Changes in Satellite-Derived Impervious Surface Area at US Historical Climatology Network Stations

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Submitted to: ***ISPRS Journal of Photogrammetry and Remote Sensing***

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Keywords: impervious surface area, land cover change, urbanization, climate station siting

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ABSTRACT

The difference between 30 m gridded Impervious Surface Area (ISA) between 2001 and 2011 was evaluated within 100 and 1000 m radii of the locations of climate stations that comprise the US Historical Climatology Network. The amount of area associated with observed increases in ISA above specific thresholds was documented for the climate stations. Over 32% of the USHCN stations exhibited an increase in ISA of ≥ 20% between 2001 and 2011 for at least 1% of the grid cells within a 100 m radius of the station. However, as the required area associated with ISA change was increased from ≥1% to ≥10%, the number of stations that were observed with a ≥20% increase in ISA between 2001 and 2011 decreased to 113 (9% of stations). When the 1000 m radius associated with each station was examined, over 52% (over 600) of the stations exhibited an increase in ISA of ≥ 20% within at least 1% of the grid cells within that radius. However, as the required area associated with ISA change was increased to ≥10% the number of stations that were observed with a ≥20% increase in ISA between 2001 and 2011 decreased to 35 (less than 3% of the stations). The gridded ISA data provides an opportunity to characterize the environment around climate stations with a consistently measured indicator of a surface feature. Periodic evaluations of changes in the ISA near the USHCN and other networks of stations are recommended to assure the local environment around the stations has not significantly changed such that observations at the stations may be impacted.

1. INTRODUCTION

The impact of environmental factors (e.g., land use/land cover), and changes in these factors, on observed near-surface air temperature have been the topic of numerous studies (Karl et al, 1988, Gallo et al 1996, Hale et al 2006, Pielke et al 2007a, Pielke et al 2007b, Christy et al 2006, Christy et al 2009, Mahmood et al 2010, Fall et al 2011). Recommendations are available for the placement of climate stations that consider surrounding environmental factors (NOAA 2002, WMO 2012). However, as has been pointed out (e.g., Gallo et al 1996, Fall et al 2011) even if surface air temperature stations are initially placed at ideal locations, the surrounding region may develop over time and alter the environment of the station and the recorded observations.

The influence of environmental factors on station observations, based on the station location (station siting) and the surrounding environment, has been the topic of several studies. Gallo et al (1996) utilized the results of a climate station-observer survey of land cover within 100, 1000, and 10,000 m of USHCN stations to assess the influence of land cover within these radii on diurnal temperatures at the stations. Hanamean Jr. et al (2003) assessed satellite derived land cover within 1000 and 5000 m of station locations in an assessment of the influence of vegetation within these radii on maximum and minimum temperatures. In a review that included general recommendations of urban station location assessment Oke (2006) defines several environmental factors and spatial scales of interest relevant to observations in urban environments. Leroy (2010) presented a classification system for rating stations based on the environmental factors that potentially could influence the station observations. The optimal classification for temperature observation included a recommendation that the station “measurement point“ may be located “at more than 100 m from heat sources or reflective surfaces (buildings, concrete surfaces, car parks etc.).” The classification system presented by Leroy (2010) for temperature observations are similar to those included in the WMO guidelines for meteorological observations (WMO, 2012).

Impervious surface area (ISA) represents a physical characteristic of the land surface that is correlated with the amount of urban-related features (e.g., asphalt, concrete, rooftops) within an observed area (Arnold and Gibbons 1996). Oke (2006) recommended ISA as one of the factors that can be utilized to characterize the environment of climate stations. The U.S. Geological Survey's (USGS) National Land Cover Database provides impervious surface products at five year intervals beginning in 2001 (Homer et al., 2015). The ISA dataset was developed from Landsat data (Xian and Homer, 2010) and represents the fraction of impervious surface area in a 30 m grid cell. This spatial resolution facilitates evaluation of ISA within relatively close proximity to land surface structures, e.g., climate stations, which may be impacted by changes in nearby ISA. The 2001 NLCD 30-m ISA dataset was utilized by Elvidge et al, (2007) as a reference in their global inventory of ISA at a 1-km resolution.

