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Impacts of the San Francisco Bay Area shelter-in-place during the COVID-19 pandemic on urban heat fluxes

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\textbf{ABSTRACT}

The purpose of this study was to make quantitative connections between changes in social and economic activities in northern California urban areas and related Earth system environmental responses to the COVID-19 pandemic in 2020. We tested the hypothesis that the absence of worker activities during Shelter-in-Place in the San Francisco Bay Area detectably altered the infrared heat flux from parking lots, highways, and large building rooftops, caused primarily by quantitative changes in the reflective properties in these different classes of urban surfaces. The Landsat satellite’s thermal infrared (TIR) sensor imagery for surface temperature (ST) was quantified for all the large urban features in the Bay Area that have flat (impervious) surfaces, such parking lots, wide roadways, and rooftops. These large impervious surface features in the five-county Bay Area were first delineated and classified using sub-meter aerial imagery from the National Agriculture Imagery Program (NAIP). We then compared Landsat ST data acquired on (or near) the same dates from the three previous years (2017–2019) for all these contiguous impervious surfaces. Results showed that all the large parking lots, roadway corridors, and industrial/commercial rooftops across the entire Bay Area urban landscape were detected by Landsat ST time series as significantly cooler (by 5\degree C to 8\degree C) during the unprecedented Shelter-in-Place period of mid-March to late-May of 2020, compared to same months of the three previous years. The explanation for this region-wide cooling pattern in 2020 that was best supported by both remote sensing and ground-based data sets was that relatively low atmospheric aerosol lower (PM$_{2.5}$) concentrations from mid-March to late May of 2020 resulted in weaker temperature inversions over the Bay Area, higher diurnal surface mixing, and lowered urban surface temperatures, compared to the three previous years.

1. Introduction

In response to the worsening COVID-19 pandemic, the San Francisco Bay Area Shelter-in-Place (SiP) directive was issued on March 17, 2020 for San Francisco, Santa Clara, San Mateo, Marin, Contra Costa and Alameda counties, affecting a combined population of more than 6.7 million persons. There are two main mechanisms through which SiP could affect the environment in the Bay Area primarily as a consequence of lower vehicle traffic: (1) changes in air quality from lower vehicle emissions and (2) alteration of the reflective properties and temperatures of roads and parking lot surfaces from the absence of densely grouped vehicles.

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Vehicle traffic over most Bay Area’s bridges during rush hours declined by 70% at the start of the SiP period, according to the Bay Area Toll Authority (2020). A month later, the Environmental Protection Agency and other air quality monitoring networks (Lukanov and Smith, 2020) reported that fine particulate matter (PM$_{2.5}$) and nitrogen dioxide (NO$_2$) air pollution levels in the Bay Area had dropped by more than 30%. These were the most readily documented environmental impacts of the COVID-19 SiP directive in the Bay Area, but there could have been other related changes in urban ecosystem and the atmosphere that were more difficult to detect.

Aerosols, commonly measured as atmospheric PM$_{2.5}$ concentrations, reflect and absorb solar radiation and can reduce the amount of shortwave radiation reaching the ground (Yu et al., 2002; Lai, 2016). On the coolest days of the year, the aerosol difference between urban and rural areas is generally relatively low and the aerosol radiative effect normally heats the atmosphere and reduces the solar radiation reaching the surfaces of the urban and rural areas by a similar magnitude (Han et al., 2020). In warmer seasons, airflow intensity and temperature gradients related to aerosol levels decrease over cities, weakening the heat exchange in both vertical and horizontal directions and raising surface temperatures more in urban areas than in nearby rural areas. On high particulate and carbon monoxide days during late fall and winter months in the Bay Area, relatively calm conditions are associated with development of a strong surface-based air temperature inversion (BAAQMD, 1998) and a pronounced Bay Area urban heat island effect is observed.

Another indicator of urban surface heating is tropospheric ozone, a short-lived pollutant with an atmospheric lifetime of hours to weeks. Ozone in the urban atmosphere is a secondary gas formed by the interaction of solar radiation with hydrocarbons (including methane) and nitrogen oxides (NO$_x$), which are emitted primarily by vehicle emissions and fossil fuel power plants. Urban warming has been closely tied to higher ozone concentrations, as heating accelerates these chemical reactions in the atmosphere (Clark and Karl, 1982). Kar et al. (2010) reported that urban area footprints in California could be detected from satellite observations as enhanced ozone plumes with general similarity to corresponding NO$_2$ tropospheric column concentrations.

