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Article

Using satellite surface temperature data to monitor urban heat island

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SUMMARY

Exposure to heat is a growing concern nationwide. Temperatures can be elevated in cities compared to surrounding rural areas, referred to as an "urban heat island" (UHI) effect, which is intensified during heat waves. The lack of dense networks of air temperature measurements results in few studies on urban heat. Now, a vast amount of high spatial and temporal satellite data on land surface temperature is available. We identified satellite datasets with the longest surface temperature records but different spatial and temporal resolutions: Landsat (1985-current, biweekly at 60 m and 100 m spatial resolution) and the Moderate Resolution Imaging Spectroradiometer (MODIS) data from the Terra and Aqua satellites (2000-current, daily at 1 km spatial resolution). We investigated how satellites with different spatial and temporal resolutions detect UHI effects differently. We hypothesized that 1) a dataset's spatial resolution impacts the precision of detected UHIs spatially, since high spatial resolution Landsat data better captures spatial variability in temperature, and 2) daily surface temperature data can detect temporal patterns of UHIs and heatwave frequencies. We analyzed Landsat and MODIS satellite data in the Washington, D.C. and Baltimore region. We found that Landsat describes higher spatial variability of the UHI effect than MODIS data. However, MODIS data shows more consistent seasonal surface temperature patterns than Landsat when compared to in situ air temperature measurements. MODIS data was also able to consistently measure the frequency of heat waves. This study demonstrates the value of NASA satellite data for urban heat and climate change studies.

INTRODUCTION

Heat stress is a growing concern for urban populations due to the frequent occurrence of extreme heat (1). Climate change results in more intense, frequent, and longer-duration heat waves (2). Cities are particularly vulnerable to heat stress due to the impacts of heat waves and the urban heat island (UHI) effect, where urban cities have greatly elevated temperatures compared to surrounding rural land (3). Cities are much warmer than their surrounding rural landscapes, particularly during the summer (4). This is mainly caused by two factors: increased anthropogenic emissions from vehicles, air conditioners, industrial activity, and power plants (urban functions) compared to rural areas, and the change of vegetated surfaces to more heat-trapping materials such as buildings, streets, and urban materials (4). The UHI effect intensifies during heat waves, and the resulting high urban temperatures are unevenly distributed across urban populations (1). Clear evidence exists of the increased risk to people's health caused by intensifying temperatures, particularly for low-income communities, children, the elderly, the disabled, and racial/ethnic minorities: one study found a higher likelihood of death among residents in areas with less green space (1). By 2100, climate change could expose between half and three-quarters of the global population to dangerous climate conditions (2).

Mitigation of urban heat stress caused by heatwaves and the UHI effect requires a deep understanding of variations in temperature across communities and over time, and the contributing factors to these differences. The lack of dense networks of air temperature measurements results in few studies on urban heat and its association with anthropogenic factors and urban functions (3–7). Consistent and spatially comprehensive temperature data using in situ measurements requires significant time, money, and effort, and thus can only be obtained from weather stations. Only using ground sensors, such as sparse weather station temperature measurements, makes UHIs too difficult to identify and visualize, and biases can arise based on whether weather stations are close together or concentrated in urban areas. Satellite remote sensing datasets provide surface temperature maps at different spatial and temporal resolutions, with each satellite having unique strengths and weaknesses. For example, Landsat has been collecting global surface temperature data biweekly since 1982 at high spatial resolutions (60 m for Landsat 4,5,7 and 100 m for Landsat 8 and 9) (8). However, the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra and Aqua satellites provides daily global land surface temperature maps at 1 km spatial resolution from 2000 to the present (9). Satellite thermal infrared remote sensing offers a broad, simultaneous view of the urban heat environment, enabling a detailed assessment of urban hotspots and their connection to nearby natural areas (10).

Many studies have examined how the UHI effect relates to land cover, land use, and urban layout (11–14). However, few studies have used ground truth data collection to investigate differences in how satellite data with different spatial and temporal resolutions detect UHIs, which is important when deciding what satellite to use for investigating UHIs, heatwaves, and climate change, as well as how accurate each satellite's data is. This study aims to investigate how satellite data with different spatial and temporal resolutions detect UHI effects differently.

