CO_2 AND CARBON EMISSIONS FROM CITIES

Linkages to Air Quality, Socioeconomic Activity, and Stakeholders in the Salt Lake City Urban Area

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Observations and modeling of atmospheric CO_2 in the Salt Lake City, Utah, area help to quantify and understand urban carbon emissions and their linkage to air quality.

Fossil fuels, such as coal, petroleum, and natural gas, have supplied the energy that powered the Industrial Revolution and economic development, serving as the "life blood" of modern societies (Andres et al. 2012). While the use of fossil fuels has lifted millions out of poverty and dramatically improved living standards in the United States and other parts of the world, the adverse effects of fossil fuel combustion are becoming increasingly evident.

When coal, petroleum, and natural gas are combusted for energy, the carbon that serves as the backbone of these fossil fuels is mostly emitted to the atmosphere as carbon dioxide (CO_2), the key greenhouse gas that is responsible for the bulk of anthropogenic climate change (IPCC 2014; Gurney et al. 2015). Fossil fuel combustion simultaneously releases other air pollutants, such as mercury, nitrogen oxides (NO_x), particulate matter (PM), and volatile organic compounds (VOCs) (Akimoto 2003; Watts et al. 2016).

Cities, with their large, dense populations, are where substantial fossil fuel combustion takes place (International Energy Agency 2008) and where air pollution impacts are concentrated (see the sidebar for additional information). As the global population increasingly resides in cities (Seto et al. 2012), the role of urban areas in determining the future trajectory of carbon emissions is magnified. Because anthropogenic carbon emissions are intimately tied to socioeconomic activity through fossil fuel combustion, research efforts into cities' carbon emissions provide opportunities for

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stakeholder engagement and for guidance on other environmental issues, such as air quality.

Furthermore, cities and subnational entities around the world have announced commitments to reducing greenhouse gas emissions (International Energy Agency 2009; UNFCC 2017). In the United States, the declared intention to withdraw from the Paris Agreement has shifted the focus of greenhouse gas emission reduction efforts away from the federal level to state and local levels, where cities are playing a central role (https://www.nytimes.com/2017/06/01/climate/american-cities-climate-standards.html?_r=0).

Despite many cities' ambitious goals for greenhouse gas reduction, verifying whether these targets are met is a difficult task. The urban environment is characterized by extreme heterogeneity in land use and human activity (Gurney et al. 2015). However, cities are also arenas where diverse observations and data streams are available. Examples include meteorological data, air quality monitoring, and a variety of socioeconomic datasets, such as detailed census data, cell phone network data, traffic information, and building characteristics. When these assets are combined with advances in instrumentation, computing, and communications that lie at the heart of the "Smart City" revolution (Dameri and Rosenthal-Sabroux 2014), progress can be made on quantifying and understanding the underlying processes that control carbon emissions from cities, leading to informed decisions about how to most effectively implement emissions reduction goals.

SOURCES OF CO_2 EMISSIONS AND HETEROGENEITY WITHIN THE URBAN ENVIRONMENT

Cities are concentrated sources of CO_2 emissions to the atmosphere. At the fundamental level, the CO_2 emissions in cities can mostly be traced to the combustion of fossil fuels, such as petroleum, coal, and natural gas (Fig. SB1). The chemical energy stored in the hydrocarbons comprising these fossil fuels is released as heat when they are combusted, and CO_2 is produced as a by-product of the combustion, through oxidation (brown arrows). To a large extent, a similar process is happening within living organisms, such as humans and vegetation, which oxidize organic material for energy (green arrows). Vegetation is one of the only sinks for CO_2 within cities, assimilating atmospheric carbon during the daytime through photosynthesis. The combustion of fossil fuels drives the dominant spatial patterns for CO_2 emissions within the city. Key processes include automobile-related tailpipe emissions, industrial emissions, and home heating. These processes simultaneously co-emit pollutants, such as NO_x and fine particulate matter. Electricity production also releases large quantities of CO_2 if the power plant relies on fossil fuels (mainly natural gas or coal), but for most cities in developed nations these emissions take place away from urban settlements because of concerns about ancillary emissions of other species (e.g., NO_x, carbon monoxide, particulate matter) that lead to air quality degradation. One of the challenges of quantifying and understanding CO_2 emissions from cities is the finescale variations associated with road networks, commercial buildings, and residences that result in similar heterogeneity in emission patterns (Fig. 1). Variations in atmospheric CO_2 concentrations detected by the measurements result from a combination of the aforementioned emissions with meteorological processes, for example, mixing within the boundary layer (PBL) and advection by mesoscale and synoptic systems.

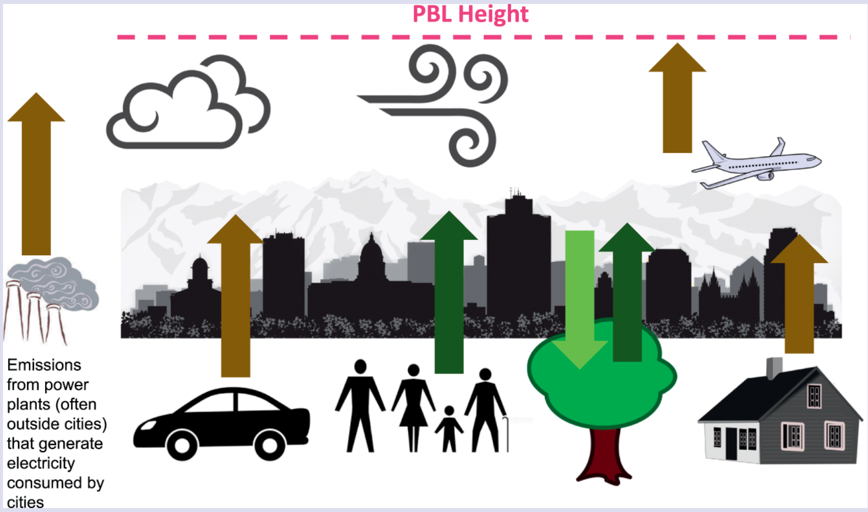

Fig. SB1. Sources of CO_2 emissions and heterogeneity within the urban environment.

In this paper we describe a research effort centered in the Salt Lake City (SLC), Utah, metropolitan region, which is the locus for one of the longest-running urban CO_2 networks in the world.