Diurnal cycles affect urban heating patterns, which can occur during day- or night-time periods, and their magnitude is commonly controlled by synoptic weather patterns such as wind and humidity (Oke et al., 1991). Urban surface heating often peaks during clear, calm evenings and is typically a result of delayed cooling of the city compared to surrounding rural areas (Barring et al., 1985). Previous studies have shown that water bodies reach their highest surface temperature during night-time hours of all the urban surfaces (Yang and Zhao, 2015; Syaffi et al., 2016), and therefore can act as a nocturnal heating source for a city. In a temperature study of Phoenix, Arizona, Lee et al. (2012) surmised that the heating of urban surfaces during the day-time hours set the peak daily temperature across the city, and this overheating was dissipated during the night-time hours in an exponential decay function provided that there was high convection motion over the urban surface. During the night, eddies can mix and transport relatively colder air in contact land surface upward, while also circulating relatively warmer air toward the surface from higher atmospheric layers (Iacobellis and Cayan, 2013).

Day-time surface heating patterns across urban areas have been mapped from satellite-derived surface temperature (ST) retrieved from thermal infrared (TIR) sensors, such as Landsat 8 Enhanced Thematic Mapper Plus (ETM+) (Rayan et al., 2016; Malakar et al., 2018; Xiao et al., 2018). In different regions of California, ST data from satellites have been used to understand the relationships between diurnal variations of air temperature and soil surface TIR emission properties (Potter and Coppernoll-Houston, 2018 and 2019), and by other investigators to test data fusion algorithms for producing moderate-resolution ST data by merging daily MODIS and periodic Landsat TM datasets (Weng et al., 2014).

This study used Landsat TIR data to generate new quantitative estimates of changes in total urban activities that changed during the COVID-19 SiP period of 2020 in the five main San Francisco Bay Area counties. The Landsat satellite’s TIR sensor imagery for ST was quantified for all the large (> 5000 m$^2$) urban features in the Bay Area that have flat (impervious) surfaces, such as parking lots, wide roadway corridors, and commercial rooftops. It has been reported that imperious surfaces can have a measurable warming effect on urban temperature conditions (Xiao et al., 2007; Weng, 2012). In a study of Phoenix Arizona, Hoehne et al. (2020) found that sensible heat flux from urban surfaces was comprised of 67% from roadways, 29% from parking lots, and 3.9% vehicles, and that concrete and asphalt pavements emit 15% and 37% more sensible heat compared to the bare ground, respectively. However, the influence of the impervious composition and geography on surface heating and cooling has rarely been quantified across large metropolitan areas (Nie and Xu, 2015).

This combination of satellite data and ground-based monitoring records for PM$_{2.5}$ and NO$_2$ air pollution levels were used test the hypothesis that the absence of worker activities during the 2020 SiP period detectably altered the infrared heat flux from parking lots, highways, and large industrial/commercial building rooftops. One hypothesis is that such changes were caused mainly by variations in the surface reflective properties (including brightness) in these different classes of non-vegetated urban features during the COVID-19 SiP period. The absence of most vehicles on major roadways and in commercial parking lots during the SiP could have altered the surface reflective properties and the daytime ST of these imperious surfaces, whereas large rooftop surface reflective properties would not have changed during the SiP period due to absence of vehicular traffic. The capability to compare the time series of satellite ST for a large sample of each of these differentiated imperious feature classes will enable the testing of this hypothesis, and then facilitate further analysis of the effects of changing air pollution levels in 2020.

The outcome of this analysis produced an assessment of the differences in ST from all differentiated urban work-related feature classes, which, when aggregated over sub-regions, can serve as a key quantitative indicator of how COVID-19 has altered the Bay Area environmental footprint. The location-specific differences in ST for large urban (imperious surface) heating between 2020 and previous years may be used to inform our understanding of many other related environmental changes, including urban greenhouse gas and other air pollutant emissions. The methods tested and refined in the Bay Area for ST changes could also be extended to other major urban areas of the country where extended lock-downs during COVID-19 outbreaks have been linked to notable environmental changes.
2. Methods

2.1. Segmentation and classification of urban land cover features

All the large potential “dark object” (non-vegetated) urban features in the five Bay Area counties were delineated and classified using sub-meter (60-cm pixel size) imagery from the most recent visible-near infrared (RGB-NIR) aerial data collections (source: 2018 National Agriculture Imagery Program–NAIP; www.fsa.usda.gov). An object-based classification of this NAIP imagery was applied using the segmentation and feature extraction tool in the ENVI 5.5 software package. This Object-Based Image Analysis (OBIA) was a unsupervised classification technique that generates polygon objects and their key attributes such as compactness, elongation, and 4-band spectral means and textures, and has been used successfully for high-resolution urban feature mapping in the past (Zhou and Wang, 2007; Hossain and Chen, 2019).

