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THE STUDY OF OZONE VARIATIONS IN THE LAS VEGAS METROPOLITAN AREA USING REMOTE SENSING INFORMATION AND GROUND OBSERVATIONS

George Xian[a*,] and Mike Crane[b]
[a]SAIC/[b]U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS),
Sioux Falls, SD 57198

Abstract

Urban development in the Las Vegas Valley, Nevada, has grown rapidly in the past fifty years. Associated with this growth has been a change in landscape from natural cover types to developed urban land mixed with planned vegetation canopy throughout in the metropolitan area. Air quality in the Las Vegas Valley has been affected by increases in anthropogenic emissions and concentrations of carbon monoxide, ozone, and criteria pollutants of particular matter. Ozone concentration in the region is generally influenced by synoptic and mesoscale meteorological conditions, as well as regional transport of pollutants from the western side of Las Vegas. Local influences from ground-level nitrogen oxide emissions and vegetation canopy coverage also affect ozone concentration. Multi-year observational data collected by a network of local air monitoring stations in Clark County, Nevada, indicate that ozone maximums develop in May and June, while minimums exist primarily from November to February. Ozone concentrations are high on the west and northwest sides of the valley. A nighttime ozone reduction in the urban area characterizes the heterogeneous features of spatial distribution for average ozone levels in the Las Vegas urban area. The urban vegetation canopy has a locally positive effect by reducing ozone in urban areas. Decreased ozone levels associated with increased urban development density suggests that the highest ozone concentrations are associated with medium- to low-density urban development in Las Vegas.

Key words: urbanization, ozone, remote sensing, Las Vegas

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[*] Corresponding author address: George Xian, SAIC at USGS EROS, Sioux Falls, SD 57198; e-mail:xian@usgs.gov

1. INTRODUCTION

Ozone (O_3) is one of the strongest atmospheric oxidants and is designated as a criteria pollutant in the atmospheric surface layer. Ambient ozone concentration found in the lower troposphere is an environmental concern because it can damage and destroy both plants and animals (Cvitaš et al., 2005). Additional health effects include eye irritation and breathing difficulty for asthmatics (NRC, 1991; EPA, 1994). The primary National Ambient Air Quality Standard (NAAQS) for ozone includes a one-hour standard of 0.12 parts per million by volume (ppm) and an eight-hour standard of 0.08 ppm (EPA, 1993). High ozone concentration exposure has also caused crop and forest loss in the United States (EPA, 1996; Moy et al., 1994).

The ozone production cycle is driven by solar radiation or photons of sunlight (*hv*). However, combustion, which leads to the formation of nitrogen oxides ($NO_x = NO + NO_2$) and volatile organic compounds (VOC), also increases the concentration of ozone at the ground level (Boubel et al., 1994). Most anthropogenic emissions of VOCs and nitrogen oxides leading to distinct chemical features in the atmosphere are associated with urban growth and industrial activities. Heavy anthropogenic pollution can increase ozone concentration to a harmful level. Aneja et al. (1999) suggested that large amounts of mobile emissions of VOCs and NO_x in conjunction with strong solar radiation and high daytime temperature during late spring and summer accounted for a large number of high ozone days for three metropolitan areas in North Carolina. Zhang et al. (2004) concluded that industrial emissions of VOCs and NO_x led to an extreme diurnal variation of surface ozone in Houston, Texas. The ambient ozone levels were elevated significantly exceeding NAAQS during the daytime. A surface NO_x maximum occurred during the night and caused an extensive urban-scale hole of surface ozone.

Air quality is generally affected by synoptic and mesoscale meteorological and climate conditions. Urban land use and land cover (LULC) conditions can sometimes substantially affect the surrounding mesoscale meteorology (Pielke et al., 1999; Marshall et al., 2004) and local and regional climate change (Kalnay and Cai, 2003). These changes will have direct or indirect impact on meteorological fields and air quality. Nowak et al. (2000) showed that increased tree cover in urban areas reduced local ozone concentration by a few parts per billion by volume (ppbv) during the daytime; however, nighttime ozone concentration increased due to reduced wind speed and loss of NO_x scavenging of ozone from increased deposition of NO_x. Civerolo et al. (2000) suggested that additional vegetation cover in urban areas could affect pollutant concentrations and dispersal, energy demand, and biogenic emissions in surrounding areas. However, the spatial distribution of ozone concentration varied significantly with surface wind direction. Ozone could substantially increase in downwind areas.