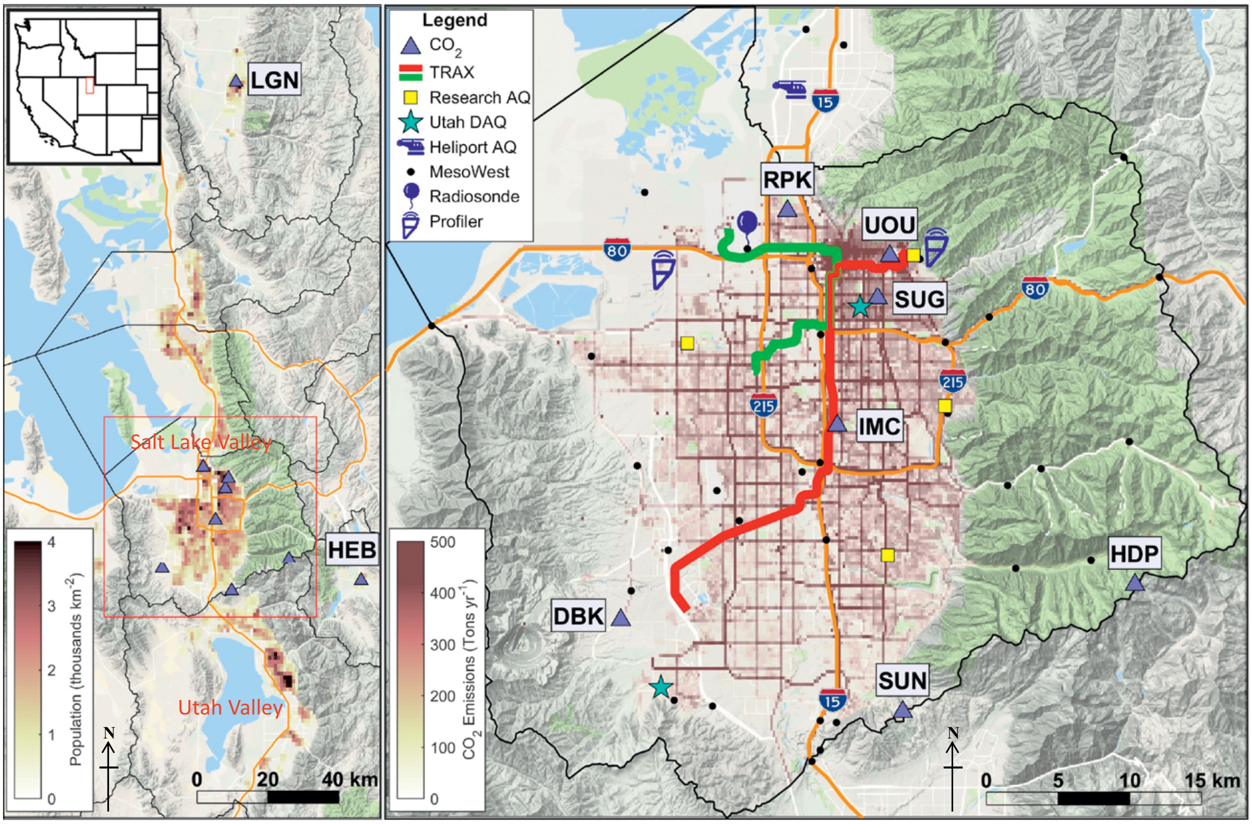

Fig. 1. (left) Map of key measurement sites in northern Utah and (right) zooming into the red box encompassing the SLV. The SLV Greenhouse Gas Monitoring System includes 1) CO_2 sites (purple triangles), 2) light-rail-based GHG observations (red and green lines), 3) atmospheric profiling instruments (profiler symbols), and 4) MesoWest meteorological sites (black dots). Additionally, research-purpose air quality sites (yellow squares) and state of Utah Division of Air Quality sites (cyan star) are shown too. Population density is displayed in the left panel; estimates of CO_2 emissions from the Hestia high-resolution inventory is in the right panel. The major interstate highways are marked (orange lines). The helicopter pad where the news helicopter equipped with air quality and meteorological instruments is based is shown at the northern part of the figure, near Interstate 15. Radiosondes (balloon symbol) are launched near the Salt Lake City International Airport. The underlying terrain map is from Google.

This network is enhanced with a) air quality observations, b) novel mobile observations from platforms on light-rail public transit trains and a news helicopter, c) dense meteorological observations, and d) modeling efforts that include atmospheric simulations and high-resolution emission inventories. Thus, the Salt Lake area provides a rich environment for studying anthropogenic emissions and for understanding the relationship between emissions and socioeconomic activity. In addition to describing the observations, we present three sample applications of the data. This work has benefited from and contributed to the interests of multiple stakeholders, including policymakers, air quality managers, municipal government, urban planners, industry, and the general public.

Some key questions driving this research effort include the following:

- How accurate are current emission estimates, and can proposed carbon reduction targets be detected from atmospheric measurements?
- How do local terrain and meteorology interact with emission patterns to produce variations in atmospheric CO_2?
- What is the quantity of greenhouse gases co-emitted with air quality–relevant pollutants, and how much co-benefits in carbon reduction and air quality improvement can be realized?
- What will be the future trajectory of carbon emissions, considering changes in population, technology, and urban extent?

Salt Lake Valley Greenhouse Gas Monitoring System. SLC anchors an urban region extending north to south along the Wasatch Mountains of northern Utah, commonly referred to as the Wasatch Front

(Fig. 1). The Wasatch Front, currently with a population of over 2 million, is where ~80% of Utah's population resides and is among the fastest-growing urban regions in the United States (Utah Foundation 2014a). SLC is the state capital and is contiguous with other municipalities within a mountain valley (the Salt Lake Valley), with an aggregate population in excess of 1 million.

The Salt Lake Valley (SLV) offers a number of advantages for greenhouse gas monitoring and engaging the broader nonscientific community:

1) The SLV has well-defined physical boundaries, with the Great Salt Lake to its northwest and mountains surrounding the urbanized area (Fig. 1). This facilitates determination of background levels of greenhouse gas and pollutants, which represent concentrations relatively unaffected by upstream urban emissions.
2) The deep SLV can trap emitted species within the SLV, leading to large signals of anthropogenic activities (see below).
3) SLC is a midsized city with a critical mass of urban infrastructure, emissions, stakeholders, and datasets. But compared to much larger megacities, SLC's smaller size makes the underlying information and stakeholders relatively accessible. Furthermore, midsized cities are some of the most rapidly expanding around the world (Creutzig et al. 2016).
4) The SLC government has committed to steep reductions in community greenhouse gas emissions by 2040 (Salt Lake City Corporation 2017). These ambitious goals should result in readily observable changes in the atmospheric composition within the SLV in the coming years.

Against the backdrop of the four advantages mentioned above, we have established the Salt Lake Valley Greenhouse Gas Monitoring System (Fig. 1), which consists of a network of long-term stationary measurement sites [Utah Urban Carbon Dioxide Network (UUCON)], light-rail-based mobile measurements, and meteorological observations that aid in the interpretation of the greenhouse gas observations. The greenhouse gas observations are combined with measurements of air quality–relevant pollutants that are often co-emitted with greenhouse gases (see the sidebar for additional information).

Table 1. The urban CO_2 sites along the Wasatch Front in northern Utah. NCAR: National Center for Atmospheric Research.