Based on visual inspection of the underlying true-color composite NAIP imagery, and also based on local site visits to airports and shopping center parking lots during the May 2020, the unique object attributes for approximately 1400 large (each greater than 5000 m² or 1.25 acres in contiguous area) were manually defined and classified from the OBIA segmented feature results. The four impervious surface classes created from this visual inspection method were (1) office parking lots, (2) retail parking lots, (3) roadway corridors, and (4) industrial/commercial rooftops. For comparison of ST variations to these asphalt and concrete covered surfaces, 140 large water body polygons in the San Francisco Bay ponds of northern Santa Clara County were also identified and classified.

2.2. Landsat ST images

The thermal infrared sensor (TIRS) is an instrument on the Landsat 8 satellite that collects images within the thermal range (10–12.5 μm; USGS, 2018). Landsat image data are retrieved every 16 days, with each scene being 170 km nort–south by 183 km east–west. The TIRS has a pixel size of 100 m. At the end of 2017 re-gridded to 30 m to match Landsat multi-spectral bands.

Landsat Level-2 ST products (in units of Kelvin) have been generated from Landsat Analysis Ready Data (ARD) collection for Top of Atmosphere (TOA) reflectance and Top of Atmosphere Brightness Temperature (TOA BT) bands, together with Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Emissivity Database (GED) data, and ASTER Normalized Difference Vegetation Index (NDVI) image data (USGS, 2018). Landsat ARD products were generated from the highest quality data in the Landsat Level 1 Collection (Landsat 4–7 Tier 1 (T1) and Landsat 8 T1 and Tier 2 (T2) scenes). The Emissivity Standard Deviation band has known-out-of-bound values, which originate from the spurious retrievals of emissivity >1.0; this typically occurs when there is undetected cloud in the ASTER Temperature Emissivity Separation (TES) algorithm (Cook et al., 2014).

For the period starting on February 1, 2017 and ending July 31, 2020, a total of 102 cloud-free Landsat ST images covering the five Bay Area counties were identified and downloaded from the USGS Earth Explorer online portal at https://earthexplorer.usgs.gov/. The flyover time for Landsat in the Bay Area was around 11:45 AM every 16-days.

2.3. Statistical analysis

Each yearly Landsat ST time series was interpolated by linear regression (using the R interpolate.linear function; Hijmans and van Etten, 2012) for each Landsat pixel location into a standard weekly (7-day) interval for the months of February to July for each of the years 2017 to 2020. The zonal tabulation and statistics in R (using the ‘extract’ function; Hijmans and van Etten, 2012) were used next to calculate Landsat weekly ST means and standard deviations of all raster cell values falling within each OBIA polygon for impervious surface features. Standard errors (SE) of the mean ST for classes of urban surface features were next computed, and a significant difference (at $p < 0.05$; 95% confidence level) between feature class ST was resolved whenever two mean values were separated by two SE of their respective class mean values (McDonald, 2014).

Non-linear time series analysis of ST change over the weeks in a year was carried out with second-order polynomial regression. In polynomial regression, different powers of the $X$ (week of the year, in this case) variable were used to test whether they increase the $R^2$ significantly over simple linear regression (McDonald, 2014). At a weekly interval number of 25 for every year, any Pearson’s $R^2$ greater than 0.5 was considered significant at $p < 0.05$ (95% confidence level) for a two-tailed test (Kenney and Keeping, 1962).

2.4. Weather station records

To address uncertainty in the anticipated results, specifically in the comparison of satellite ST observations during the 2020 SIP period to any other year during the same week of the year, it was important to control for natural temporal variability, specifically with respect to localized meteorology. Therefore, we followed the methods published by Potter and Coppernoll-Houston (2018) to evaluate all major variations in Landsat ST in terms of daily average solar irradiance, minimum and maximum surface air temperature, and precipitation (previous 24 h) using ground-based measurements from the California Irrigation Management Information System (CIMIS) and the National Weather Service (NWS) networks of public weather station datasets operating in the five-county Bay Area.