We selected satellites with the longest surface temperature records but different spatial and temporal resolutions: Landsat and Terra and Aqua MODIS. We focused on our study regions in Washington, D.C. and Baltimore, two big cities in the eastern U.S. We compared the spatial resolutions

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and land surface temperature maps measured by Landsat and MODIS. We also compared the accuracy of the satellite datasets compared to weather station air temperature data and their capability to detect the heatwave frequency. We hypothesized that 1) spatial resolution impacts the precision of UHI boundaries and that Landsat data is more spatially detailed, and 2) daily satellite-derived surface temperatures can detect the temporal patterns of UHI effects and heatwave frequencies. Our analysis showed that the Landsat surface temperature is quite accurate, with temperature differences from field samples ranging from 0.95 °C to 2.31 °C. Landsat surface temperature data has more spatial variability (larger standard deviation in the temperature values) than MODIS surface temperature data due to MODIS measuring the mean temperature over a larger pixel. However, even aggregated to MODIS's spatial resolution, the Landsat surface temperature dataset still had a larger spatial variability than that of MODIS. Our study confirmed our hypotheses because we found that high spatial resolution data, such as Landsat, have better precision and clarity of UHI boundaries than low spatial resolution data, such as MODIS. We also found that daily MODIS surface temperature can detect UHI and heatwave temporal patterns similar to those measured by weather stations.

RESULTS

To test our hypotheses, we first took ground samples to evaluate the accuracy of satellite observations, then compared the spatial resolutions of Landsat and MODIS-measured land surface temperature. Lastly, we compared the Landsat and MODIS land surface temperature data with weather station air temperature data.

Field Measurements and Comparison to Landsat Surface Temperature

In order to evaluate the accuracy of satellite-measured surface temperature, we extracted Landsat 8 or 9 surface temperature data in Washington D.C. and Baltimore region and geolocated Landsat 8 or 9 pixels (disaggregated 30 m from the original 100m spatial resolution data) on two parking lots at NASA Goddard Space Flight Center (GSFC), a grassland field, and a parking lot at Centennial High School (**Figure 1**). We then randomly sampled 15 surface temperatures using a handheld radiometer and compared satellite-measured and field-measured surface temperatures (**Table 1**). The temperature differences ranged from 0.95 °C to 2.31 °C.

Spatial Variability of Landsat and MODIS Surface Temerature Maps

To investigate the differences in surface temperature estimates by different satellites, we compared the Landsat land surface temperature maps with daily Terra MODIS surface temperatures (**Figure 2**). We compared the maximum land surface temperatures in each pixel from Landsat 8 at 30 m spatial resolution, the same data aggregated to 1 km spatial resolution, and the Terra MODIS measurements at 1 km spatial resolution in the Washington D.C. and Baltimore metropolitan region in 2022 (**Figure 2**). The Landsat 8 data at 30 m spatial resolution provides clear and precise UHI boundaries in the Washington D.C. and Baltimore metropolitan region in 2022. The hotspots include Baltimore City, Washington, D.C., and the region surrounding Dulles Airport. The aggregated 1 km Landsat 8 surface temperature provides similar spatial features to the 30 m Landsat surface temperature map. However, the 1 km MODIS land surface temperature data shows less spatial variability and has a lower average temperature than that of the 1 km Landsat surface temperature map. The maximum temperature in 2022 observed by MODIS is cooler than that observed by Landsat, even when the data is aggregated to the spatial resolution of MODIS.

Temporal Variability of MODIS and Landsat Land Surface Temperature (LST) and Comparision With Maximum Daily Air Temerature Data

To explore the temporal difference between Landsat and MODIS land surface temperatures, as well as their connection with the maximum daily air temperature, we extracted the mean Landsat and MODIS surface temperatures from the weather stations of three airports: Baltimore/Washington International (BWI, 39.17329°N, -76.68408°W), Dulles (38.93485°N, -77.44728°W), and Reagan (38.84721°N, -77.03454°W). A 1 km circular area centered at each weather station in each airport was drawn, and the average MODIS and Landsat