ISA has been included in numerous studies that characterize or assess land cover changes, particularly urbanization (Elvidge et al 2007, Xian et al 2007, Xian et al., 2012). An impervious surface metric that relies on satellite imagery provides a uniform data source for urban land cover extent and intensity. The method is useful for regional scale urban land change analysis and should be applicable to other forms of urban landscape delineation, such as individual developments and neighborhoods. The results from the analysis of updating impervious surface distribution in the Gulf of Mexico region reveal the spatial patterns of impervious surface and urban land cover transition (Xian et al., 2012).

Through analysis of land use, land cover, and ISA changes and comparisons with baseline information, transitions of nonurban land to urban land and urban intensifications within urban areas, as well as how fast and in what areas the changes have occurred can be determined in a large area. A continuous record (1984-2010) of ISA developed from Landsat data (Sexton et al 2013) was used to evaluate long-term urban land cover change in the Washington, D.C.-Baltimore, MD metropolitan area. Song et al (2016) utilized the data included in the Sexton et al (2013) analysis to analyze the magnitude, timing, and duration of ISA change within the Washington D.C.-Baltimore, MD region. Zhang and Weng (2016) utilized a time-series of Landsat data from 1988 to 2013 in an analysis of the annual dynamics of ISA in the Pearl River Delta of China.

ISA has also been combined with gridded satellite-derived land surface temperature (Xian and Crane 2006, Yuan and Bauer 2007, Zhang et al 2009, Imhoff et al 2010, Zhang et al 2010), and gridded air temperatures (Gallo and Xian 2014) in studies that included spatial analyses of urban heat islands. The spatial analysis of UHI using ISA and MODIS land surface temperature (LST) across the conterminous United States (CONUS) suggested that urban areas are substantially warmer (2.9 °C annual average) than the non-urban fringe, except for urban areas in biomes with arid and semiarid climates (Imhoff et al., 2010). The analysis and observational results also show that the urban heat island amplitude both increases with city size and is seasonally asymmetric for a large number of cities across most biomes.

The U.S. Historical Climatology Network (USHCN) temperature dataset is routinely used "to quantify national- and regional-scale temperature changes in the conterminous United States" (NOAA 2016). In a study of the influence of land cover on observed diurnal temperature range, Gallo et al (1996), utilized the results of a climate station-observer survey of land cover within 100, 1000, and 10,000 m of USHCN stations. Land cover within 100 m of the climate stations resulted in the greatest influence on the observed diurnal temperature range, with the influence of land cover decreasing as the surveyed radii increased. Since the station observers were relied on for the determination of dominant land cover classes within the various distances from the stations, there was potentially some subjectivity and inconsistency introduced into the land cover determinations. The 30 m gridded USGS ISA data provides an opportunity to characterize the environment around USHCN climate stations with a consistently measured indicator of surface features. This updated characterization of the land surface change within the vicinity of climate stations could ultimately be used to assess the influence of these changes on the climate variables observed at the stations.

The objective of this study was to assess and document the change in ISA from 2001 to 2011 at USHCN station locations across the conterminous United States using NLCD 2001 and 2011 impervious surface products.

2. MATERIALS and METHODS

2.1 Data Sets Utilized

The USGS NLCD ISA product represents fractional cover of imperviousness in each 30 m grid cell. Small or large ISA magnitude represent less or more imperviousness coverage and therefore the percent ISA has been used to define different urban land cover categories in the NLCD land cover product. While available at five year intervals (2001, 2006, and 2011) only the 2001 and 2011 ISA data sets were evaluated in this study to maximize the potential difference and contrast in ISA. The ISA change product was produced using an approach for updating new impervious surface growth and intensification (Xian et al., 2011; Xian et al., 2012). This method is consisted of three major procedures: training data refinement, creation of regression models, and change comparison. The method employed the baseline year NLCD impervious surface product as the baseline estimate and Landsat imagery pairs between baseline and target years as the primary data source for identifying changed areas.