In this study, spatial and temporal urban development information derived from satellite remote sensing data in 2002 was used to explore the impact of urban land use and land cover on ozone concentration and distribution. Spatial distributions of different urban development densities were investigated for possible anthropogenic emission sources. Urban development density was determined using satellite remote sensing data in conjunction with high-resolution orthoimagery. Multi-temporal and spatial ozone concentration and climate observation data from the National Air Monitoring Stations/State and Local Air Monitoring Stations (NAMS/SLAMS) network of the Clark County Department of Air Quality Management (www.accessclarkcounty.com/air_quality/) were analyzed to identify characteristics of ozone concentration and distribution in the area. The network routinely measures the ambient concentration of criteria pollutants including O_3 and NO_x, as well as surface temperature and wind conditions. The study also used urban area vegetation canopy information using a normalized difference vegetation index (NDVI) calculated from Landsat satellite imagery. The cumulative and interactive effects of urban LULC conditions, urban vegetation canopy covers, climate conditions, and their impacts on ozone and other pollutants in the valley were also investigated.

2. BACKGROUND

The Las Vegas Valley, located in the southern part of Nevada, is characterized by an arid climate and desert landscape. Moisture air masses rarely reach the valley, and dry air masses predominate over the Valley and produce clear and partly cloudy skies for most of the year. Summer is generally hot, whereas winter is generally mild. Surface meteorology in the valley is characterized by prevailing southwesterly winds. Lower wind speeds are prevalent during the winter months,

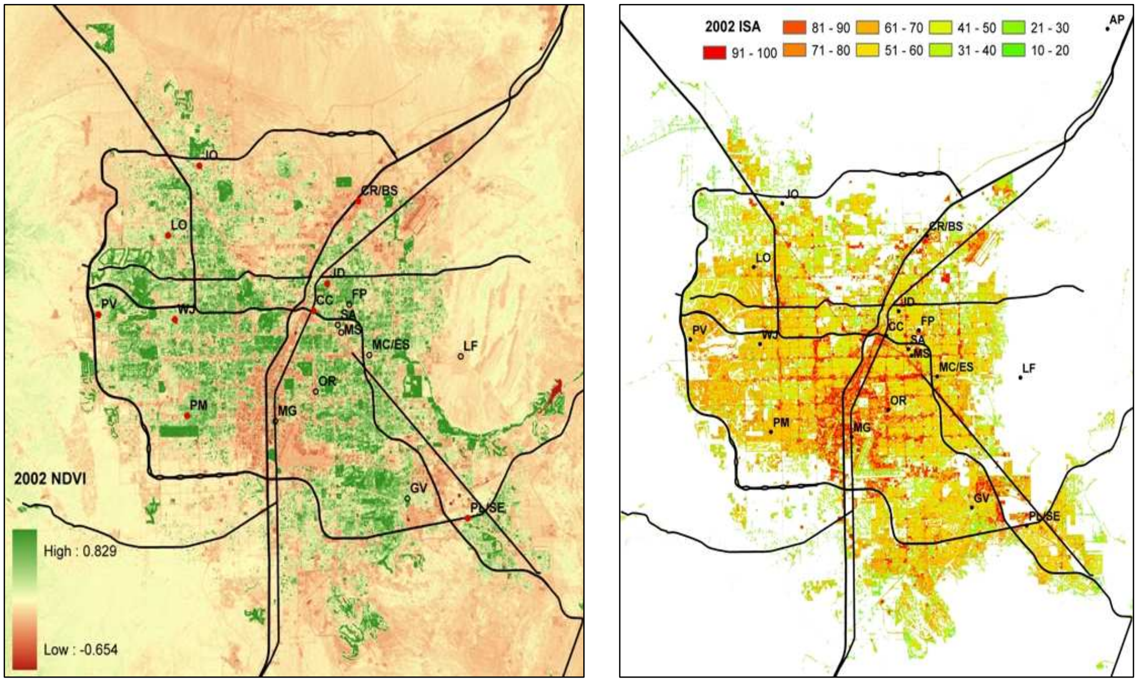

Figure 1. 2002 NDVI (left) and urban area percent impervious surface (right) in the Las Vegas Valley. The Clark County air quality management monitoring sites are also listed in the figures.