Atmospheric sounding (profiling) records of the daily column air temperature at the noontime period (12:00 PM) from the NWS radiosonde at the Oakland International Airport were acquired from the University of Wyoming Department of Atmospheric Sciences (available online at http://weather.uwyo.edu/upperair/sounding.html) for the first weeks of April, May and June in 2019 and 2020. Radiosonde data collected at airports around the globe are generally reported at the 22 mandatory levels which include at least 10 pressure (p) levels greater than 200 hPa (Zhang et al., 2019).
2.5. Air quality data

Daily average PM$_{2.5}$ concentration data sets for Bay Area sampling locations were obtained from the Environmental Protection Agency (EPA) Air Quality System (AQS) online database. The EPA guidebook to AQS sensors lists photometric (light scattering) sensors to measure PM$_{2.5}$, optimized for the measurement of the respirable fraction of airborne dust, smoke, fumes, and mists in industrial and other indoor and outdoor environments.

Monthly averages for tropospheric NO$_2$ column density for the Bay Area (gridded at 13 × 24 km pixel resolution) were obtained from the Ozone Monitoring Instrument (OMI) spectrometer aboard NASA’s Aura satellite (Krotkov et al., 2019; Bauwens et al., 2020). The OMI NO$_2$ image data (version 4) available from the NASA Goddard Earth Sciences Data and Information Services Center include: (1) use of a new daily and OMI field of view specific geometry dependent surface Lambertian Equivalent Reflectivity (GLER) product in both NO$_2$ and cloud retrievals and (2) use of improved cloud parameters (effective cloud fraction and cloud optical centroid pressure) from a new cloud algorithm (OMCDO2N).

2.6. In situ measurements of surface temperatures

Several south Bay Area locations were visited during late May of 2020 to make measurements of surface temperatures across large vacant parking lots near airports and (closed) indoor shopping centers. On the day and during the hour (11 AM to 12 PM) of a 2020 Landsat flyover (May 21, 2020), data on thermal emission temperatures were recorded from a hand-held FLIR Model TG267 spot TIR instrument for paved impervious surfaces and from the painted and glass surfaces of cars and trucks parked on nearby streets. Transects across seven large vacant lot locations were walked, taking a surface temperature measurement every five meters.

3. Results

3.1. Urban feature class mapping

The OBIA of 2018 NAIP 4-band imagery for all large impervious surfaces (> 5000 m$^2$ in contiguous area) in the five county Bay Area resulted in 1377 contiguous urban features with an average area coverage of 6184 m$^2$ or 1.5 acres (Fig. 1). Each of these polygons were assigned by visual inspection of digital street maps and the underlying NAIP true-color imagery into the following surface classes: 307 office parking lots, 162 retail parking lots, 427 roadway corridors, and 191 industrial/commercial rooftops. The roadway corridors included elongated sections of all the major highway surfaces in the Bay Area (US-101, I-880, I-680, I-580, and CA-85), in addition to runways of the international airports in San Francisco, Oakland, and San Jose. It was visually verified for each of these large

Fig. 1. Map of the five-county San Francisco Bay Area showing the locations (in blue outlines) of the largest impervious surface features, classified as either parking lots, roadway corridors, or industrial/commercial rooftops, derived from OBIA of 2018 NAIP 4-band imagery. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
impervious surface features that green vegetation cover was minimal in each of these surface feature areas.

### 3.2. Air pollution changes for the Bay Area

The tropospheric NO\(_2\) column concentration data from the Aura OMI averaged over all large Bay Area urban surface features showed that air pollution levels were consistently 25–35\% lower during the 2020 SiP period of March to May than in any of the three previous years (Fig. 2). The variance levels between the urban feature samples for average NO\(_2\) column concentrations, calculated for all the months of all the years (2017 to 2020), were consistently low with two SE of the mean concentration ranging from 0.03 to 0.15 \(\times 10^{15}\) molecules cm\(^{-2}\), such that these differences in NO\(_2\) density between the 2020 SiP period and all the other years were significant at a confidence level of \(p < 0.05\). The period of March to May in 2019 showed the highest average NO\(_2\) concentrations in the Bay Area of all four years analyzed, and when mapped across the region, the difference between the 2020 SiP period and 2019 was most apparent in Alameda and San Mateo counties near the San Francisco Bay, and also in northern Santa Clara County and downtown San Jose (Fig. 3).