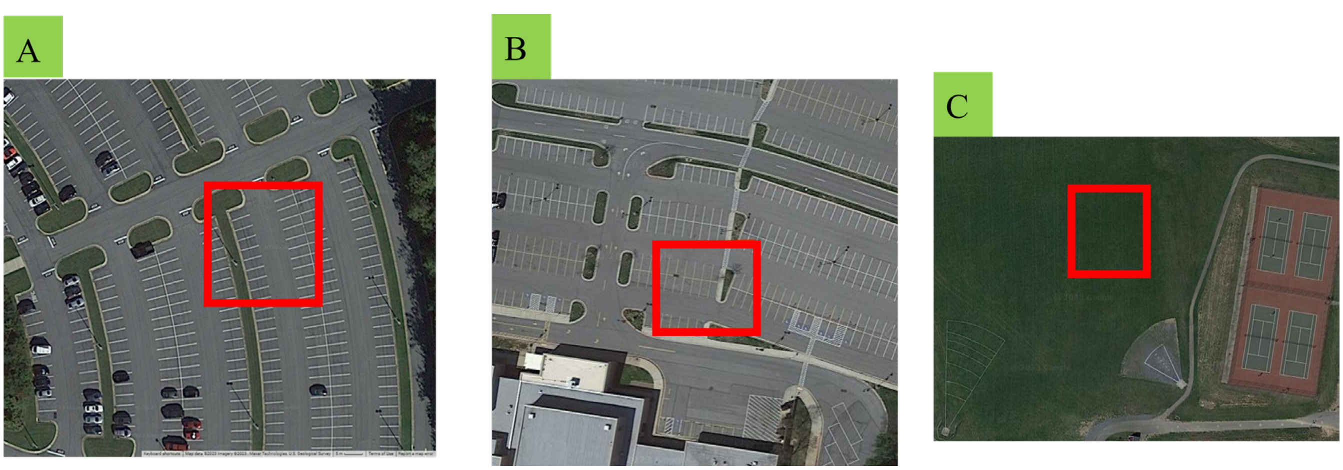

Figure 1: Aerial views of field sample sites. When verifying Landsat surface temperature measurements with an infrared thermometer, we chose (A) two parking lots in Goddard Space Flight Center (GSFC), (B) one parking lot in Centennial High School (CHS), and (C) one grass field in CHS. The Landsat pixel boundary is denoted with the red squares.

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Dates	Land Surface Type	Landsat 8 or 9 (°C)	Field Samples (°C)	Temperature Difference (°C)
7/14/2023	GSFC Parking Lot 1	45.38	44.43	0.95
7/14/2023	GSFC Parking Lot 2	44.08	45.60	1.52
7/30/2023	CHS Parking Lot	42.39	40.60	1.79
7/30/2023	CHS Grass Field	36.20	33.89	2.31

Table 1: Comparison of satellite-observed and field-sampled surface temperature. Date, land surface type, Landsat 8 or 9 surface temperature measurement, and field measurement of surface temperature for the four pixels analyzed, two of which were at GSFC parking lots, one at CHS parking lot, and one at a CHS grass field.