while higher wind speeds are frequently seen throughout much of the spring. A strong pattern of local winds—upslope in a westerly gradient during the day and a reversed direction at night—generated by local topography and temperature also characterize the valley. The formation and dispersion of ozone follows the natural daily and seasonal cycle. During the daytime, the photochemical dissociation of NO_2 and formation of ozone can be described as

$$NO_2 + h\nu \rightarrow NO + O \qquad (1)$$
$$O + O_2 \rightarrow O_3 \qquad (2)$$
$$NO + O_3 \rightarrow NO_2 + O_2 \qquad (3)$$

The emission of NO from automobile engines in the urban area and the subsequent chemical reaction described in Equation 3 are responsible for partial destruction of surface ozone.

3. DATA AND METHODS

To better understand ozone distribution in the Las Vegas urban area, both surface ozone observational data and urban LULC information were analyzed. Surface observational data, including O_3, NO_x, and temperature from ten Clark County air quality management monitoring sites were selected. The ten sites included City Center (CC), J.D. Smith (JD), Lone Mountain (LO), Palo Verde (PV), Paul Meyer Park (PM), S.E. Valley (PL), Walter Johnson (WJ), Winterwood (WW), Joe Neal (JO), and Craig Road (BS). All data were recorded 24 hours a day in one-hour intervals. The earliest records from CC and PL sites started in 1996. Most records from other sites started after 1999.

Urban development in the Las Vegas region was determined using the percent anthropogenic impervious surface. Impervious surface area (ISA) is usually defined as roofs, roads, parking lots, driveways, and sidewalks. ISA is considered a key indicator of environmental quality and can be used to address complex urban environmental issues. A strong relationship exists between percent ISA and urban use (Xian and Crane, 2005). ISA data obtained from historical Landsat imagery have proven to be a useful source for monitoring urban growth. Xian and Crane (2005) used three ISA threshold categories, 10–40% for low-density, 41–60% for medium-density, and 61–100% for high-density developments, to investigate urban growth in the Tampa Bay, Florida, watershed. Percent ISA was demonstrated to be useful for quantitatively describing urban LCLU categories and densities, as well as spatial changes in the watershed. Urban LCLU conditions for the Las Vegas Valley in 2002 were determined using remotely sensed data from Landsat Enhanced Thematic Mapper Plus (ETM+) instruments as the primary sources for estimating multi-temporal sub-pixel ISA distribution. NDVI was also calculated using Landsat reflectance bands for vegetation canopy coverage estimation.

4. RESULTS AND DISCUSSION

4.1 Spatial and Temporal Ozone Level Variations

The spatial distribution of vegetation canopy and urban land use conditions estimated from Landsat-derived NDVI and ISA in 2002 for the Las Vegas Valley are presented in Figure1. Also displayed in the figures are the spatial locations of Clark County air quality management monitoring sites. Despite the arid climate that characterizes the environs of the Las Vegas Valley, the green areas visible on the NDVI image indicate a relatively dense vegetation canopy existing throughout much of the urban area. Strong greenness intensities are associated with most residential areas. A better delineator of urban extent is the percent ISA. For the Las Vegas valley, the ten percent ISA value provides an excellent differentiation between urban and rural landscapes. In 2002, the areal extent of urban land encompassed about 620 km^2. Urban land use expanded in almost all directions across the valley, with the higher percent ISA categories expanding from the downtown and Las Vegas strip to the southeast and northwest portions of the city.