Site code	Site name	Lat (°N)	Lon (°W)	Elevation (m MSL)	Inlet height (m AGL)	Start year	Notes
DBK	Daybreak	40.5383	112.0697	1,582	5.05	2004	Prior to Oct 2015 inlet height was 9 m AGL
HEB	Heber	40.5067	111.4036	1,721	4.2	2015	
HDP	Hidden Peak	40.5601	111.6454	3,351	17.1	2006	Responsibility of HDP site shifted to the University of Utah from NCAR in 2016
IMC	Intermountain Medical Center	40.6602	111.8911	1,316	66	2016	On top of a 13-story-tall hospital building
LGN	Logan	41.7616	111.8226	1,392	3.23	2015	
RPK	Salt Lake Center for Science Education	40.7944	111.9319	1,289	3.25	2009	
SUG	Sugarhouse	40.7398	111.8580	1,328	3.86	2005	Moved to the current location from a similar residential location 1.45 km away on 29 Jan 2008
SUN	Suncrest	40.4808	111.8371	1,860	4.22	2015	
UOU	University of Utah	40.7663	111.8478	1,436	36.2	2001	Moved to the current location from a separate building ~250 m away on campus in 2015

GREENHOUSE GAS AND AIR QUALITY OBSERVATIONS.

UUCON, one of the longest-running network of urban CO_2 sites in the world, was started in 2001 by researchers at the University of Utah (Pataki et al. 2003; Mitchell et al. 2018). The CO_2 observations are calibrated with reference gases traceable to the World Meteorological Organization calibration scales. Details of the instrumentation, data, calibration, and quality assurance (QA)/quality control (QC) method can be found in Pataki et al. (2003, 2006) and Mitchell et al. (2018). The network, whose data are displayed in real time online (http://air.utah.edu), has expanded over the years and includes sites in residential, commercial, mountaintop, and suburban/rural areas (Fig. 1; Table 1). Since 2015 two additional sites outside the SLV were established along the Wasatch Front. These are in the towns of Logan (LGN) and Heber (HEB), in the Cache and Heber Valleys, respectively (Fig. 1). The Cache Valley has a population of >100,000, while Heber Valley has a population of >10,000. Thus, the Salt Lake, Cache, and Heber Valleys are separated by one to two orders of magnitude difference in population size, but each is undergoing rapid population expansion.

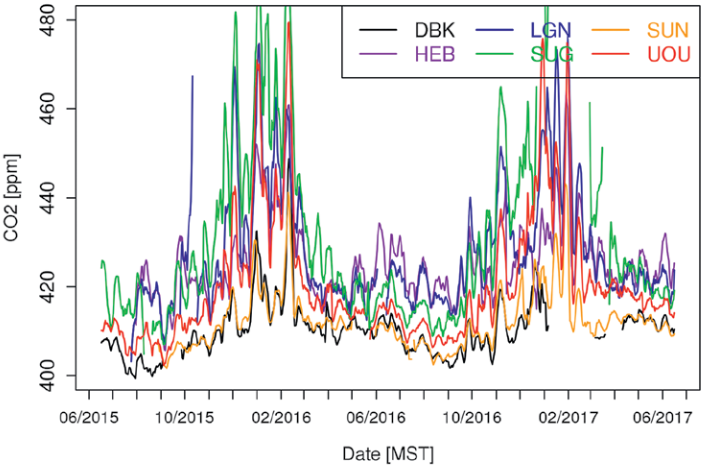

Fig. 2. Time series of observed CO_2 at a subset of sites in the UUCON over two years, from mid-Jun 2015 to 2017. Daily average concentrations are smoothed with a 7-day running average.

Several processes across spatial and temporal scales are visible in the CO_2 observations (Fig. 2). A seasonal cycle is discernible at all the sites, with elevated values in the winter and reduced levels during the summer. The processes contributing to the seasonal cycle are well understood. These involve meteorological, biological, and anthropogenic factors (see the sidebar for additional information). During the summer, a deeper summertime planetary boundary layer dilutes emissions and reduces the measured CO_2 concentration. In the winter, suppressed vertical mixing leads to a buildup of CO_2, with especially pronounced events occurring during prolonged meteorological stagnation episodes, referred to colloquially as "inversions" or scientifically as "persistent cold-air pools" (Doran et al. 2002; Whiteman et al. 2014; Lareau et al. 2013). Combined with the seasonal cycle in meteorology are seasonal variations in anthropogenic and biological fluxes. Winter emissions increase as a result of natural gas combustion for heating (Gurney et al. 2012). Biological fluxes include the emission of CO_2 from plants and animals from respiration and the removal of CO_2 during the summer growing season from photosynthesis that becomes inactive during the winter.

At submonthly time scales, CO_2 variations are often coherent across the multiple sites in northern Utah (Fig. 2). These are related to synoptic events that advect air masses with higher or lower CO_2 (Wang et al. 2007) as well as coincide with the buildup and cleanout of urban areas.

The average diurnal cycle of CO_2 (Fig. 3) reveals information about both atmospheric mixing and socioeconomic activity (Strong et al. 2011). At Sugarhouse (SUG) and the University of Utah (UOU), elevated CO_2 is observed in the morning and late afternoon, corresponding to rush hour periods. The morning rush hour peak is lagged at UOU as a result of its location at higher elevation on the valley bench, to the east of SLC (Fig. 1). The morning rush hour peak is higher than the late afternoon counterpart, as a result of the shallower mixing depth in the morning. For the same reason, the enhancements during the winter, when mixing depth is significantly shallower, are also more pronounced. Diurnal variations are smaller at Daybreak (DBK) and Suncrest (SUN), both of which are located far from the urban corridors.

An example of the strong imprint of human activities on CO_2 can be found in contrasting the diurnal pattern on 4 July 2016 (Fig. 3c) with the average pattern from the period July–August 2016 (Fig. 3b). On 4 July the significant enhancements late into the evening can be observed at SUG and even SUN, which sits 500 m above the valley floor. We suspect these features correspond to emissions on this major holiday from additional traffic, backyard parties, and fireworks that are lofted to the higher-elevation SUN site.

