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Tropospheric ozone and its regional transport over Cape Town

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HIGHLIGHTS

- We investigate the local variation and transport of O_3 pollution over Cape Town.
- The concentration of O_3 is higher at Cape Point than at two sites near the city.
- Emissions from the industrial Highveld contribute to O_3 pollution in Cape Town.
- Pollutants from the Highveld are transported to Cape Town via four major pathways.
- The pollutant transports mostly occur in March and September.

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ABSTRACT

As part of efforts to understand the sources of air pollution in Cape Town, this study investigates the local variation of tropospheric ozone (O_3) and identifies possible advection paths of O_3 pollution from a remote source to Cape Town. Measurements of O_3 and wind from three sites in the Cape Town area were analyzed to study the local variations of O_3. At each site, the diurnal variation of O_3 is found to be mainly driven by photochemical production while the seasonal variation of O_3 is mostly driven by wind conditions. The highest concentration of O_3 is observed at the remote site (Cape Point) while lowest O_3 concentration is observed at the sub-urban site (Goodwood), where there are chemical sinks of O_3 such as NO_x. Atmospheric pollution over southern Africa was simulated to study the regional transport of O_3. The simulations show that extreme O_3 levels in Cape Town can be caused by air pollution transported from the industrial Highveld of South Africa, in the lower troposphere. Such extreme O_3 pollution events over Cape Town are simulated to occur in January (14%), March (44%), April (28%) and September (14%). Lagrangian trajectories suggest four paths by which air parcels can be transported from the industrial Highveld to Cape Town: a north-easterly path which is the most frequent route, a tropical deviation route, a deviation along the south coastline and an oceanic deviation path which is the less frequent route. The major advection paths associated with poor air quality in Cape Town are the north-easterly route and the path along the south coastline of the country. Hence the study suggests that emissions in the industrial Highveld may contribute to O_3 concentration in the Cape Town area.

1. Introduction

Tropospheric ozone (O_3) is an air pollutant that can cause negative impacts on natural ecosystems (Paolleti, 2009), crop yields (Avnery et al., 2011), materials (Massey, 1999; Lee et al., 1996) and human health (WHO, 2006; Lippman, 1989). However, unlike many other air pollutants, O_3 is not emitted into the atmosphere but rather, produced after a series of chemical reactions that involve other pollutants such as nitrogen oxides ($NO_x = NO + NO_2$), volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of sunlight (Atkinson, 2000; Liu et al., 1980; Crutzen, 1974). These reactive chemicals are associated with vehicular emissions, making O_3 a common pollutant in urban environments and a major component of urban smog (Sillman, 2003).

Previous studies have associated O_3 and its precursors with an unusual smog pollution (locally known as brown haze) visible between April and September in the Cape Town area (Piketh et al., 2004; Wicking-Baird et al., 1997), but only few studies have investigated the link between the polluted haze and air pollutants from sources outside of the city. Most studies on air quality in Cape Town have focused on the impacts of local drivers on air pollution. Jury et al. (1990) showed that the steep topography in Cape Town and stable atmospheric conditions imposed by a high pressure system during April to September enhance the accumulation of air

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pollutants and the resulting brown haze. Local emissions were identified as the main cause of the brown haze. Wicking-Baird et al. (1997) attributed about 65% of the visible degradation from the brown haze to local vehicular emissions and about 22% of it to local industry. Walton (2005) identified the Caltex oil refinery and Consol Glass as major point sources of emissions, and the Central Business District and townships (i.e. Khayelitsha and Mitchell's Plain) as the major source areas. Kalognomou (2009) showed that joint occurrences of high anthropogenic emissions and low-level temperature inversions, which are frequent in Cape Town, generally lead to high concentrations of pollutants over the city. Hence, air pollution episodes observed within Cape Town are usually attributed to local conditions (Scorgie and Raylene, 2004; City of Cape Town, 2013). However, recent studies by Jenner and Abiodun (2013) and Abiodun et al. (2013) have used atmospheric chemistry-transport simulations to suggest a link between extreme air pollution over Cape Town and the transport of air pollutants from the industrial Highveld, which is the main source area of anthropogenic emissions in South Africa (Collett et al., 2010; Wenig et al., 2003). Nonetheless, Jenner and Abiodun (2013) only investigated the transports of sulfur, while Abiodun et al. (2013) only studied the transport of nitrogen compounds without considering their influence on local O_3 pollution. In addition, none of these studies indicated the paths by which air pollutants are transported from the industrial Highveld to Cape Town.