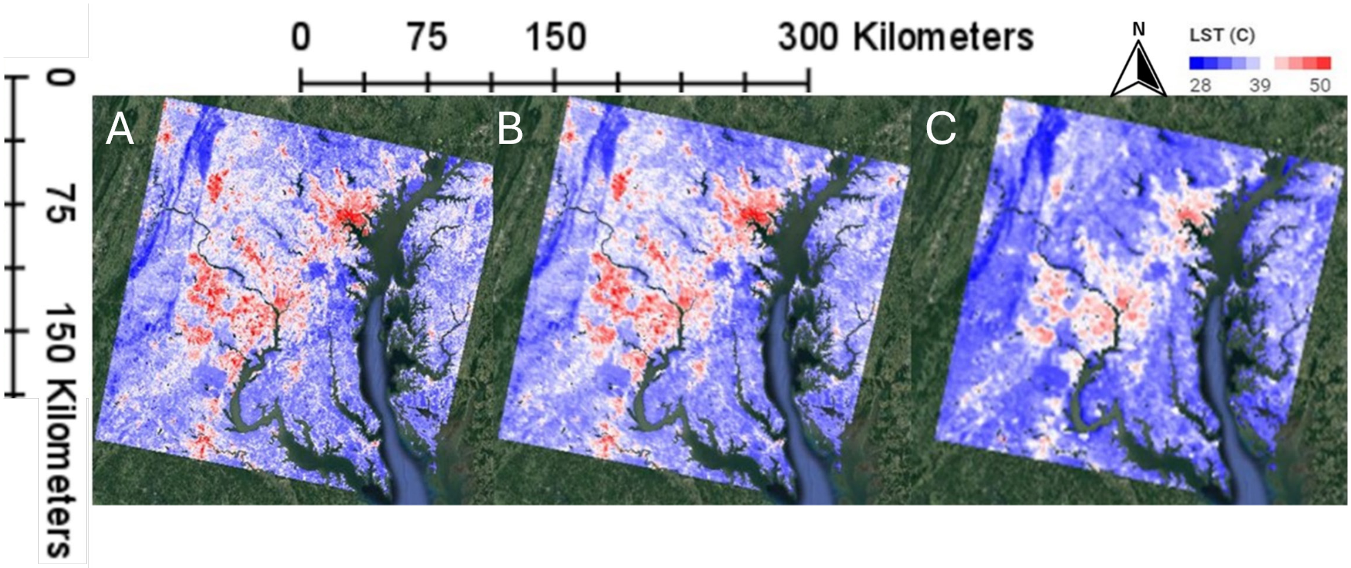

Figure 2: Comparison of Landsat and MODIS land surface temperature (LST) data. Three maps of the LST measurements in the Washington, D.C. to Baltimore region in the summer of 2022, with (A) the average of the two highest Landsat 8 measurements per pixel (100 m spatial resolution), (B) the same Landsat data aggregated to the MODIS 1 km resolution, and (C) the average of the two highest MODIS measurements per pixel (1 km spatial resolution). The mean temperature on this map was 36°C for Landsat and 34°C for MODIS.

LSTs in those regions were calculated and compared to the maximum daily air temperature measurements at each airport. A full year (2022) of data was used to observe all four seasons.

We compared the daily maximum air temperature observed at the three airports with Terra MODIS, Aqua MODIS, and Landsat 8 & 9 land surface temperature data collected in 2022 (**Figure 3**). We found a few features: First, MODIS has more observations than Landsat. Second, the surface temperature estimates from these three different satellites varied. Surface temperature from Aqua MODIS tends to be warmer than those measured by Terra MODIS. Aqua MODIS is an afternoon satellite, passing over each location at 1:30 pm local time, while Terra MODIS is a morning satellite, passing over a location around 10:30 am. Aqua MODIS should measure the maximum daily temperature. Landsat and Terra MODIS have similar acquisition times (10:30 am). However, Landsat tends to have higher temperatures than Terra MODIS. Lastly, the satellite-observed surface temperature data tend to reflect day-to-day increases and decreases but may slightly over- or under-estimate from the morning/afternoon measurements. However, in the summertime, the satellite-observed surface temperature tends to be higher than the air temperature. Satellite measurements are similar to the maximum daily air temperature in wintertime or cooler days. In general, we found Terra MODIS correlates with the daily maximum air temperature.

To analyze if the satellites can consistently measure heatwaves in a specific region, we calculated the number of days with air temperature or surface temperature greater than 32.2 °C (90 °F) for each satellite dataset, which we refer to as "hot days," and compared satellite and weather station hot days at three airports from years 2001-2023 (**Figure 4**). We defined heatwaves as the number of days a year over 32.2 °C based on the northeast US heatwave temperature threshold – when the maximum shade temperature is greater than or equal to 32.2 °C (90 °F) (15,16). In general, the number of hot days observed by Terra MODIS correlates with the number of hot days in the last 20 years for all three airports. Aqua MODIS consistently overestimates the number of hot days compared to Terra MODIS and maximum daily temperature, particularly for the BWI and Dulles airports. Landsat does not provide daily LST data, so it was not included in this analysis.

DISCUSSION

We derived several conclusions from analyzing our in-situ data, satellite data, and weather station data. First, our field data confirms that Landsat surface temperature measurements are accurate with minimal error ranging from 0.95 °C to 2.31 °C. This deviation is also observed in other studies, which have found a mean difference between