Daily average PM\(_{2.5}\) concentrations from three Bay Area urban sampling locations showed that the 2020 SiP period had consistently lower PM\(_{2.5}\) levels than in any of the three previous years (Fig. 4). Both average daily and/or maximum (single-day) PM\(_{2.5}\) concentrations were lower during the period from late March through May 2020 than in the other three years (Table 1) at these EPA sampling locations. Although there was high day-to-day variations in PM\(_{2.5}\) concentrations in all years, likely due to synoptic weather variations such as shifts in wind speed and direction, 2020 showed the lowest standard deviation of any of the four years and the lowest single-day PM\(_{2.5}\) concentration, never exceeding 13.2 \(\mu\text{g m}^{-3}\). The differences in daily PM\(_{2.5}\) concentration between 2020 and the previous three years was greatest at the Jackson Street sampling location just north of downtown San Jose, at 40\% lower in 2020 than in either 2018 or 2019. Whereas the SiP period of 2020 showed notably lower for PM\(_{2.5}\) concentrations at the Jackson Street and 99th Avenue locations than in the previous three years, the Knox Avenue location showed readings in 2020 similar to 2019 and lower than 2017 and 2018 PM\(_{2.5}\) concentrations.

### 3.3. Landsat ST changes for urban feature classes

Time series comparisons of Landsat ST image data from 2017 to 2020 (February to July of each year) showed that all the large parking lots, roadway corridors, and industrial/commercial rooftops across the Bay Area were detected as significantly \((p < 0.05)\) cooler (by between 8\(^\circ\) and 10\(^\circ\) \(\text{C}\)) during the SiP period of mid-March to late-May of 2020 compared to any of the three previous years (Fig. 5). For all the impervious surface classes, the weeks of 2020 when the lowest ST were observed, relative to the previous three years ST averages, were the last week of March and the second week of June. Industrial/commercial rooftops in the Bay Area were found to be considerably warmer, by around 5\(^\circ\) \(\text{C}\), than the ST of parking lots and roadways during all four years.

A close-up example of the contrast in Landsat ST maps for early April of two years (2018 and 2020) illustrated the difference in surface cooling measured during the SiP period of 2020 (Fig. 6). This area centered on the Great Mall shopping complex in Milpitas included several urban creeks and golf courses, as a contrast of vegetated features to the impervious surfaces that dominate this portion of northern Santa Clara County. The rooftops of dense industrial/commercial building complexes corresponded to nearly all the hotspots (> 44\(^\circ\) \(\text{C}\)) in the April 2018 map, which were then measured in April 2020 at closer to 35\(^\circ\) \(\text{C}\). Landsat ST for the paved parking lots surrounding these buildings was measured at around 38\(^\circ\) \(\text{C}\) in the April 2018 map and at closer to 34\(^\circ\) \(\text{C}\) in April 2020. Landsat ST for creek corridors and golf courses was measured at around 25\(^\circ\) \(\text{C}\) in the April 2018 map and at closer to 21\(^\circ\) \(\text{C}\) in April 2020.

The majority of large impervious surface features in the Bay Area were detected with Landsat ST values cooler than 40\(^\circ\) \(\text{C}\) (104\(^\circ\) \(\text{F}\)) during the early-June period of 2020, in contrast to the same time period of the years 2017–2019, when the majority of these same

![Fig. 2. Tropospheric NO\(_2\) column concentration data from Aura OMI averaged over all large Bay Area impervious surface features (shown in Fig. 1) for the months of February to July for the years 2017 to 2020.](image-url)
Impervious surface features were detected with Landsat ST values warmer than 42.5°C (108°F). There were fewer than 15 large impervious surface features in the Bay Area that were detected with average Landsat ST values in excess of 47°C (115°F) during the SiP period of 2020. These included three large parking lots located in Santa Clara and Alameda counties, and ten industrial/commercial rooftops mainly located in northern Santa Clara County.

The average ST levels of all of the impervious surface classes were continuously warmer (by between 15°C and 20°C) than any of the large South Bay ponds analyzed for ST changes. However, even these pond surfaces were relatively cooler (by as much as 10°C) throughout most of the 2020 SiP period, compared to the three previous years.

The correlation of individual impervious feature ST (from any of the 2020 Landsat image dates shown in Fig. 5) to the average brightness of the impervious surface derived from the recent NAIP red band reflectance was not significant at ($p < 0.05$). Nor was the Landsat ST of individual impervious features correlated significantly to the feature’s total area coverage (in m$^2$), nor to the degree of elongation of the individual surface features, despite the finding that roadways features were normally 10 times more elongated than most parking lot or rooftop features.
3.4. In situ measurements of surface temperatures

Measurements of surface temperatures using a portable TIR sensor across large vacant parking lots near airports and indoor shopping centers at the time of a 2020 Landsat flyover (May 21) were compared to the Landsat ST point values extracted for that same day and time. Results showed no difference \((p < 0.05)\) in the average surface temperature (estimated at 42-43\(^\circ\)C) between the Landsat ST and in situ ST \((N = 75\) sampling points). The variance among in situ ST measurements was higher than among the 30-m pixel ST values from Landsat \((2\ SE = 1.4\ ^{\circ}\text{C} \text{ versus} 1.0\ ^{\circ}\text{C}, \text{respectively})\), which was expected due to many variations in the brightness of the parking lot markings and asphalt differences at the scale of a few meters on the ground.