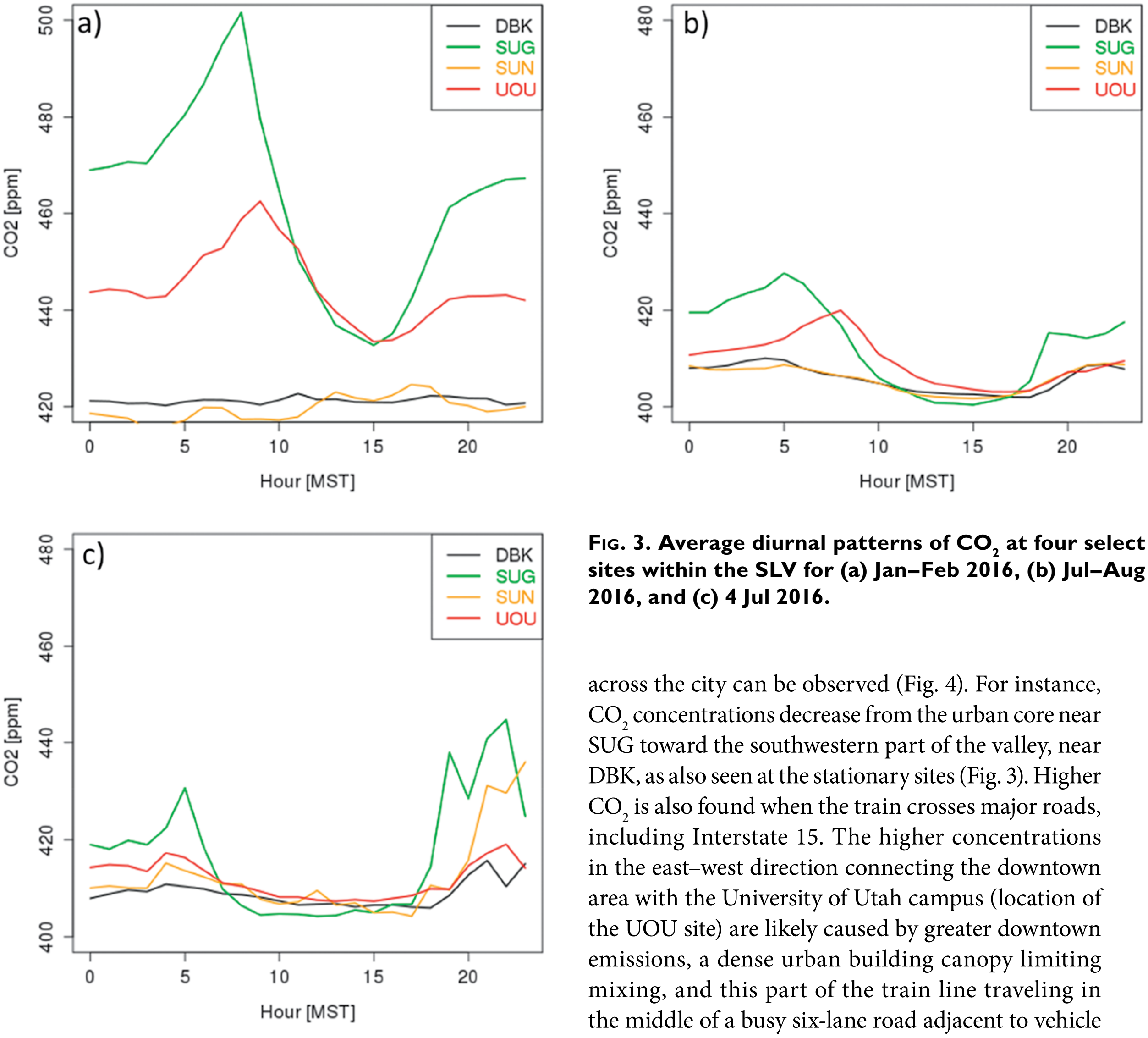

Fig. 3. Average diurnal patterns of CO_2 at four select sites within the SLV for (a) Jan–Feb 2016, (b) Jul–Aug 2016, and (c) 4 Jul 2016.

Light-rail-based mobile measurements. Toward addressing the need for understanding spatial variations in CO_2 and other species across the SLV, we have access to a van-based mobile laboratory for on-road measurements (Bush et al. 2015). In addition, we installed a novel measurement platform on the roof of light-rail public transit trains (Mitchell et al. 2018). The light-rail-based measurements commenced in December 2014 and are ongoing. Research-grade instruments deployed on the light-rail include a model 205 dual-beam ozone monitor from 2B Technologies, an ES-642 remote dust monitor (for $PM_{2.5}$) from Met One Instruments, and an ultraportable greenhouse gas analyzer from Los Gatos Research (LGR) for measuring CO_2, methane (CH_4), and water vapor (H_2O). By deploying research-grade instrumentation on electricity-powered light-rail trains that repeats observations along dedicated rail lines, coherent spatiotemporal patterns across the city can be observed (Fig. 4). For instance, CO_2 concentrations decrease from the urban core near SUG toward the southwestern part of the valley, near DBK, as also seen at the stationary sites (Fig. 3). Higher CO_2 is also found when the train crosses major roads, including Interstate 15. The higher concentrations in the east–west direction connecting the downtown area with the University of Utah campus (location of the UOU site) are likely caused by greater downtown emissions, a dense urban building canopy limiting mixing, and this part of the train line traveling in the middle of a busy six-lane road adjacent to vehicle tailpipe emissions. See Mitchell et al. (2018) for more details regarding the measurement setup and observed patterns in other species, such as CH_4, $PM_{2.5}$, and O_3.

News helicopter–based criteria pollutant measurements. In addition to the light-rail-based mobile observations, in 2015 we instrumented a local news helicopter stationed in the SLV (Fig. 1) with research-grade instrumentation to measure $PM_{2.5}$ and ozone (O_3) (Crosman et al. 2017). This is currently the only helicopter-based vertical profiling of pollutants in real time over an urban area within the United States, at a frequency of four to six flights per week. The ozone and $PM_{2.5}$ sensors utilized on the helicopter are the same as described on the light-rail train in the previous section. Significant day-to-day and intraurban variations are observed in the helicopter vertical profiles (Fig. 5), which provide insight into the depth and spatial variation in pollutants across the city as