The aim of the present work is to investigate the regional transport of O_3 (especially from the industrial Highveld) to Cape Town and its influence on the local air quality. The paper studies the characteristics of observed O_3 in the Cape Town area and uses atmospheric chemistry-transport simulations to study the regional transport of O_3 over South Africa. Section 2 gives a description of the data and methods used in this study. Section 3 presents the results and their discussion while Section 4 gives the conclusions of the study.

2. Data and methods

2.1. Observed air quality and wind data

This study analyzed air quality and wind data over the Cape Town area. The local municipality operates a network of 14 air quality stations (Fig. 1) to monitor principal air pollutants that contribute to the brown haze and affect human health (City of Cape Town, 2005). However, only few of those stations monitor O_3 on a continuous basis. The study uses data of ambient O_3 concentration from two stations (Molteno and Goodwood) regulated by the municipality of Cape Town, and additional data obtained from the Global Atmosphere Watch station at Cape Point regulated by the South African Weather Service. Unfortunately, none of the three stations monitors VOC species, while measurements of other O_3 precursors (i.e. NO_x and CO) were only available from the Goodwood station. Therefore, NO_x and CO data from Goodwood are used to study the role of anthropogenic emissions on the local variation of O_3 concentration.

The Goodwood station is located in a suburb and semi-industrial environment. Ambient O_3 concentrations measured at this station might account for pollution from domestic, industrial and traffic emissions from nearby busy roads and highways. The Molteno station is partially enclosed by mountains in the city bowl, not far from the Central Business District; hence, the station at Molteno might record accumulated pollution from intense traffic emissions. The Cape Point station is located in the south of the Cape Peninsula, in a natural reserve and marine environment away from substantial human activity. Although the site attracts local and international tourists, anthropogenic emission rates at Cape Point are likely to be much lower than those at Molteno and Goodwood. The Cape Point station is the oldest O_3 monitoring site within the region, and several studies have been conducted to assess the variation of O_3 in such a clean environment (Oltmans, 1981; Scheel et al., 1990; Oltmans and Levy, 1994). In this study, air quality and wind data for the period 2001–2004 at each of the three sites were analyzed to study the spatial and temporal variations of O_3 concentration in the Cape Town area.

Fig. 1. The location of air quality monitoring stations within the Cape Town area. Different colors are used to show the different suburbs of the Cape Town Metropolitan. Red squares on the map locate sites from which O_3 and wind measurements were obtained for this study. Source: www.capetown.co.za/airqual with some modifications. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Model description and set-up

The study applies the International Centre for Theoretical Physics (ICTP) regional atmospheric-chemistry model (hereinafter, RegCM) to simulate the regional climate and pollution transport over South Africa for 4 years (2001–2004). The RegCM is a hydrostatic and terrain-following coordinate model (Pal et al., 2007; Giorgi and Anyah, 2012) that has been successfully tested over South Africa (Sylla et al., 2009). The climate module of RegCM uses different parameterization schemes to represent atmospheric processes. In this study, the simulations used the CCM3 scheme (Kiehl et al., 1996) for radiation calculations, the mass-flux cumulus scheme of Grell (2005) with Fritsch and Chappell (1980) closure for convection, and the Holtslag and Boville (1993) parameterization for the boundary layer. For the surface layer land–atmosphere