Ancillary data including nighttime stable-light satellite imagery (NSLS) from the NOAA Defense Meteorological Satellite Program (DMSP), slope, and elevation were also used to create regression tree models for predicting new percent impervious surface in changed areas. Three major steps were required for this process including modeling an impervious surface, comparison of model outputs, and final product clean-up. In the modeling step, DMSP nighttime lights imagery in the baseline year was superimposed on the NLCD impervious surface product in the same year to exclude low density impervious areas outside urban and suburban centers to ensure only urban core areas be used to provide a stable and reliable training dataset. Two training datasets, one having a relatively large urban extent and one having a relatively small extent, were produced through imposing thresholds of nighttime lights imagery on the baseline impervious product. In the comparison step, each of the two training datasets combined with the baseline year Landsat imagery was separately applied with regression tree algorithms to build up regression tree models (Xian and Homer, 2010).

Two sets of regression tree models were created and used to produce two baseline year synthetic impervious surface products. Similarly, the same two training datasets were used with the target year Landsat and DMSP NSLS images to create two sets of regression tree models and produce two target year synthetic impervious surface products to ensure that only stable predictions are chosen as intermediate products. In the cleanup step, the two synthetic product pairs were then compared to remove false estimates due to strong reflectance from nonurban areas and to retain the baseline impervious values in the unchanged areas. The target year impervious surface was updated individually in every Landsat scene over the entire CONUS, with individual scene products subsequently mosaicked together to produce a seamless target impervious surface product. To produce the NLCD 2006 impervious surface product, 2001 is the baseline year and 2006 is the target year. For the NLCD 2011 impervious surface product, the baseline and target years are 2006 and 2011.

In the NLCD 2011 product, additional process was implemented in addition to identifying new impervious features for 2011 because the process was sensitive enough to capture many previously unidentified impervious areas from earlier periods (Homer et al., 2015). It would have inaccurately placed the change in the wrong period by identifying these areas as 2011 change. To correct this, an intensive combination of hand editing and automated processes was implemented to identify and sort potential additions into the proper NLCD period (2001, 2006, or 2011). This process was extensively dependent on the use of high-resolution imagery from each period to accurately identify and sort the additions captured in 2011. All other impervious features were also checked during this process, enabling overall accuracy to be improved. These special edits were only focused on the eastern half of CONUS because this area had the most inaccuracies from earlier periods. The additional processing resulted in a much improved impervious product throughout all published years and a more consistent national product.

While the accuracy assessment associated with the 2011 ISA dataset is still under evaluation, a user accuracy (Story and Congalton, 1986) of 67% was determined for grid cell changes in ISA between the 2001 and 2006 ISA datasets (Wickham et al., 2013). Additionally, a user accuracy of 99% was associated with a grid cell identified as exhibiting no change in ISA between 2001 and 2006. The spatial location accuracy of the Landsat data used in preparation of the ISA dataset is 30 m or less (Landsat, 2016).

The climate stations evaluated in this study included those that comprise the US Historical Climatology Network (USHCN). The USHCN dataset is a subset of the NOAA Cooperative Observer Program Network with locations “selected according to their spatial coverage, record length, data completeness, and historical stability” (NOAA 2016). The USHCN dataset includes stations with temperature records that originate in the late 1800s and early 1900s (Karl et al, 1988). The USHCN station location information (version 2.5) was acquired from NOAA’s National Centers for Environmental Information (formerly the National Climatic Data Center, NOAA 2016). The data retrieved included station name, a station identification value, and latitude and longitude values for 1218 stations within the conterminous US.

