. These include: (1) the effects of synoptic weather systems, such as low-pressure systems and fronts (Cairns and Corey, 2003; Chen et al., 1997; Colle and Mass, 1995); (2) atmospheric convection caused by radiative heating, such as produced by thunderstorms (Dickerson et al., 1987; Cooper et al., 1998; Darby et al., 2002); (3) boundary layer processes (Bader et al., 1987; Sturman et al., 2003; Angevine and Mitchell, 2001); (4) terrain forced flow over mountainous regions (Carnuth and Trickl, 2000; Nyeki et al., 2002; Dommen et al., 2003); (5) orographic injection of pollutants (Barros et al., 2000).

Dommen et al. (2003) proposed the existence of forced transport of air pollutants over the Alps but the detailed mechanisms were not given. The work presented here is based on the detailed mechanism for terrain forced vertical and horizontal transport shown in Fig. 1. The flow of air over complex terrain imparts a vertical component to the wind fields. This vertical component transports air pollutants from the surface upward into the middle and upper troposphere. When the pollutants reach a high altitude there is much less deposition, colder temperatures reduce many reaction rates and therefore pollutants may be transported over long distances by horizontal winds.

Horizontal winds transport air pollutants from sources to the mountains where vertical winds transport them upward. A key feature of this proposed mechanism is that the vertical winds are initiated by the momentum of air over the mountains and this is distinct from mountain or gravity waves. Gravity waves occur under stable atmospheric conditions and are limited to incident flow angles that follow mountain ridgelines. Although there are no prominent weather events necessarily associated with the momentum initiated wind flows these can be traced by the vertical distribution of the mixing ratios of trace gases including water vapor (H_2O), ozone (O_3), carbon monoxide (CO), nitrogen oxides (NO_x), volatile organic compounds (VOCs), including formaldehyde (HCHO) and aerosol particles.

Mountains that are high and large enough to perturb the synoptic wind field prevail over the Earth's surface include the Sierra-Nevada mountains in the north-western America, the Andes mountains in South-western America and the Himalayan mountains in the Tibet basin. Simulations of the western US during the wintertime were made with an online-coupled meteorological and atmospheric chemistry model in order to evaluate this proposed vertical transport mechanism. The modeling domain includes the highly complex terrain of the Sierra-Nevada Mountains and nearby Great Basin with four cross sections chosen to study the vertical distribution of the vertical wind fields, Fig. 2. The mixing ratios of HNO_3, O_3 and CO were used as air pollutant tracers. In Section 2, the

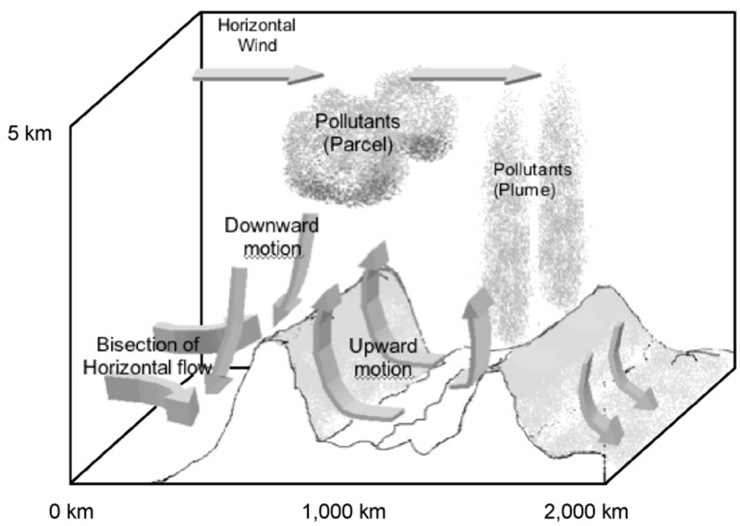

Fig. 1. Schematic diagram for the vertical transport by terrain.