Comparison of in situ parking lot surface temperatures to that of vehicles parked on nearby streets showed that the highly reflective surfaces of cars and trucks \((N = 35\) vehicle samples) resulted in thermal emission temperatures 9.3\(^{\circ}\text{C}\) lower on average than the asphalt surfaces of parking lots. Nonetheless, the variance among in situ measurements for the cooler vehicle surfaces was higher than for the nearby asphalt surfaces \((2\ SE = 3.1\ ^{\circ}\text{C} \text{ versus} 1.4\ ^{\circ}\text{C}, \text{respectively})\).

### Table 1

Summary of PM\(_{2.5}\) concentration daily data from three Bay Area urban sampling locations shown in Fig. 4 (EPA, 2020). All units are in \(\mu\text{g m}^{-3}\).

| Location                  | 2020     | 2019     | 2018     | 2017     |
|---------------------------|----------|----------|----------|----------|
| San Jose – Jackson Street |          |          |          |          |
| Average (Apr-May)         | 4.87     | 8.76     | 8.21     | 6.59     |
| Maximum                   | 10.10    | 16.80    | 18.50    | 14.70    |
| Standard deviation        | 2.29     | 2.88     | 3.80     | 2.59     |
| Two SE                    | 0.60     | 0.76     | 1.00     | 0.81     |
| San Jose – Knox Avenue    |          |          |          |          |
| Average (Apr-May)         | 6.24     | 5.38     | 8.30     | 7.18     |
| Maximum                   | 11.50    | 13.10    | 17.80    | 13.70    |
| Standard deviation        | 2.03     | 3.17     | 3.44     | 2.56     |
| Two SE                    | 0.51     | 0.80     | 0.87     | 0.65     |
| Oakland – 99th Avenue     |          |          |          |          |
| Average (Apr-May)         | 6.12     | 6.16     | 7.93     | 6.57     |
| Maximum                   | 13.20    | 13.90    | 18.80    | 16.80    |
| Standard deviation        | 2.71     | 3.48     | 3.90     | 3.10     |
| Two SE                    | 0.70     | 0.90     | 1.01     | 0.80     |

Fig. 5. Landsat ST values averaged over all large Bay Area impervious surface features and South Bay ponds (shown in Fig. 1) for the months of February to July for the years 2017 to 2020.
3.5. Weather patterns in the Bay Area 2017 to 2020

Three CIMIS weather stations operating in Bay Area counties (locations shown in Fig. 7) provided precipitation and solar radiation flux data for 2017 to 2020 to evaluate any anomalies and natural variations in local weather conditions that may have occurred during the 2020 Sip period. All three CIMIS stations reported the same patterns, namely that the 2020 Sip period was not an extreme weather season, but instead was somewhat drier and sunnier than in any of the years or 2017 to 2019. Total seasonal precipitation during the 2020 Sip period averaged 162 mm at these CIMIS stations, compared to a wide range of total precipitation varying between 152 and 520 mm for the same seasons in 2017 to 2019.

Average daily solar radiation flux during the 2020 Sip period was slightly higher (at around $240 \pm 3 \text{ W m}^{-2}$) compared to the range of average daily solar radiation flux varying between 220 and 230 W m$^{-2}$ during the same seasons in 2017 to 2019 (Fig. 8). These CIMIS records also confirmed that there was no detectable rainfall in the Bay Area either on or just before any of the dates of Landsat ST image acquisitions over the period from 2017 to 2020 that could have altered surface evaporative cooling.

The National Weather Service station location at San Jose International Airport which is surrounded by numerous large impervious surfaces was selected to illustrate an urbanized diurnal temperature range (DTR) over the past four years (Fig. 9). This record of daily maximum minus minimum air temperature showed that the period of March to May of 2020 had the highest average DTR of the four years at 11.5°C, with 2017 to 2019 average DTRs for this same period at 11.3, 10.9, and 10.6°C, respectively. The higher DTR in late May and for much of June in 2020 largely accounted for this difference from the previous years’ periods.