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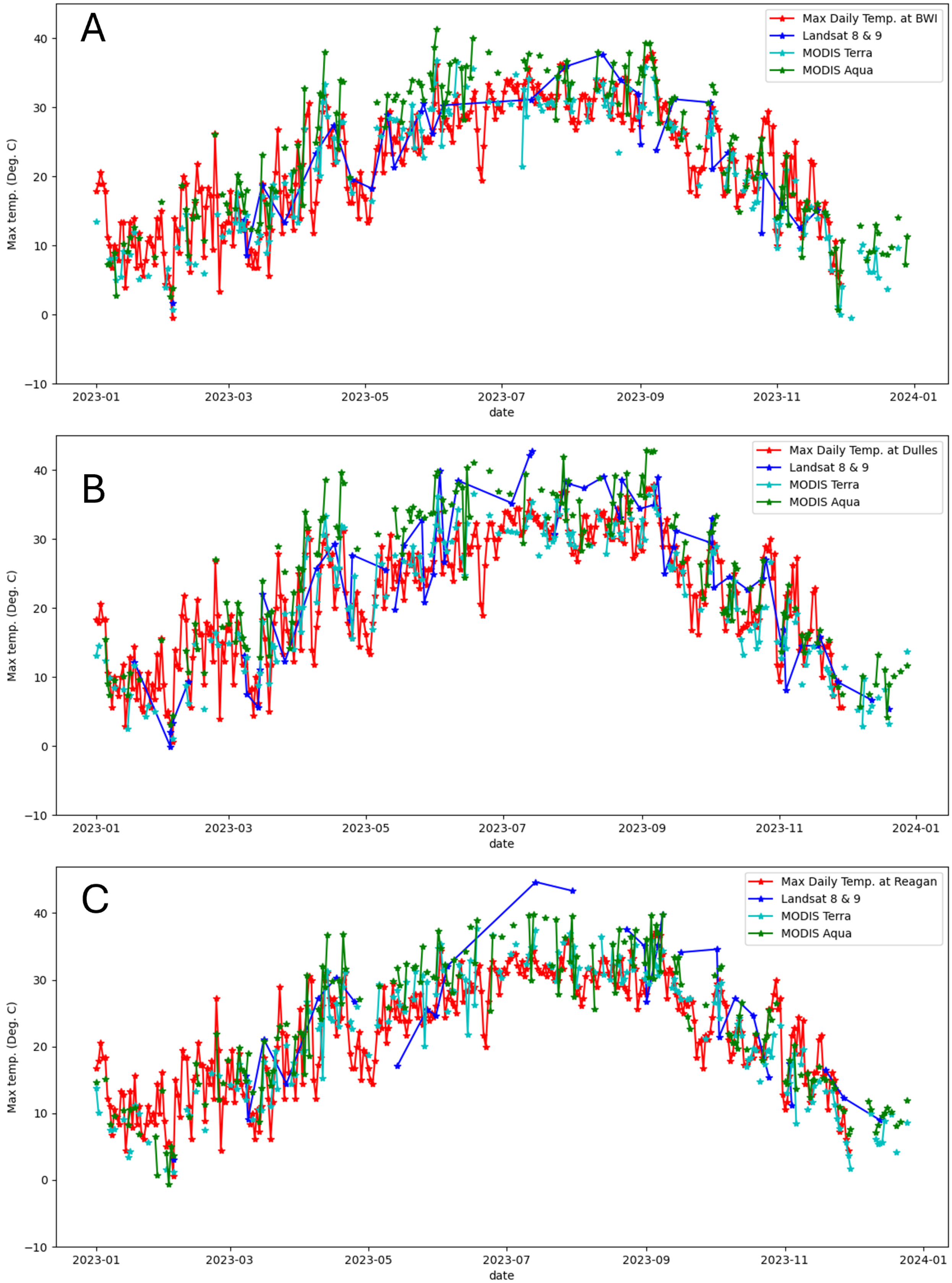

Figure 3: Time series of surface and air temperatures: Aqua MODIS, Terra MODIS, and Landsat 8 and 9 surface temperature measurements as compared to the daily maximum temperature measurements for (A) the Baltimore/Washington International (BWI), (B) Dulles, and (C) Reagan airport weather stations.