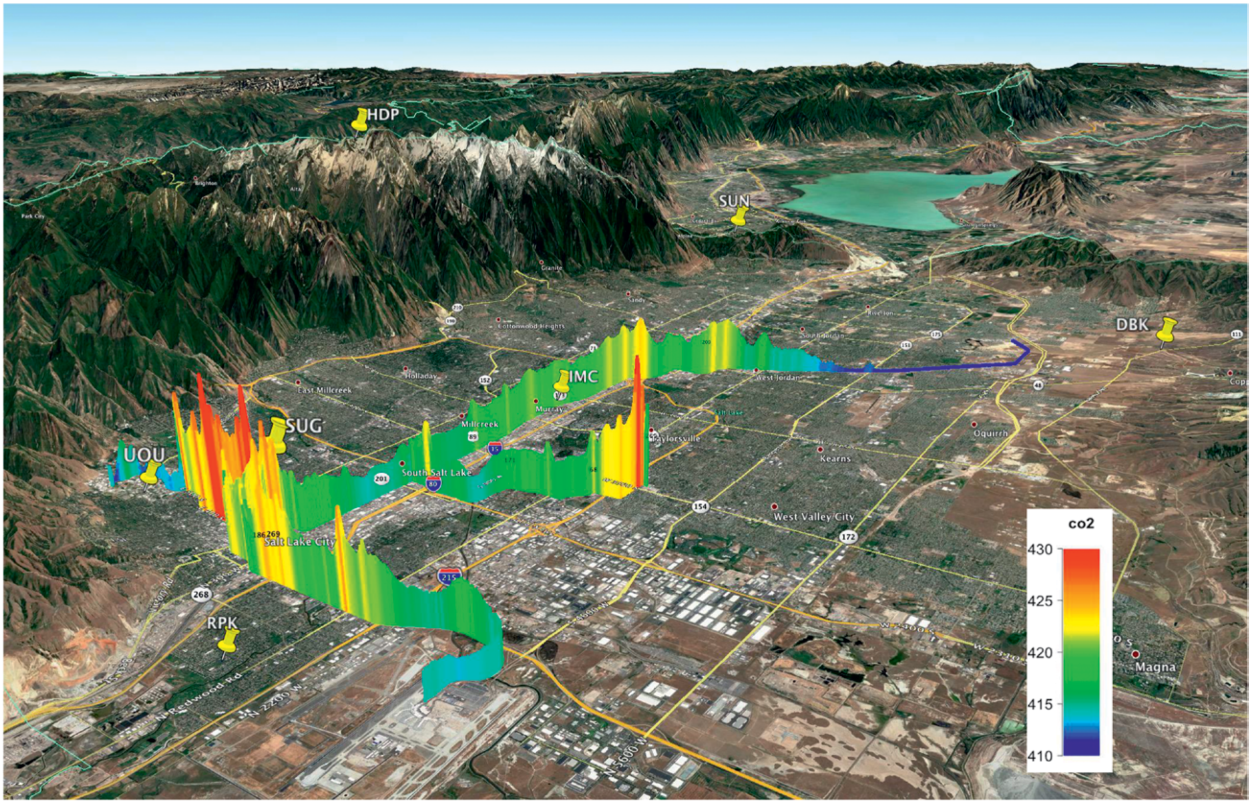

FIG. 4. Spatial distribution of CO_2 as observed on light-rail routes (Utah Transit Authority's Red and Green Lines; see Fig. 1), looking in the southeast direction toward the Wasatch Mountains. Observations over Jul and Aug 2015 taking place between 0500 and 2400 MST were averaged in spatial bins of ~40 m for this plot. The stationary CO_2 sites and their three-letter codes (Fig. 1; Table 1) are shown as yellow pins. The underlying three-dimensional map is from Google Earth (Google, Landsat/Copernicus, INEGI).

well as provide a proxy estimate for mixing heights across the urban landscape (Horel et al. 2016; Blaylock et al. 2017). The depth over which O_3 depletion takes place provides a unique dataset that can be combined with meteorological observations for understanding the linkages between variations in surface CO_2 concentrations and boundary layer height (see below).

METEOROLOGICAL OBSERVATIONS. An extensive array of meteorological observations—both surface based and vertical profiling—are available on a routine basis in the SLV. Key meteorological sites mentioned below are indicated in Fig. 1.

The National Weather Service (NWS) launches twice-daily

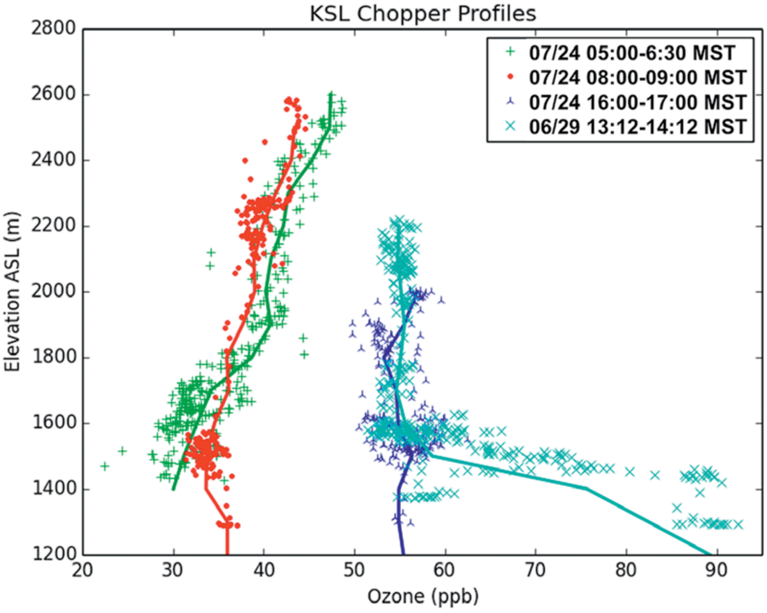

FIG. 5. Vertical profiles of O_3 from the KSL-TV news helicopter from 29 Jun and 24 Jul 2015. Individual measurements (dots), with best fit (solid line), are marked.

radiosondes at the Salt Lake City International Airport in the northwestern quadrant of the SLV, the only radiosonde launch location in Utah. Complementing the NWS soundings are multiple atmospheric profiling instruments deployed throughout the SLV. In the northeastern foothills of the SLV, temperature profiles are obtained by a radiometer operated by the state of Utah's Division of Air Quality, while at the same location the MesoWest group at the University of Utah operates a Vaisala CL31 laser ceilometer. The ceilometer backscatter profiles allow for characterization of the depth and vertical profiles of boundary layer pollution and have been utilized to understand wintertime cold-air pool structure (Young and Whiteman 2015). A wind sodar has also been deployed by the MesoWest group at the Salt Lake County Landfill several kilometers west of the airport, which provides boundary layer wind profiles of frequent lake- and land-breeze flows observed in this portion of the SLV.

During the past 10 years, the University of Utah MesoWest Mesonet (UUNET) research-grade meteorological observational network has expanded from only a few stations in northern Utah to over 25 stations. In addition to the UUNET network, data from surface weather platforms operated by a variety of city, state, and national government agencies as well as public and private entities are collected and archived by MesoWest (Horel et al. 2002) at temporal intervals between 5 min and 1 h. A representative subset of these networks is shown by the black dots in Fig. 1. The spatial coverage afforded by the network enables the generation of hourly high-resolution meteorological reanalyses (Tyndall and Horel 2013).

The considerable measurement capabilities comprising the SLV Greenhouse Gas Monitoring System enables several applications, described in the next sections.