The seasonal O_3 variation for the Las Vegas Valley was obtained from multi-year measurements from ten selected sites. To evaluate O_3 spatial distribution in the valley, the monitoring sites were grouped by geographic region : (1) southern side, including PL, PM, and WW sites; (2) northern side, including BS, CC, JD, LO, JO, PV, and WJ sites; (3) western side, including JO, LO, PM, PV, and WJ sites; and (4) eastern side, including BS, CC, JD, PL, and WW sites. Figure 2 displays monthly average O_3 distributions and their daytime and nighttime changes in the valley. The total O_3 concentrations reach their peaks in May and June, and concentrations are consistently higher on the west side of the valley as opposed to the east side (Fig. 2a). A small seasonal variation is evident in the north/south distribution of ozone, with higher concentrations occurring in the northern part of the valley during winter, and the southern region experiencing higher O_3 during summer. These relationships also hold true for daytime and nighttime ozone distributions (Figs. 2b and 2c). Ozone concentrations in the northern part of the valley are slightly larger than those in the southern side, except in the summer when ozone amounts in the south overpass those in the north. The

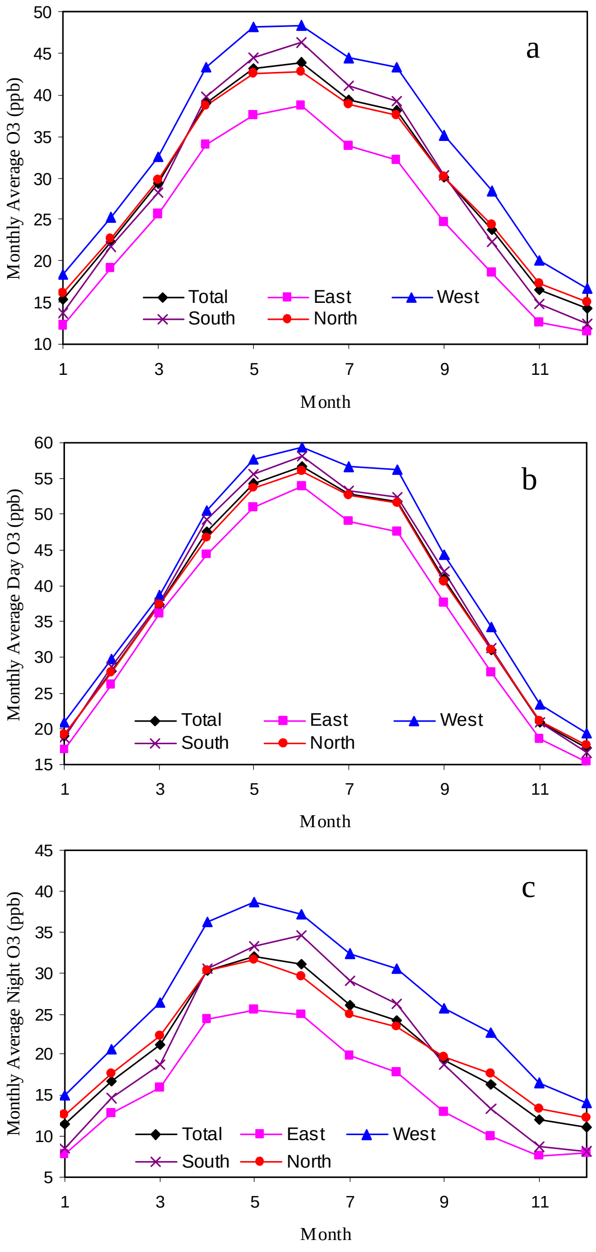

Figure 2. Multi-year monthly average O_3 distribution in the Las Vegas Valley (a) and corresponding daytime (b) and nighttime (c) O_3 changes

daytime and nighttime ozone distributions displayed in Figure 2 also suggest that daytime O_3 levels are much higher than those at night. The daytime O_3 (Fig. 2b) has less variation than that at night (Fig. 2c). The spatial distribution of O_3 concentration exhibits more variation at night.

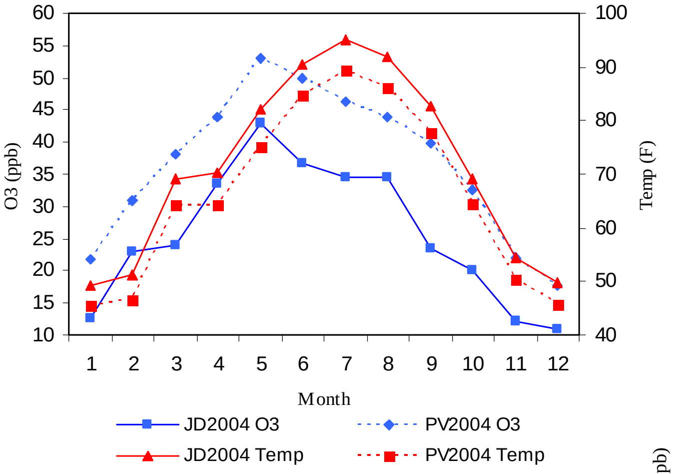

Figure 3. Monthly average ozone levels and related air temperatures for JD and PV sites in 2004