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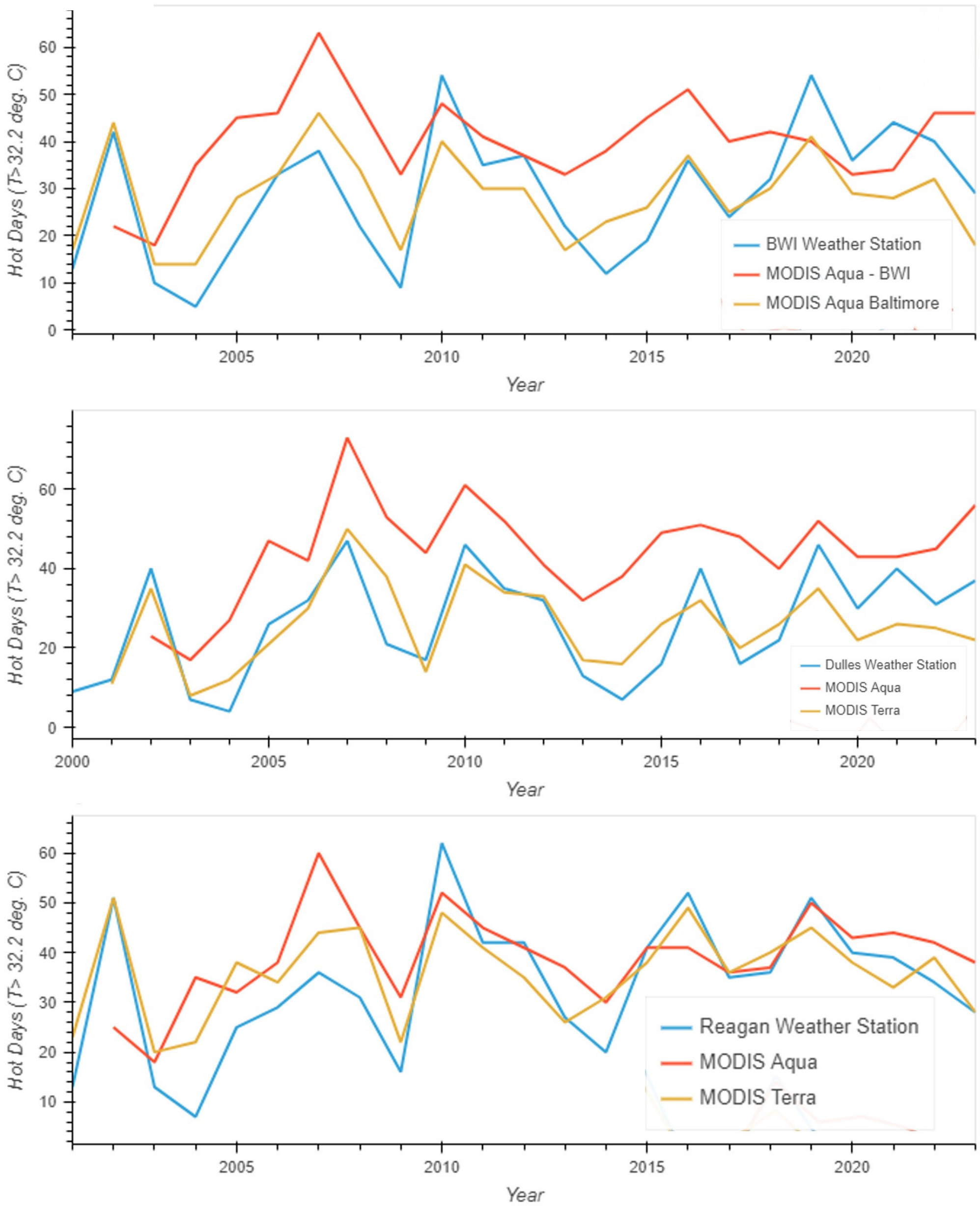

Figure 4: Comparison of the number of days with temperature greater than 32.2 °C. The number of days with a temperature higher than 32.2 °C observed by weather stations, Terra MODIS, and Aqua MODIS from 2001-2023 at the BWI, Dulles, and Regan airports.

Landsat LST and in situ LST of 1.0 °C and 0.7 °C for Landsat 7 (17, 18). Sources of variability between our field measurement and Landsat measurement could include variations in atmospheric conditions, variations in land surface emissivity, and sensor calibration issues. Second, we also found that the Landsat dataset shows more spatial variability than MODIS surface temperatures, confirming our first hypothesis that spatial resolution impacts the spatial precision of UHI boundaries (**Figure 2**). However, MODIS provided greater temporal frequency for temperature observations: almost daily at 1 km spatial resolution (**Figure 3**). This confirms our second hypothesis that daily satellite-derived surface temperature measurements can detect temporal patterns of UHI effects and heatwave frequencies. Finally, the number of hot days, as measured by Terra MODIS, correlates with the number of hot days at the BWI, Dulles, and Reagan weather stations, further supporting our second hypothesis.

The spatial temperature difference between Landsat and Terra MODIS may be due to the difference in emissivity datasets used by the MODIS and Landsat data products. MODIS measures emitted longwave radiation, which is converted to radiant temperature (19). The radiant temperature is converted to kinetic surface temperature with one value per pixel in the 1 km spatial grid. The emissivity dataset used for our Landsat observations was the 2008 ASTER global emissivity dataset, which is an outdated

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calculation to convert radiance to temperature, and recent urban surface expansion is not visible in this emissivity data (20). It is worth noting that MODIS data has errors due to missing data from clouds and gaps between swaths (21).

Terra MODIS observes a similar pattern of the number of hot days. However, we hesitate to claim that MODIS can detect heat waves since there is no single accepted definition for heat waves. The lack of an accepted definition for heat waves presents problems and inconsistencies in analyses of increasing heatwaves with global change. Additionally, the criteria to define heat waves depends on many factors such as location and humidity. However, our results are encouraging, as they suggest that Terra MODIS surface temperature observations can be used as a reasonable parameter in the detection of future heat waves.