2.2 Analysis of Data

The 2001 and 2011 ISA data sets were acquired from the U.S. Geological Survey (USGS 2014) and differences in the ISA values from 2001 to 2011 were computed. Next, the difference in ISA was binned into increments of 10% into ten categories. Thus, for each grid cell, ISA differences less than 10% through differences of 100% were available for analysis at 10% increments. The USHCN station location information provided with the USHCN data set (Version 2.5; NOAA, 2016) was used to extract the ISA differences within 100 and 1000 m of the provided station locations. The location information for the USHCN stations is nominally 30 m accurate (Hausfather et al, 2013). The USHCN station location information is expected to be representative of the station location; however, this information is based on the location of the rain gauges at the stations and the location of the temperature sensors may vary from this location. Based on a preliminary review of temperature sensor location information available for 1029 of the 1281 USHCN stations (NOAA NCEI, 2016), over 90% of the temperature sensors were located within 50 m of the reported station locations used in this analysis. Thus, the 100 and 1000 m radii utilized in this study are appropriate for assessment of ISA at the reported station locations and the location of the temperature sensors associated with the stations. The availability of accurate location information for the temperature sensors at all USHCN stations is encouraged.

The area associated with the two radii (100 and 1000 m) from the station location was intersected with the raster ISA grid (e.g., Figure 1) and the number of pixels associated with ISA change for each 30 m – grid cell included in the areas was documented. A minimum of one-half the area of a pixel was required to be within the intersected radii to be included in the analysis. Analysis for each station included computation of the percent area that experienced an ISA change, computed as the number of grid cells with an observed ISA change (e.g. ≥ 20%) per the minimum number of grid cells potentially within the radii (100 or 1000 m). ISA changes of ≥ 10, 20, or 50% between 2001 and 2011 were evaluated for the grid cells within both the 100 and 1000 m radii of each station. Station statistics were additionally summarized for the entire USHCN dataset.

3. RESULTS and DISCUSSION

3.1 Local Analysis

Increases in ISA within the 100 and 1000 m radii of each station were characterized by both the percentage increase in ISA from 2001 to 2011 and the percentage of area within the 100 and 1000 m radii associated with the observed increases in ISA. Figure 1 shows an example of the station characterization for change in ISA. The analysis for the USHCN station located at Roseau, MN, indicates that a single 30x30 m grid cell within the 100 m radius exhibited a change in ISA (of 40-49%) between 2001 and 2011. This grid cell represents approximately 3% of the area within the 100 m radius of the station location. Thus, the analysis of this station indicates that within the 100 m radius, 3% of the area exhibited a ≥ 10% (as well as ≥ 20%) increase in ISA between 2001 and 2011. As only a single grid cell exhibited change within the 100 m radius, none of the area within the 100 m radius exhibited a ≥50%