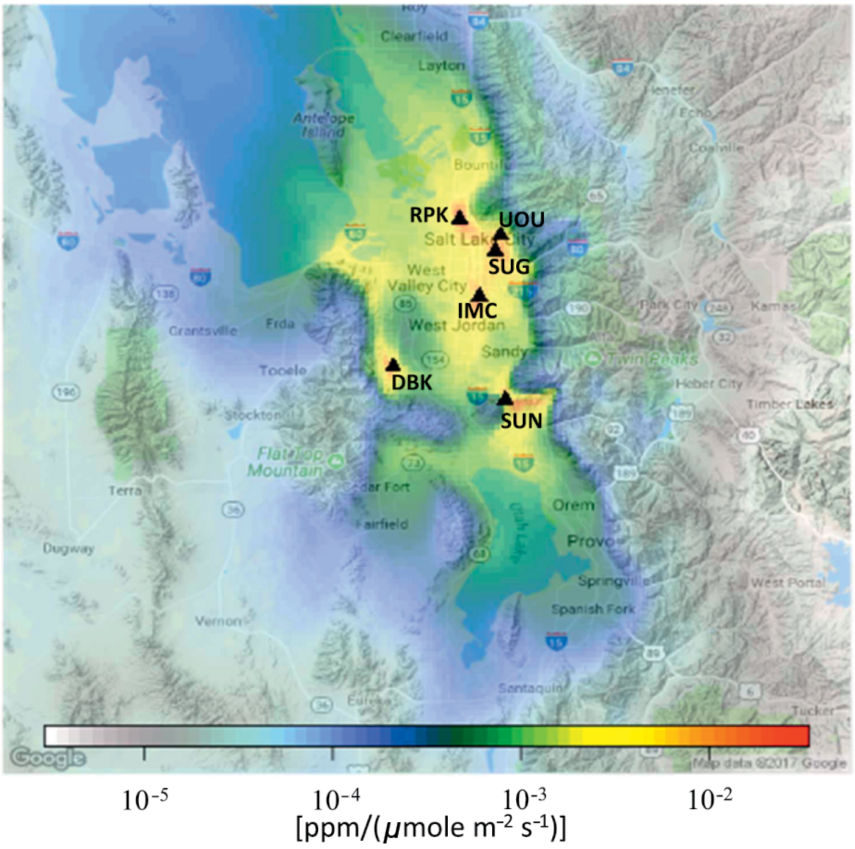

Fig. 6. Summertime average footprints showing contributions from all of the stationary sites (triangles) within the SLV. The composite footprint from all of the stations is shown to illustrate the spatial coverage across the SLV. The footprints were simulated by the STILT model, driven by HRRR meteorological fields. A total of 200 particles were released every hour between 16 Jun and 31 Aug 2015 at each site and tracked back 24 h to generate the footprints. The underlying terrain map is from Google.

APPLICATION I: MRV FOR GREENHOUSE GAS EMISSIONS.

Greenhouse gas emissions reduction targets, whether at the international (e.g., Paris Agreement), state/province (e.g., California, Ontario), or municipal levels (e.g., Salt Lake City), have led to an urgent need for monitoring, reporting, and verification (MRV) capabilities (National Research Council 2010). In particular, numerous cities have made pledges for greenhouse gas reductions (Duren and Miller 2012; Gurney et al. 2015; UNFCC 2017; Salt Lake City Corporation 2017) that should be independently evaluated with observations. Likewise, as societies seek to undergo decarbonization by transitioning to renewable energy, it is imperative to understand the actual impact on carbon emissions.

Toward this end, the variations in CO_2 observed by the network (Figs. 2–4) provide a "top down" constraint on carbon fluxes around urban areas, after accounting for atmospheric advection and mixing. In essence, variations in CO_2 contain the signature of carbon emissions but are modified by horizontal advection and vertical mixing, particularly with the rapid dilution within the planetary boundary layer (see the sidebar for additional information). The top-down constraint from observed CO_2 provided thus depends on atmospheric transport, which determines the source regions (footprint) of the measurement site. Unraveling the influence of atmospheric transport to reveal the source regions usually necessitates the use of atmospheric models. We have driven a time-reversed Lagrangian particle dispersion model—the Stochastic Time-Inverted Lagrangian Transport (STILT) model (Lin et al. 2003)—with mesoscale meteorological fields from the High-Resolution Rapid Refresh (HRRR) model (Benjamin et al. 2016). Sample outputs from the atmospheric simulations are found in Fig. 6, which shows the aggregate footprint of the stationary measurement sites. The aggregate footprint indicates that the measurement network from the stationary sites is sensitive to emissions over a broad swath of the SLV, with stronger sensitivity around individual sites. Also, the sites at the southern end (SUN and DBK) are influenced by emissions from the neighboring Utah Valley to the south.

Combining atmospheric modeling with CO_2 observations has yielded fruitful results in the SLC area. Strong et al. (2011) used a multibox model to investigate how meteorological, anthropogenic, and biological processes influence CO_2 diel cycles within the SLV. McKain et al. (2012), employing information similar to that shown in Fig. 6, showed the capability of the measurements to detect increases or decreases in carbon emissions. More recently, Mitchell et al. (2018) found varying trends in CO_2 between the urban core of the SLC area as contrasted with the more rural southwestern part of the SLV, where suburban expansion is underway, suggesting contrasting emissions patterns from urban development.

In this effort to apply atmospheric modeling to interpret CO_2 observations, the fidelity of atmospheric models and their driving meteorological fields needs to be carefully assessed (Nehrkorn et al. 2013; Mallia et al. 2015; Lauvaux et al. 2016). Thus, the dense meteorological observations in the SLV (Fig. 1) are of significant value in evaluating the fidelity of the atmospheric models. In this way, meteorologists and atmospheric scientists, such as those in the American Meteorological Society (AMS) membership, can play important roles by providing expertise in properly interpreting the CO_2 measurements, as illustrated in the next section.

APPLICATION 2: INFERRING METEOROLOGICAL PROCESSES.

CO_2 is a passive tracer that has been historically underutilized to infer and better understand meteorological transport processes. In recent years, linking complex thermally driven circulations with CO_2 concentrations in urban areas has received increasing interest (e.g., Arrillaga et al. 2018; Hedelius et al. 2017). Some areas with sea-breeze influences have been found in some cases to have higher summertime CO_2 concentrations than other areas, but more research is needed to better understand these relationships (Lan et al. 2017). The SLV is an ideal environment for such research. Because of the surrounding complex topography and the high density of meteorological and trace gas observations, the SLV is a natural laboratory for observing the interactions between terrain-driven flows (e.g., lake breezes, urban circulations, and valley/slope/canyon flows) and atmospheric tracer transport, such as CO_2. In the SLV the impact of changes in the Great Salt Lake level, which results in variations in lake-breeze frequency and intensity (Zumpfe and Horel 2007), on modulating CO_2 concentrations is unknown and a needed area of future research. The long record of both CO_2 concentrations and meteorological measurements in the Salt Lake Valley provides a unique dataset for future work on this topic. Recent observational and modeling studies have quantified the impact of lake-breeze circulations on the spatiotemporal criteria pollution across the city, with the lake breezes found to trap high concentrations of O_3 and $PM_{2.5}$ within a shallow boundary layer and subsequently advect this polluted layer rapidly through the Salt Lake Valley during the afternoons (Crosman and Horel 2016; Horel et al. 2016; Blaylock et al. 2017).

An example of utilizing both meteorological and trace species data to provide insight into mountain and lake exchange processes in the SLV is shown in Fig. 7. A nocturnal surface-based inversion resulted in a buildup of CO_2, and NO_x titration of boundary layer O_3 over the night (see the typical morning summertime profile between 0500 and 0630 MST 24 July in Fig. 5) throughout the SLV each night between 27 and 29 June 2015. However, the nocturnal buildup of CO_2 is much higher (>460 ppm) at the Salt Lake Center for Science Education (RPK) (Fig. 7), which is at a lower elevation and closer to urban emissions than the DBK site (Fig. 1). The highest CO_2 was observed on 27 June, resulting from a pronounced nocturnal temperature inversion (not shown) that confined the urban emissions within a shallow near-surface layer. On 29 June, stronger southerly flows of 4–6 m s^{-1} resulted in turbulent mixing and a weaker nocturnal temperature inversion, with smaller CO_2 enhancements (Figs. 7a,c). In contrast, at DBK weak downslope winds (2–3 m s^{-1}) from adjacent mountain slopes transported cleaner nonurban background air from the higher elevations on all three nights (Figs. 7c,d). This infusion of air from the surrounding topography at DBK also means that this urban location is less impacted by NO_x titration of O_3 than at RPK, with nighttime O_3 observed to be ~20 ppb higher near DBK compared to RPK.