This study evaluated the accuracy of satellite-observed surface temperature measurements, particularly the Landsat data. The spatial and temporal differences in surface temperature observed by Landsat and MODIS suggest that each satellite has its own strengths and weaknesses. Each has its own applications. Satellite surface temperature data with high temporal resolution has the potential to determine heatwave frequency in specific locations within an urban area or remote locations more effectively than weather stations. Satellite surface temperature data with high spatial resolution can measure variations in temperature in specific locations within communities to gain a deeper understanding of the types of surfaces that contribute to the high temperatures. With this data, we can clearly understand which areas are most dangerous and need more green space and vegetation. Ultimately, satellite-derived surface temperature products can be used to monitor and address the effects of climate change on those most at risk to extreme heat, which is becoming increasingly vital in a world with so many people exposed to increasingly dangerous climate conditions (2).

MATERIALS AND METHODS

Study Site and Datasets

Our study sites included the Washington, D.C. and Baltimore metropolitan region (**Figure 5**). This region

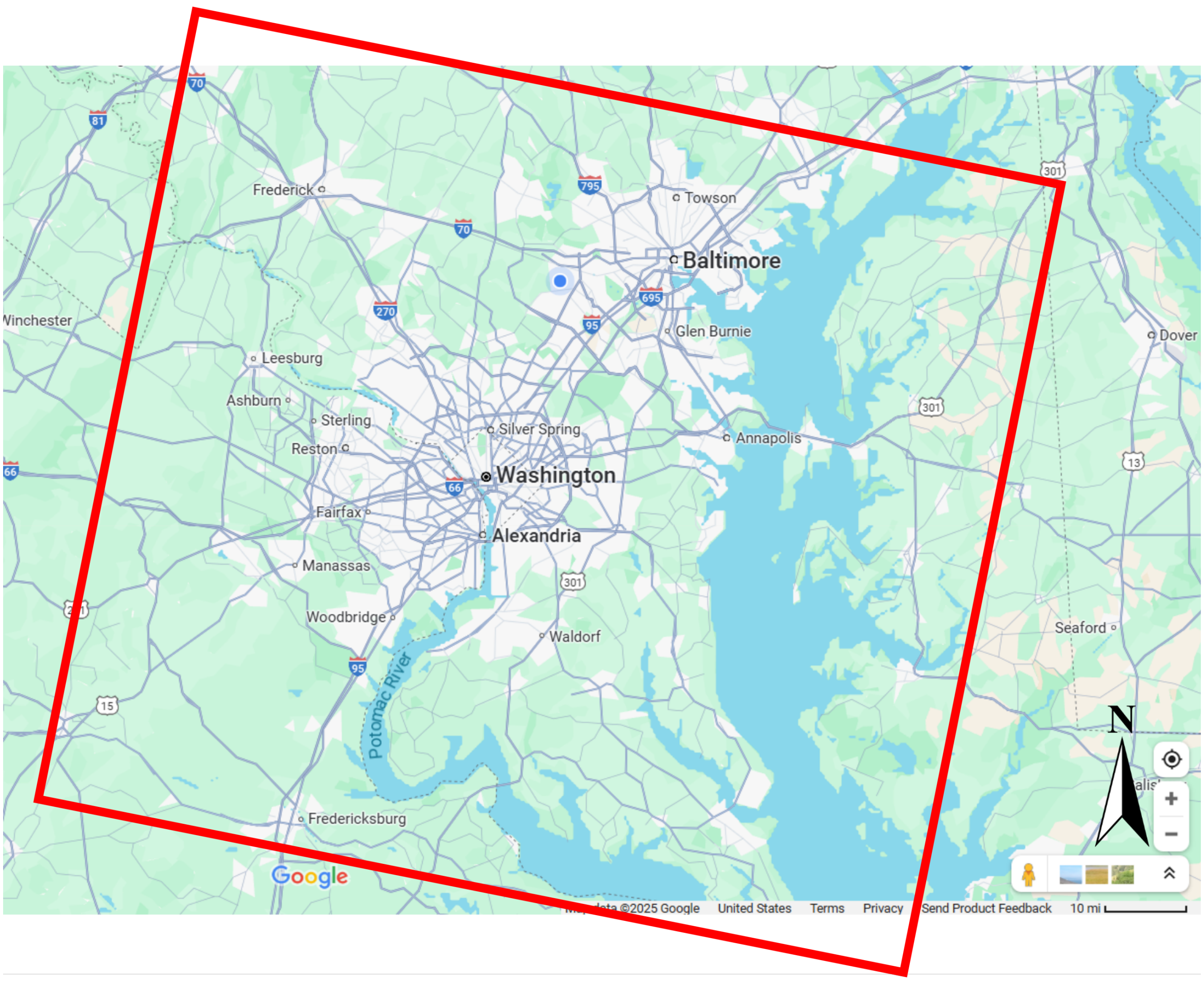

Figure 5: Study site. Map showing the Washington, D.C. and Baltimore metropolitan region. Taken from Google Maps.