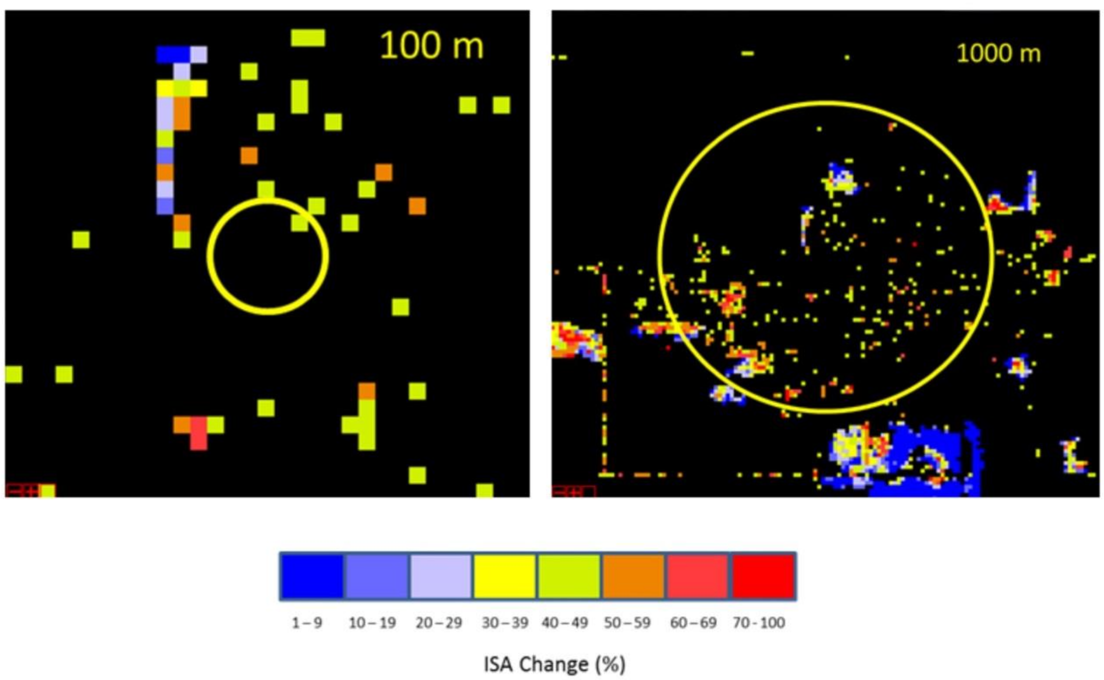

Figure 1. ISA change from 2001 to 2011 for Roseau, MN, USHCN station within 100 (left) and 1000 m radii of station location.

increase in ISA for this station. A similar analysis for the Roseau, MN station within the 1000 m radius of the station indicated that 8.2% of the area exhibited a ≥ 10% increase in ISA between 2001 and 2011 while 8% of the area exhibited a ≥20% increase. Additionally, within the 1000 m radius, 2.6% of the area exhibited a ≥ 50% increase in ISA.

A second example includes an analysis of the St. George, UT station (Figure 2). The analysis for this USHCN station indicates that within the 100 m radius 56% of the area exhibited a ≥10% (and ≥20%)

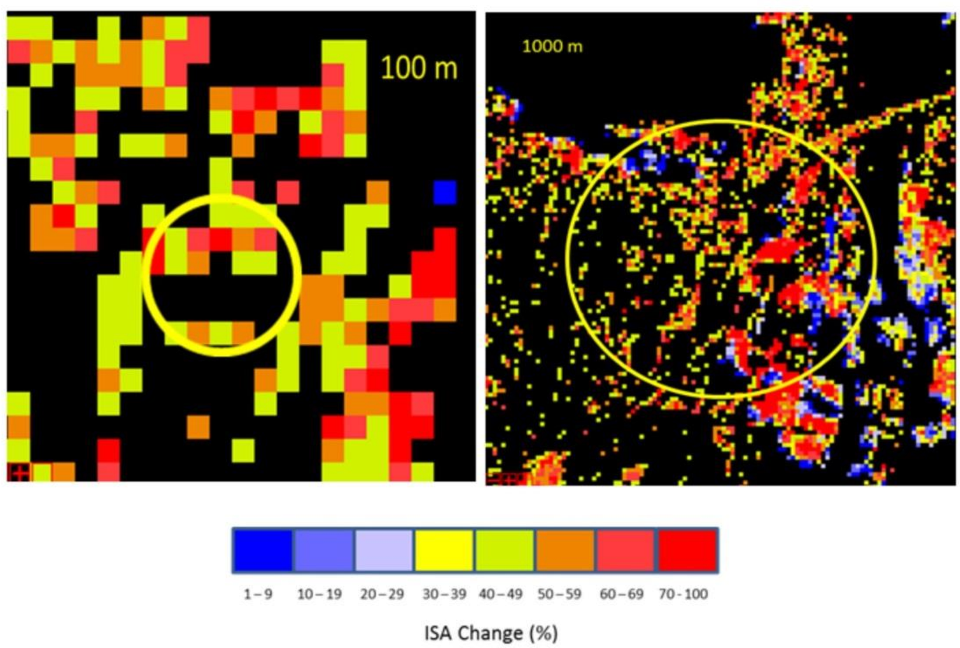

Figure 2. ISA change from 2001 to 2011 for St. George, UT, USHCN station within 100 (left) and 1000 m radii of station location.

