Atmospheric Environment 57 (2012) 55–62

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Intraseasonal variability of surface ozone in Santiago, Chile: Modulation by phase of the Madden–Julian Oscillation (MJO)

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HIGHLIGHTS

► Surface ozone concentration in Santiago, Chile varies intraseasonally by phase of the Madden–Julian Oscillation.
► Phase of the Madden–Julian Oscillation also affects the diurnal cycle of ozone concentration in Santiago.
► Days with low (high) ozone corresponded to days with anomalously high (low) cloud cover.

ARTICLE INFO

Article history:
Received 18 January 2012
Received in revised form
16 April 2012
Accepted 18 April 2012

Keywords:
Surface ozone
Intraseasonal
Santiago
Madden–Julian Oscillation

ABSTRACT

In Santiago, Chile, summertime surface ozone (O_3) concentrations regularly exceed local and international health thresholds due to high antecedent pollutants, frequent clear skies, and warm surface air temperatures. However, few (if any) studies exist that have examined the intraseasonal variability of surface O_3 or its modulation by phase of the Madden–Julian Oscillation (MJO). Therefore, the main objectives of this study were to investigate the intraseasonal variability of surface O_3 and the meteorological parameters known to affect O_3 concentrations during summer months in Santiago, and connect any observed variability to phase of the MJO. Ozone concentrations at seven stations in the Chilean National Air Quality Information System (SINCA), along with upper-air, surface, and reanalysis data, were used to create composites for each phase of the MJO. Results confirm that for the Santiago metropolitan region, both maximum daily O_3 concentrations, as well as the diurnal cycle of O_3, depend on MJO Phase. Ozone concentrations were highest during Phases 5 and 6 and lowest during Phases 1 and 2. Cloud cover anomalies best agreed with this pattern of O_3 variability, with low (high) cloud cover anomalies occurring during days with high (low) ozone. Surface temperature and strength and height of the lower-troposphere temperature inversion had similar, but less pronounced, connections to O_3, with slightly warmer surface temperatures and stronger inversions closer to the ground occurring on days with higher O_3. Wind velocity was found to vary little between days with low and high ozone.

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1. Introduction

Ozone (O_3) is one of the most important trace gasses in the troposphere. As a secondary pollutant, its concentrations are controlled by complex processes involving anthropogenic emissions, chemical reactions between primary pollutants and ultraviolet solar radiation, and meteorology. It strongly affects human health, vegetation, and ecosystems in industrial, suburban, and rural areas worldwide and is expected to increase significantly during the 21st century. In Santiago, Chile, maximum hourly O_3 concentrations regularly reach between 100 and 150 parts per billion by volume (ppbv) in summer, occasionally peaking above 320 ppbv in the eastern (downwind) part of the city (Gramsch et al., 2006), well in excess of Chilean (0.075 ppmv hourly maximum) and U.S. (0.08 ppmv 8-h concentration) health thresholds. Ozone exposure at these levels produces harmful structural changes in human cells, specifically lesions in the centriacinar area of the lungs at the ends of the terminal bronchioles (Lippmann, 1989; Burnett et al., 1997). These effects cause respiratory problems, especially in those with chronic lung diseases, and can seriously damage the lining of the lung when inhaled over a long-period of time (Sanhueza et al., 2003). Even short-term (daily and weekly) exposure to ambient tropospheric O_3 has been associated with adverse effects on public health and increased mortality (Bell et al., 2004). For all these reasons, studies that determine the behavior of O_3 across a range of temporal and spatial scales are important.

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1352-2310/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.atmosenv.2012.04.040

However, intraseasonal variability of ground-level O_3 has yet to be comprehensively examined. Therefore, the main objectives of this study were to (1) investigate the intraseasonal variability of surface O_3 and related meteorological parameters during summer months in Santiago, Chile, and (2) connect any observed variability to phase of the leading mode of atmospheric intraseasonal variability, the Madden–Julian Oscillation (MJO; Madden and Julian, 1971).

The MJO manifests itself as a large-scale convective anomaly over the maritime continent. Its most basic feature consists of an eastward moving region of deep convective clouds and heavy precipitation bounded on both the west and east by regions of suppressed convection and minimal precipitation. Zonal circulations connect the two regions, with lower-troposphere (near 850-hPa) anomalous westerly (easterly) winds to the west (east) of the deep convection; in the upper troposphere (near 200-hPa), the circulation anomalies reverse (Madden and Julian, 1972). The convective anomalies have been observed to remain between the Indian Ocean and 180°, while the circulation anomalies have been observed to circumnavigate the tropics.

The oscillation has significant interaction with the extratropics, including teleconnections to the Western Hemisphere. Modeling studies of Berbery et al. (1992) and Mechoso et al. (1991), as well as the theoretical findings of Hoskins and Karoly (1981) and Bladé and Hartmann (1995), confirmed that the MJO modulates Rossby wave activity. Sardeshmukh and Hoskins (1988) found a pathway to the extratropics in both hemispheres, noting that a divergence field in easterly flow asymmetric about the Equator (a consequence of deep convection) led to an extremely effective Rossby wave source in the subtropical westerlies. Barrett et al. 2012 used this pathway to explain modulation of winter precipitation in Chile by phase of the MJO. A similar technique was used for this study to explain the link between intraseasonal ground-level O_3 variability in Santiago and the MJO. Detailed reviews of the MJO are presented in Madden and Julian (1994), Lau and Waliser (2005), and Zhang (2005).