Air temperature soundings (shown from the surface to 5000 m height; Fig. 10) measured by the NWS radiosonde at the Oakland International Airport showed that, in both early April and early June, warming temperature profiles to around 2500 m height were markedly lower in 2020 than in 2019 by between 5°C and 15°C. The air temperature profiles from both of these monthly periods also showed a strong inversion pattern in 2019 with a relatively warm air layer between 600 and 1200 m heights developed over a relatively cooler air layer measured below 600 m height, whereas this inversion pattern was either notably weaker or was non-existent during the entire 2020 Sip period. In early May, the difference in air temperature profiles between 2020 and 2019 was indistinguishable, which was consistent with the minor differences in ST in the Bay Area detected by Landsat between 2020 and the years 2017 to 2019 for a short period in early May (Fig. 5).
4. Discussion

The major finding of this study was that all the large parking lots, roadway corridors, and industrial/commercial rooftops across the entire Bay Area urban landscape were detected by Landsat ST time series as significantly cooler (by 5° to 8° C) during the unprecedented COVID-19 SiP period of mid-March to late-May of 2020, compared to same months of the three previous years. Moreover, in situ measurements of parking lot surface temperatures were made to validate the accuracy of Landast ST data from a satellite flyover date (in late May) of the 2020 SiP period. Large parking lots and roadways were somewhat cooler than industrial/commercial rooftops.
during all years. Although each of the impervious surface classes were always warmer by between 15° and 20° C than the large South Bay ponds, even these same pond surfaces were relatively cooler by as much as 10° C in the 2020 SiP period than in previous three years.

From the outset, this study was facilitated by selecting only the largest contiguous urban features in the Bay Area using high-resolution aerial imagery to precisely delineate those feature class boundaries and sizes. Segmentation, verification, and classification of nearly 1400 impervious surface features for a heat flux study of an urbanized landscape the size of the five-county Bay Area has never been reported before. This polygon layer enabled the consistent comparison of Landast ST values from week-to-week and year-to-year over the same large surface classes of relatively consistent coloration and brightness. The data base of these surface attributes resulted from OBIA polygon separation using 4-band NAIP imagery at 60-cm pixel resolution, and it provided a relatively high N sample number in each urban feature class to use in the statistical analysis.

Based on in situ surface temperature measurements made in May of 2020, and consistent with the findings of Hoehne et al. (2020), it was hypothesized that the densely clustered presence in 2017, 2018, and 2019 of highly reflective vehicles would have notably cooled

Fig. 9. Diurnal temperature range records from the weather station at the San Jose International Airport for the years 2017 to 2020.

Fig. 10. Comparison of air temperature soundings measured by the NWS radiosonde at the Oakland International Airport in 2019 and 2020 (Available online at http://weather.uwyo.edu/upperair/sounding.html).
most dark asphalt-covered impervious surfaces, such as wide roadways and large open-air parking lots, and absence of most of these vehicles during the 2020 SiP period would have raised the ST of those same impervious surface features. Instead, it was necessary to reject this hypothesis that changes during the COVID-19 SiP period in the heat flux from parking lots, highways, and large industrial/commercial building rooftops could be attributed mainly to variations in the surface reflective properties in these different classes of non-vegetated urban features.

Seeking alternative explanations for the 2020 urban surface cooling, it should be noted that the Santa Clara Valley area surrounding the cities of San Jose and Milpitas has the largest complex of mobile pollution sources in the Bay Area, making it a major source of carbon monoxide, particulate matter, and photochemical air pollution (BAAQMD, 1998). Photochemical precursors from San Francisco, San Mateo, and Alameda counties can be carried along by the prevailing winds from the northwest into the Santa Clara Valley, also making it a major ozone receptor area. On calm days during relatively cool late fall and winter months, elevated levels of PM$_{2.5}$ and carbon monoxide prevail, and strong air temperature inversions over the Santa Clara Valley often develop (BAAQMD, 1998). Examples of this strong inversion pattern were measured by the NWS radiosonde at the Oakland International Airport in April and June of 2019, but not during the SiP period of 2020.

Generally speaking, during daytime hours, the land surface retains heat produced by incident solar radiation and warms the air closest to the surface. As the air temperature near the surface increases, the air becomes less dense and rises, cooling gradually as it gains altitude. As long as the air closest to the surface remains slightly warmer than the air above it, this convective vertical mixing process will continue. However, when the convection process is reversed or inhibited and the air closest to the surface becomes cooler than the air above it, a temperature inversion forms (Li et al., 2019). The higher, warmer air layer becomes a barrier that prevents (polluted) air from escaping and limits the amount of relatively clean air that mixes downward again toward the land surface.