increase in ISA between 2001 and 2011 while 25% of the area within this radius exhibited a ≥ 50% increase in ISA. Within the 1000 m radius 34% of the area exhibited a ≥ 10% increase in ISA while 32% of the area exhibited a ≥ 20% increase in ISA between 2001 and 2011. Additionally, 19% of the area within 1000 m of the station location exhibited a ≥ 50% increase in ISA.

3.2 Conterminous US Analysis

The spatial distribution of stations that exhibited an increase in ISA of ≥ 20%, for any 30 m grid cell between 2001 and 2011, is displayed in Figure 3 (100 m radius). The total area within the 100 m radius of each station, that exhibited an increase of ≥ 20%, is also indicated for each station location. Over 32% of the USHCN stations exhibited an increase in ISA of ≥ 20% for at least 1% of the grid cells within a 100 m radius of the stations (Figure 3). When the 1000 m radius associated with each station was examined (not shown), over 52% of the stations exhibited an increase in ISA of ≥ 20% within at least 1% of the grid cells within that radius.

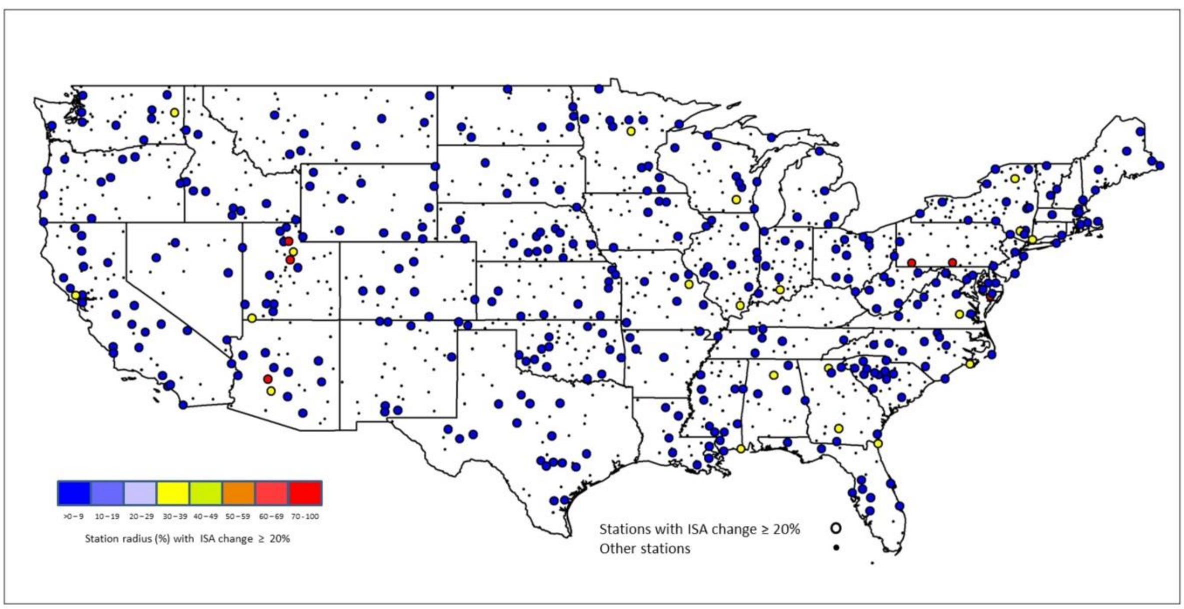

Figure 3. Percentage of area within 100 m radius of USHCN stations that exhibited an increase in ISA of ≥ 20% between 2001 and 2011. Stations that did not meet this criterion are indicated by black points (.).