During the afternoon, mixing over the deep summer daytime boundary layer results in more homogeneous CO_2 concentrations across the city than during the night (Fig. 7a). However, northerly lake breezes from the Great Salt Lake in this case bring cleaner air with lower CO_2 into the RPK area in the afternoon, whereas upslope mountain flows at DBK result in transport from the urban corridor of elevated CO_2. Lake breezes are also known to be associated with rapid increases in summertime O_3 concentrations (Blaylock et al. 2017), and earlier increases in O_3 in the northern SLV compared to a later afternoon peak in the southern SLV (Fig. 7b). A notable high O_3 afternoon associated with a lake breeze occurred on 29 June 2015, when O_3 concentrations reached as high as 90 ppb within the shallow onshore lake breeze in the lowest several hundred meters of the boundary layer as observed during a helicopter vertical profile (Fig. 5). Interestingly, the high-ozone air behind the lake-breeze front on the 29 June event was not associated with a notable gradient in CO_2, highlighting the differences between NO_x–O_3 photochemistry, emissions, and atmospheric transport.

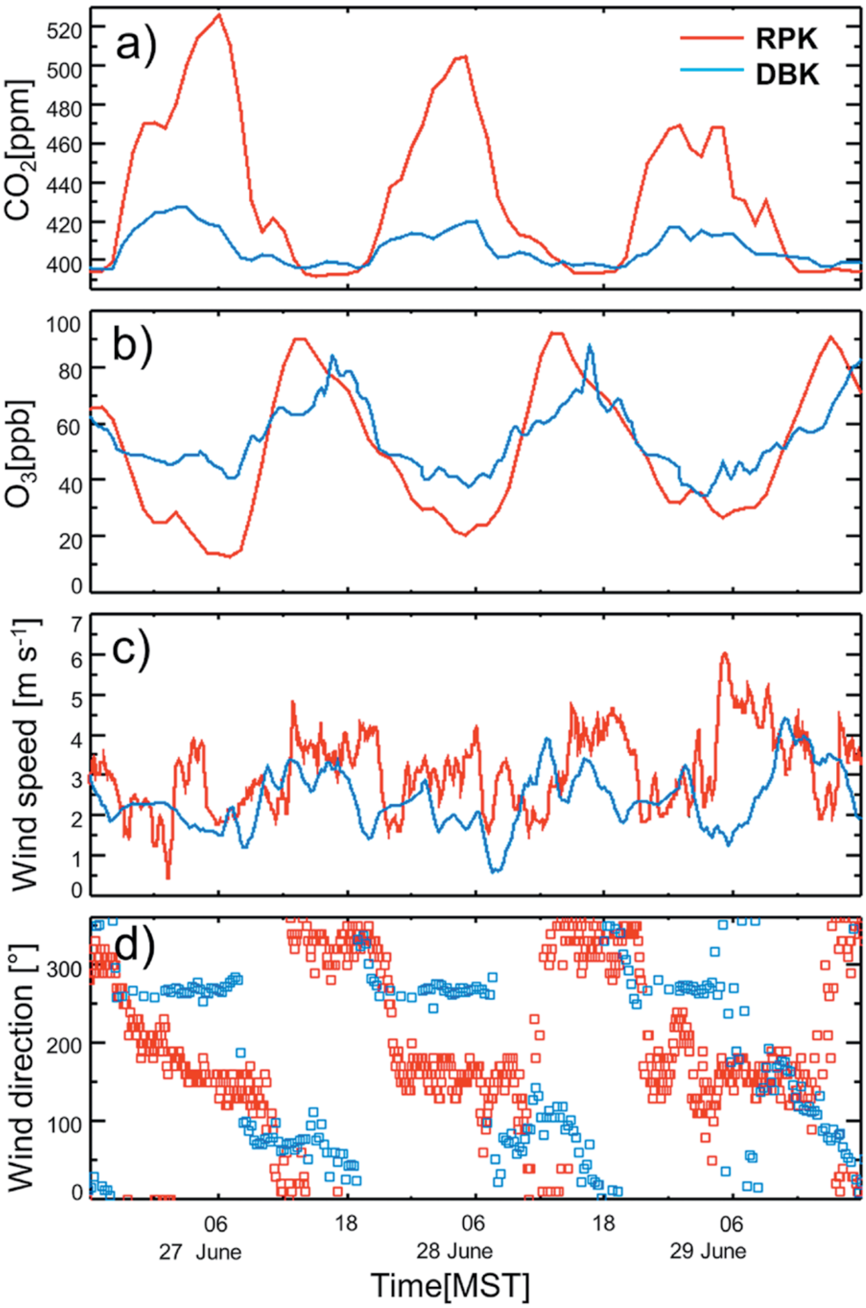

Fig. 7. Time series of trace gas and meteorological measurements between 27 and 29 Jun 2015 collected near Rose Park (RPK; red line) and DBK (blue line). (a) CO_2 concentrations, (b) O_3 concentrations, (c) wind speed, and (d) wind direction.

APPLICATION 3: AIR QUALITY. Residents of Utah suffer from episodic poor air quality at various times of the year, particularly along the urbanized

Wasatch Front. Levels of fine particulate matter ($PM_{2.5}$) in the SLV exceed the National Ambient Air Quality Standards (NAAQS) on average 18 days each winter (Whiteman et al. 2014). These originate from the infamous wintertime inversion episodes, or persistent cold-air pools, which are driven to a large extent by the surrounding topography of the SLV (Doran et al. 2002; Lareau et al. 2013).

In the summer, the Wasatch Front also experiences high levels of O_3 (DAQ 2013). Utah's Economic Development Task Force has pointed out that "poor air quality is a threat to the state's economic development and continued growth" (Utah Economic Development Task Force 2013, p. 4). The economic impacts of air quality can be wide ranging, adversely affecting recruitment and retention of talent, tourism, and health care costs. Clearly, improved air quality would greatly enhance Utah's economic conditions and quality of life with a healthier population, enhanced recruitment and retention of skilled workers, and increased tourism. Moreover, a recent survey revealed that one of the top priorities for Utah residents was reducing air pollution, just behind improving public education (Utah Foundation 2014b).

The considerable interest in improving air quality means that our work has been able to engage the public, stakeholders, and policymakers. As already illustrated in Fig. 7, observed pollutant levels tend to covary with CO_2 as a result of meteorology. Because of the chemical inertness of greenhouse gases like CO_2 and CH_4, these species can help to constrain atmospheric transport to better understand chemically reactive pollutants like O_3 and $PM_{2.5}$ (Baasandorj et al. 2017; Bares et al. 2018). Our observations reveal considerable correlations between CO_2 and pollutants like $PM_{2.5}$ and NO_x, pointing to common sources—for example, combustion of fossil fuels from automobiles and industry (see the sidebar for additional information). Naturally, this suggests significant "co-benefits" of greenhouse gas reduction along with improved air quality and health benefits (Garcia-Menendez et al. 2015; West et al. 2013). Leveraging these measurement capabilities will allow for a unique investigation of these co-benefits in real time as urban areas along the Wasatch Front reduce emissions in the coming years.