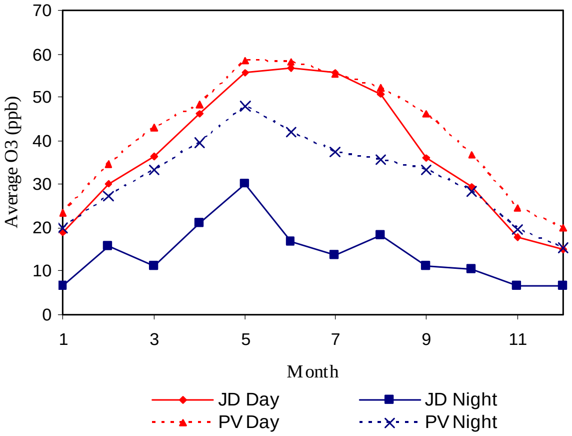

Figure 4. Monthly average daytime and nighttime ozone levels for JD and PV sites in 2004

A strong seasonal ozone pollution episode exists in the valley. To investigate the spatial and temporal change of ozone level, data from 2004 for O_3 and NO_x were selected from two monitoring sites, JD and PV. JD is located on the northeastern side of Las Vegas in close proximity to the downtown area and is surrounded by business and residential constructions. PV is located on the northwestern edge of Las Vegas, where rural land appears just off the road on the western side and new developed residential areas appear on the eastern side. Figure 3 shows monthly average O_3 levels and air temperatures for both JD and PV. The ozone level reaches its highest value of 42.86 ppb in May for the site JD and 53.14 ppb in the same month for the site PV . The monthly average air temperature reached its peak value in August for both sites, although JD was a few degrees warmer than PV because JD has a relatively lower elevation. The diurnal O_3 variations for the two sites (Fig. 4) indicated that there were no major differences for daytime ozone levels. In contrast to the daytime O_3 variations, the two sites had an approximately 10 ppb difference during the nighttime. The ozone level was much lower at JD than it was at PV during the nighttime.

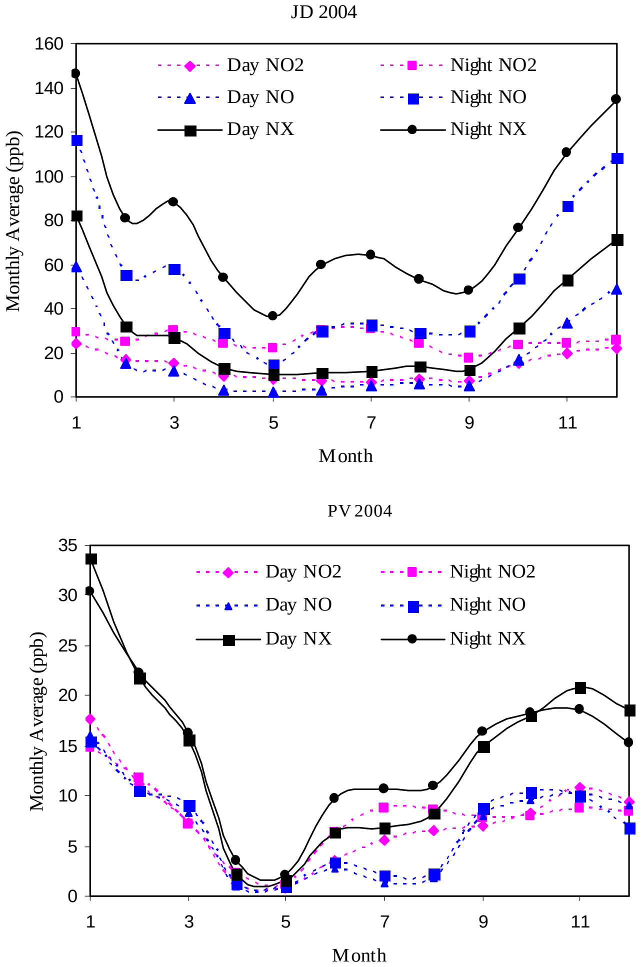

Figure 5. Monthly average N_2, NO, and NO_x concentrations for JD (upper) and PV (lower) sites in 2004