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includes Washington, D.C., Central Maryland, and Northern Virginia. Both remote sensing data and meteorological weather station data were used to compare land surface temperature maps and evaluate which satellites most closely align with weather station data. Satellite data included both land surface temperature data collected using Landsat 5, 7, 8, and 9 from 1984-2023 and MODIS from 2000 to 2023. The Landsat data is collected biweekly at 60 m (Landsat 5 and 7) and 100 m (Landsat 8 and 9) spatial resolution, but was downscaled to a 30 m grid. Landsat passes over a location around 10:30 am local time. The Landsat surface temperature product has a variety of known issues, such as gaps, blockiness, and anomalies in vegetation adjustment due to problems with the data in the ASTER GED, and so was adjusted as previously described (18,20).

MODIS is mounted on both the Terra and Aqua satellites with a 1 km spatial resolution. Terra was launched in December 1999, with land surface temperature data collected from 2000 to 2023 and passes over a location at 10:30 am local time (22). Aqua, launched in 2001, is an afternoon satellite that passes over a location at 1:30 pm local time (23). Terra MODIS and Aqua MODIS provide daily surface temperature observations at their passing time. All the satellite data used is hosted on the Google Earth Engine (GEE) cloud and was accessed through the GEE platform (24).

Additional daily maximum air temperature data from 1940-2023 collected through the Automated Surface Observing Systems (ASOS) at three airports: Baltimore/Washington International Airport (BWI), Reagan National Airport (Regan), and Dulles International Airport (Dulles) were downloaded from NOAA National Centers for Environmental Information (NCEI) (https://www.ncei.noaa.gov/). A previously published study found that the sensors used by these weather stations have error values between 0.2 °C to 0.33 °C, meaning that the data is accurate enough to identify heatwaves (25).

Field Data Samples

To evaluate the accuracy of Landsat surface temperature data, field measurements were collected using handheld infrared thermometers. Two parking lots were selected on the GSFC campus for analysis. All other data was collected within 15 minutes of the overpass time of Landsat (10:30 AM). Two sites were also selected on the Centennial High School campus, one on a grass field and one on a turf field.

The Landsat pixels on the ground were geolocated and 15 random ground samples were taken within each Landsat pixel with the infrared thermometers during the Landsat overpass. One field data collection was conducted on 7/14/2023, and the second on 7/30/2023. The thermometers were calibrated with a blackbody radiation machine. They were tested in 5 °C increments from 5 °C to 60 °C, plotting the thermometer reading and the blackbody value and using the resulting line of best fit to adjust the measurements. The resulting line of best fit was $y=1.0126x-1.9558$ with an $r2=0.9998$, where y was the true blackbody radiation and x was our infrared thermometer measurement. The average of the 15 measurements was assessed with our line of best fit equation and compared to the Landsat-measured values.

Data Analysis

To find out how identify how the surface temperature products differ spatially, Landsat data was first compared with Terra MODIS data since they have similar overpass times (10:30 am). The average of the top two maximum temperature measurements of each pixel from MODIS in 2022 was calculated and compared to the mean of the top two maximum temperature measurements from Landsat at 30 m spatial resolution, aggregated to the MODIS 1 km spatial resolution grid. Since MODIS makes an overpass every day, Landsat and MODIS data were collected on all the Landsat overpass dates, and directly compared the LST measurements of the two satellites. Any pixels with any amount of cloud cover were filtered out, leaving only clear pixel data.

To assess how Landsat surface temperature differs from MODIS surface temperature temporally, Landsat and MODIS land surface time series at the 1 km buffer area of each of the three airports (BWI, Dulles, and Regan) were extracted. Landsat data was compared with Terra and Aqua MODIS data on days with both satellites passing over. To evaluate if satellite-based surface temperatures have similar trends with air temperature, the daily maximum air temperature was also compared with the satellite-observed surface temperature for available dates in 2022.

To assess whether the satellite surface temperature can be used to monitor the trend of heat waves, we compared the number of hot days at the three airports. There is no universally accepted definition for heat waves because they also depend on other factors, such as humidity and location. In the northeast U.S., the heatwave temperature threshold is the maximum shade temperature greater than or equal to 32.2 °C (90°F) (15, 16). Additionally, at 32.2 °C (90 °F), the risk of health complications in older adults, children, and people with certain illnesses and chronic conditions increases substantially (26). We, therefore, adopted this threshold in this study. Both MODIS surface temperature data collected on the Terra and Aqua MODIS and Landsat 5, 7, 8, and 9 surface temperature data from 1984-2023 were used.

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