During winter periods in the Bay Area when high pressure systems over the coastal Pacific becomes dominant, strong surface-based air temperature inversions develop and the air pollution potential increases. These periods are characterized by winds that flow out of the Central Valley into the Bay Area and often include ground fog (BAAQMD, 1998). Colder season surface inversions in the Bay Area are formed due to diurnal cycles of solar radiation flux, as air is cooled in contact with the Earth’s cooling surface during night-time hours.

In studies using satellite cloud albedo data and hourly surface observations of air temperature at coastal airports that included Oakland in the Bay Area, Jacobellis and Cayan (2013) reported that strong temperature inversions and lower surface mixing were associated with above-normal 500 mb heights and resulted in higher land surface temperatures under stronger winds in the Bay Area. In contrast, weak temperature inversions and higher surface mixing were associated with below-normal 500 mb heights and resulted in lowered land surface temperatures under calmer winds.

This leads to the next question of how could the substantially lower PM$_{2.5}$ levels in the Bay Area during the COVID-19 SiP period have changed the temperature inversion levels in 2020 compared to the three previous years with no SiP periods? Previously published studies from elsewhere have intimated that lower aerosol concentrations (i.e., in 2020) would have resulted in weaker temperature inversions, higher surface mixing, and lower land surface temperatures during the unique COVID-19 SiP period. In support of this conclusion, Li et al. (2019) reported that higher aerosol concentrations were associated with the regular development of strong temperature inversions over central Oklahoma. Trinh et al. (2018) showed that concentrations of atmospheric NO$_2$, PM$_{10}$ and PM$_{2.5}$ all increased as temperature inversions strengthened over Hanoi City, Vietnam.

In the industrial areas of Richmond, California in the northern Bay Area, Lukanov and Smith (2020) reported that median daily PM$_{2.5}$ concentrations dropped from 6.7 µg m$^{-3}$ prior to the 2020 SiP period to 3.9 µg m$^{-3}$ during mid-April 2020, representing a 42% decrease in fine particulate levels. Additionally, this monitoring network measured the overall distribution of PM$_{2.5}$ as narrowed during SiP, with its upper and lower ends shifting downward, and NO$_2$ concentrations following a similar pattern. This report went on to document that areas with the greatest decreases in PM$_{2.5}$ and NO$_2$ were located near highways and railroad rights-of-way, suggesting that decreased traffic was as the likely cause of the observed decreases in air pollution during the 2020 SiP period. The greatest increases in atmospheric ozone concentrations occurred at locations adjacent to some of Richmond’s most industrialized areas, indicating that there was continued emissions of ozone precursors from continuously operating refinery and factory sites even during the 2020 SiP period.

These data from Richmond support the supposition that large outdoor parking lot areas and wide roadway corridors in the Bay Area experienced the greatest reduction in localized PM$_{2.5}$ concentrations during the 2020 SiP period, compared to large commercial rooftops, the South Bay salt ponds, and any vegetated (non-impervious) surfaces. This would help explain the comparatively stronger cooling patterns for parking lots and roadway surfaces in 2020 compared to the previous three years during the SiP period.

It should be noted that the Landsat data upon which this study is based were all acquired near noon-time of each day, which limited the capability to speculate on how these urban surface heating patterns could have changed in the later afternoon and night-time hours of the SiP 2020 period. Similarly, since the SiP did not extend into the hottest summer months of 2020, it is not feasible to speculate on whether the strong surface cooling effects would have persisted as well, due the vastly different solar radiation fluxes in the months of July to October, compared to March to May periods of any year.

5. Conclusions

Despite differences between the surface temperature of vacant parking lot surfaces and automobile surfaces measured in May 2020 in Santa Clara County, the general absence of vehicles on all roadways and around commercial parking areas during the 2020 SiP period, which had the potential to increase the ST of impervious surfaces by the higher reflectance of vehicle surfaces, was not strong enough to compensate for the effects of localized reductions in PM$_{2.5}$ concentrations and a regularly weaker surface-based temperature
inversion. Consistent with the findings of Lee et al. (2012), it is plausible instead that the heating of urban surfaces in the Bay Area during day-time hours of the 2020 SIP period was more rapidly dissipated during the night-time hours than in previous years, owning largely to lower PM$_{2.5}$ levels in 2020, higher diurnal variations in solar radiation fluxes, a consistently weaker temperature inversion, and relatively high convection over the urban landscape. The relatively weaker inversion pattern in the Bay Area throughout the 2020 SIP period (compared to 2019) was confirmed by sounding temperature data measured by the NWS radiosonde at the Oakland International Airport.

Disclosure statement

The authors declare no competing interests.

Declarations of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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