LOOKING TO THE FUTURE. The Salt Lake Valley Greenhouse Gas Monitoring System illustrates the potential of combining greenhouse gas observations with meteorological measurements and air pollutant monitoring to understand the "where, how, and why" of urban emissions. In the upcoming decades, as cities evolve and seek to reduce their carbon emissions, urban infrastructures such as buildings, road networks, and transit become critical, especially because of the long lifetime of urban infrastructure (Creutzig et al. 2016). In SLC, efforts are underway to understand the greenhouse gas (GHG) emissions resulting from existing urban infrastructure and the potential policy levers that could lead to significant reductions in carbon emissions (Salt Lake City Corporation 2017). Key to these efforts is a detailed high-resolution inventory of present-day emissions at building- and street-level resolution (Gurney et al. 2012; Patarasuk et al. 2016) (Fig. 1). Based on this inventory, specific road segments and urban neighborhoods have been identified as effective emission mitigation targets (Patarasuk et al. 2016).

We are also quantifying the consequences of urban growth in the SLC area by combining detailed growth scenarios (Wasatch Front Regional Council 2015) developed through public engagement (Burbidge et al. 2007) by the local metropolitan planning organization with the aforementioned methodology for detailed building- and street-level emissions. Examples of the outcome are in Fig. 8, showing carbon emissions from commercial and residential buildings projected to the year 2040 under a "business as usual" growth strategy. Growth in both commercial and residential activity is projected in the traditional SLC urban core (in-fill development), as well as the main north–south urban corridor. Expansion of residences in the southwestern part of the SLV can also be seen, and this is the only area that currently remains undeveloped (Fig. 1). The next step in this work is to understand the change in carbon emissions if more compact growth around transportation nodes recommended by many urban planners takes place instead of the more common suburban expansion (sprawl) that is often seen in cities with unregulated growth.

The fusion of knowledge in carbon emissions with urban planning and stakeholder engagement as depicted in Fig. 8 offers an avenue for dialogue with the broader community. The need for intellectual exchange between scientists and stakeholders was one of the major recommendations from a recent National Academy of Sciences (NAS) report on urban sustainability (National Academy of Sciences 2016). We plan to continue working with stakeholders—such as the municipal, county, and state governments; air quality managers; the metropolitan planning organization; and the transit agency—in SLC and beyond. While SLC is the longest-running multisite urban CO_2 network, similar measurements are taking place in a number of cities in the United States and around

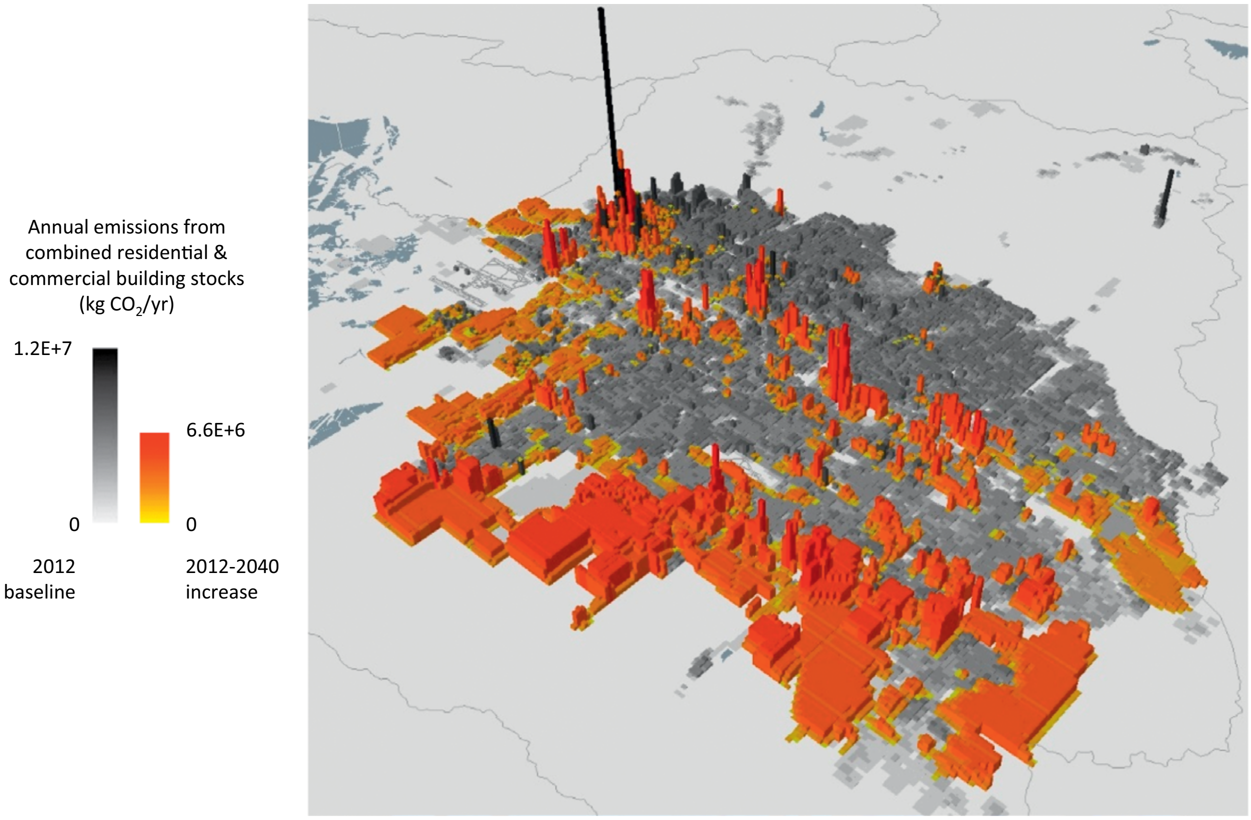

Fig. 8. Annual CO_2 emissions from commercial and residential buildings in SLV in the year 2012 (gray bar) and the additional projected emissions in the year 2040 (color bar), looking toward the northeast across the SLV. The 2012 estimates are derived from the Hestia inventory (Gurney et al. 2012; Patarasuk et al. 2016), while the 2040 estimates are based upon a business-as-usual growth scenario from the local metropolitan planning organization (Wasatch Front Regional Council 2015). Note that the heights of the bars do not indicate building heights but the CO_2 emissions from those buildings.

the world (Turnbull et al. 2015; McKain et al. 2015; Wu et al. 2016; Feng et al. 2016). These efforts open up the opportunity to compare emissions between different cities, with different sizes, climates, and urban forms, and these comparisons will improve our understanding of the processes controlling emissions and inform stakeholders and policymakers of the most effective ways to meet their mitigation targets (Hutyra et al. 2014).

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