Observational data from 2004 were used to inspect nitrogen oxide variations from anthropogenic emissions at the JD and PV sites. Figure 5 displays NO_x variations for both daytime and nighttime for the sites JD and PV in 2004. Generally, NO_x emissions were larger at JD than those at PV. The NO_x level was extremely low at PV during April and May. This removal of NO_x was caused by synoptic weather systems and local meteorological conditions during the period. There was no apparent diurnal variation in NO_x at PV, which indicates that the O_3 episode was controlled by a natural seasonal and daily cycle. The elevated ozone level during the daytime was a result of photochemical oxidation of VOCs catalyzed by NO_x in the presence of sunlight. The removal of NO_x by the dominating synoptic weather system and prevailing southwesterly winds helped increase the level of O_3 during the spring at PV. Variations at JD were different. There was an apparent diurnal variation in the NO_x level—the nighttime NO_x level was much higher than the daytime NO_x level. This high level of NO_x, which is caused by emissions from automobile engines, disrupts the natural daily cycle of surface ozone by the subsequent chemical reaction (Eq. 3). The elevated NO_x levels were attributed from continuous nighttime NO emissions from automobiles, weak horizontal and vertical advection, and dispersion. Therefore, a relatively low level of nighttime surface ozone throughout the year can be seen at the JD site.

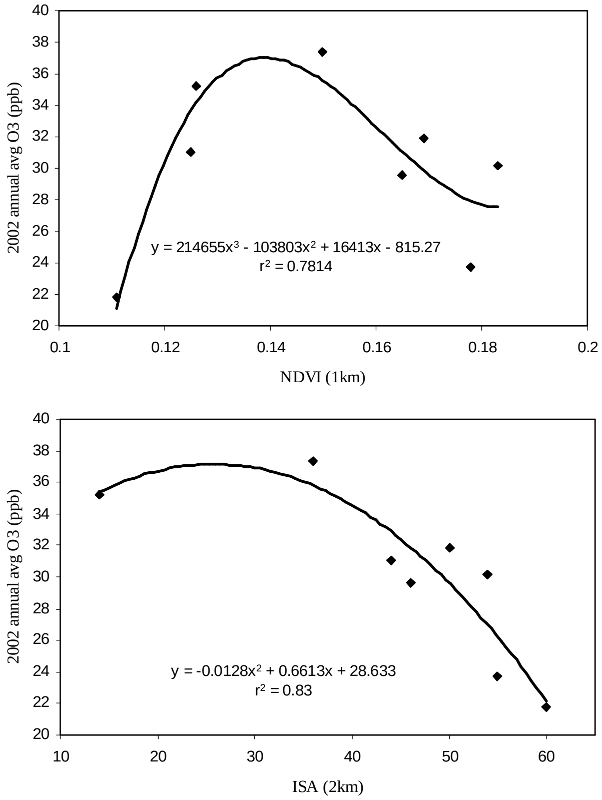

Figure 6. 2002 annual average O_3 concentration from all eight selected monitoring sites and corresponding NDVI averaged in a 1-km-by-1-km grid (upper) and ISA averaged in a 2-km-by-2-km grid (lower)