During austral summer, central Chile frequently experiences clear skies and high temperatures due to the presence of the subtropical anticyclone centered in the southeast Pacific Ocean (Schmitz, 2005; Rutllant and Garreaud 2004; Garreaud and Muñoz, 2005). Additionally, because of a persistent low-level inversion and its orographic location at the rim of the highest peaks of the Andes Mountains, Santiago is a poorly ventilated location. Furthermore, low morning mixing heights, a result of the presence of a coastal trough immediately west of central Chile, often result in above normal afternoon surface temperatures, reaching between 30° and 35 °C in Santiago (Rappenglück et al., 2000). Surface O_3 production under these conditions is favored, as the photochemical oxidation of carbon monoxide (CO) and volatile organic compounds (VOC) occurs in the presence of high concentrations of nitrogen oxides (NO and NO_2; Rappenglück et al., 2000, 2005; Elshorbany et al., 2009a, b).

The most important factor determining surface O_3 concentrations in Santiago is the amount of insolation received, as evidenced by the pronounced daily and seasonal O_3 cycles (e.g., Gramsch et al., 2006; Schmitz, 2005). On the daily cycle, surface O_3 concentrations reach a minimum of 0–5 ppbv at daybreak (0600 local time, hereafter LT) and quickly build during the day, peaking around 1400 LT and then declining again in the evening hours (Elshorbany et al., 2009a; Villena et al., 2011). On the seasonal cycle, O_3 concentrations reach a winter minimum (mean daily values less than 20 ppbv) in June and then build to a summer maximum (mean daily greater than 70 ppbv) between December and March (Gramsch et al., 2006; Elshorbany et al., 2010). Besides the relationship to insolation, other meteorological factors have also been suggested to affect O_3 concentrations in Santiago. For example, Rubio et al. (2004) found a positive linear association between maximum O_3 levels and maximum local temperature at Las Condes, with ozone exceeding 80 ppbv on 87% of days with temperature above 29 °C but exceeding 80 ppbv on only 16% of days where the temperature did not exceed 29 °C. They speculated that the relationship would be similar across other sites in the city. Rubio et al. (2004) also found that the VOC/NO_x ratio (and thus surface O_3 concentrations) increased during days with high surface temperature because of an increase in hydrocarbon evaporation and biogenic emissions. Additionally, the diurnal O_3 shoulder (slower rate of decline in afternoon O_3) has been explained by the favorable predominant afternoon wind direction from the southwest carrying biogenic emissions to the city center (Gramsch et al., 2006). In this study, we will examine these meteorological parameters as they relate to surface O_3 variability on the intraseasonal time scale. The remainder of the paper is organized as follows: data and methodology are described in Section 2; intraseasonal variability of O_3 and meteorological factors affecting the observed O_3 variability are presented in Section 3; and a discussion and conclusions are presented in Section 4.

2. Data and methods

Santiago, Chile, a city with a population of around 6 million, lies in a slightly sloped valley, with a mean elevation of 500 m that rises gradually from its low point in the west to its high point in the east. Further to the east of Santiago rises the Andes Cordillera, with peaks reaching 5500 m. A lower coastal range is located to the west of Santiago with elevations up to 2000 m. Hourly O_3 concentration data in ppbv were collected at three observing stations located in the central and eastern side of Santiago (Las Condes, Parque O'Higgins, and Independencia) during the summer months of November–February from Jan 1988–Dec 2010. Four additional stations in Santiago with data records from Jan 1997–Dec 2010 were also examined. Besides O_3, all seven of the stations also measured hourly surface wind velocity from Jan 2004–Dec 2011. All data are available publicly from the National Air Quality Information System (SINCA, http://sinca.conama.cl), operated by the Ministry of the Environment. Table 1 summarizes the ozone concentration measurements and Fig. 1 shows the topography of Santiago and the locations of the observing stations; see Gramsch et al. (2006) for a detailed description of each station, including a description of surrounding buildings, roads, and parks.

Phase of the MJO was determined using the Real-time Multivariate MJO Index (RMM; Wheeler and Hendon, 2004; hereafter WH04). The RMM is based on a pair of principal component time series derived from empirical orthogonal functions of near-equatorially averaged outgoing longwave radiation, 200-hPa zonal wind, and 850-hPa zonal wind. The projection of daily data onto the empirical orthogonal functions acts as an effective time filter and makes the index useful in a real-time setting (WH04). The RMM is divided into eight phases, each corresponding to a broad location of the MJO enhanced convective signal. Active MJO for this study was defined as one where the root sum of the two squared principal components, RMM1 and RMM2, was greater than one. It

Table 1
Ozone concentration descriptive statistics at each measuring station. Number of observations (*n*), mean, median, standard deviation, max, and min (in ppbv) of maximum daily concentrations.

Site	*n*	Mean	Median	Standard deviation	Max	Min
Las Condes	3449	70.9	69.5	44.8	475	0
Independencia	3522	48.7	46.1	32.0	364	0.048
Parque O'Higgins	3383	47.0	46.1	26.0	316	0.351