4.2 Urban LULC Impact

The spatial distributions of O_3 and NO_x suggest strong heterogeneous features in the Las Vegas Valley. Most urban land use in the valley is categorized by residential and commercial developments. The increase in anthropogenic impervious surface enhances the urban heat island effect and raises local air temperatures. This leads to an increase in VOC emissions from urban trees, vegetation, and anthropogenic sources. The urban LULC conditions displayed in Figure 1 also indicate that most monitoring sites are located in areas that have a mixture of high ISA and vegetation coverage. We used 2002 NDVI and ISA estimated from satellite imagery to calculate the averages within both a 1-km-by-1-km grid and 2-km-by-2-km grid around each of the eight selected monitoring sites, in which sites BS and WW were not included, in the valley. The 2002 annual average O_3 concentrations were plotted with corresponding NDVI and ISA coverage. Results suggested that NDVI averaged in a 1-km-by-1-km grid had higher correlation than that averaged in the larger grid. However, ISA averaged in a 2-km-by-2-km grid had higher correlation than that averaged in the smaller grid. Figure 6 shows 2002 annual average O_3 concentration corresponding to NDVI averaged in a 1-km-by-1-km grid and ISA averaged in a 2-km-by 2-km grid. The O_3 level reached its maximum with an NDVI value of 0.14, which was in the medium range for the valley. However, the O_3 level decreased as ISA coverage increased. Apparently, high urban vegetation canopy cover had a positive effect by reducing O_3 in urban areas. Higher ISA coverage also had the similar positive effect by reducing the O_3 level on built-up lands. From the discussion in previous sections we know that most surface O_3 reductions in the valley occurred at nighttime. Meteorological and chemical processes were responsible for the nighttime O_3 minimum and NO_x maximum. At night, the atmospheric condition of the Las Vegas

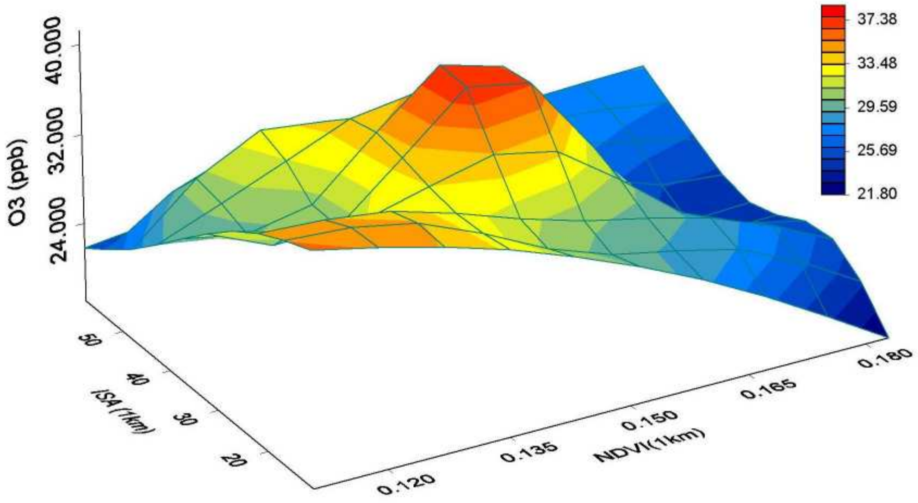

Figure 7. Three-dimensional distribution of O_3 concentration, 1-km NDVI, and 2-km ISA in the Las Vegas area

Valley was characterized by a more stable and less vertical mixture in the boundary layer. Hence, NO_x emitted from automobiles and other anthropogenic sources was easily trapped within the boundary layer. Consequently, the large abundance of NO_x near the surface led to the substantial removal of O_3 through the reaction controlled by Equation 3. This explained lower annual average O_3 levels in higher density built-up areas, even though O_3 concentration might be high during the daytime. To better understand the overall relationship of O_3 and corresponding NDVI and ISA in the valley, a three-dimensional plot is presented in Figure 7. The figure shows that the peak O_3 level is related to medium values of NDVI and ISA for the Las Vegas metropolitan area.

5. CONCLUSIONS

Our analyses reveal that ozone levels in the Las Vegas area have strong seasonal and spatial variation characteristics. Peaks of ozone concentration usually occur during May and June, while minimum values typically occur from November to February. The regional and local meteorological circulation and emissions from anthropogenic sources play a significant role in ozone formation and distribution in the Las Vegas area. The rate of nighttime ozone removal is dependent on locations in the urban area, and therefore, suggests the heterogeneous spatial distribution features for monthly and annually averaged ozone levels in the Las Vegas urban area. Urban vegetation canopy has a locally positive effect by reducing ozone in urban areas. An inverse relationship appears to exist between ozone concentrations and percent impervious surface cover, suggesting that high ozone concentrations are more closely associated with the medium- to low-density urban areas of Las Vegas.

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