Figure 4 displays the results of the analysis for changes in ISA within a 100 m radius of 20% or more, as displayed in Figure 3, but additional analysis for observed increases in ISA of 10 and 50% (as represented by the different symbols within the figure). For example, an analysis of all 1218 USHCN stations revealed that 164 stations (left vertical axis) or 13.5% of the stations (right vertical axis) exhibited a ≥ 10% increase in ISA for at least 9% (horizontal axis) of the area within a 100 m radius of the stations. Meanwhile, only 63 stations exhibited a ≥ 50% increase in ISA for at least 9% of the area within 100 m of the stations. Over 32% of the USHCN stations exhibited at least 1% of the grid cells within a 100 m radius with an increase in ISA of ≥ 20% (Figure 4). However, as the required area associated with ISA change was increased from ≥1% to ≥10%, the percentage of stations that were observed with a ≥20% increase in ISA between 2001 and 2011 decreased to 9%.

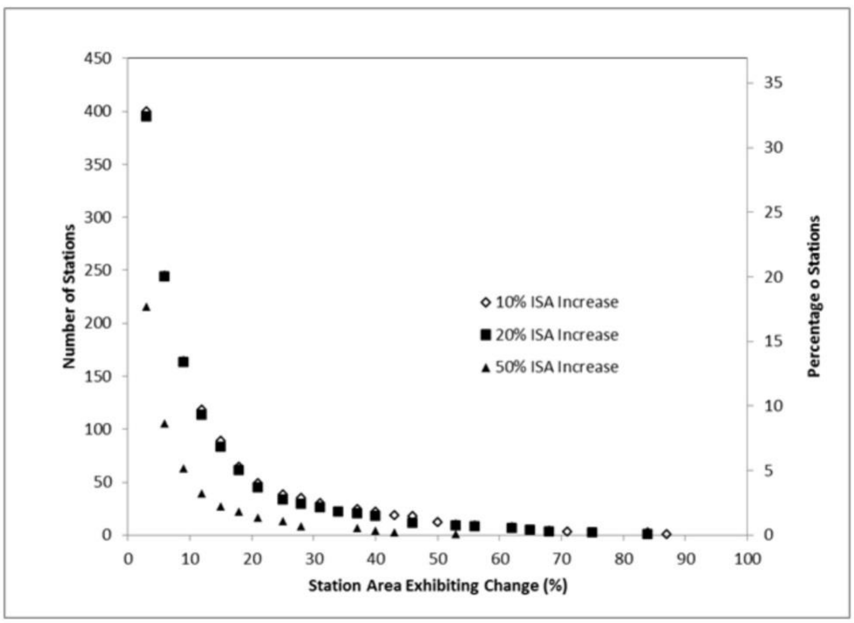

Figure 4. Number of stations, and percentage of area within 100 m radius of stations, that exhibits an increased change in ISA of 10, 20, and 50% between 2001 and 2011. Includes stations with a minimum of >1% area exhibiting increased ISA.

Meanwhile, when the 1000 m radius associated with each station was examined, over 52% (over 600) of the stations exhibited an increase in ISA of ≥20% (Figure 5) within at least 1% of the grid cells. However, as the required area associated with ISA change was increased from ≥1% to ≥10%, the number of stations that were observed with a ≥20% increase in ISA between 2001 and 2011 decreased to 35 (less than 3% of stations). Thus, as the threshold for ISA change increases, e.g., from ≥ 10% to ≥ 50% (as represented by the different symbols), and the area associated with this threshold remains constant, (horizontal axis), the number of stations that exhibit increased ISA (left vertical axis) is decreased (Figures 4 and 5).

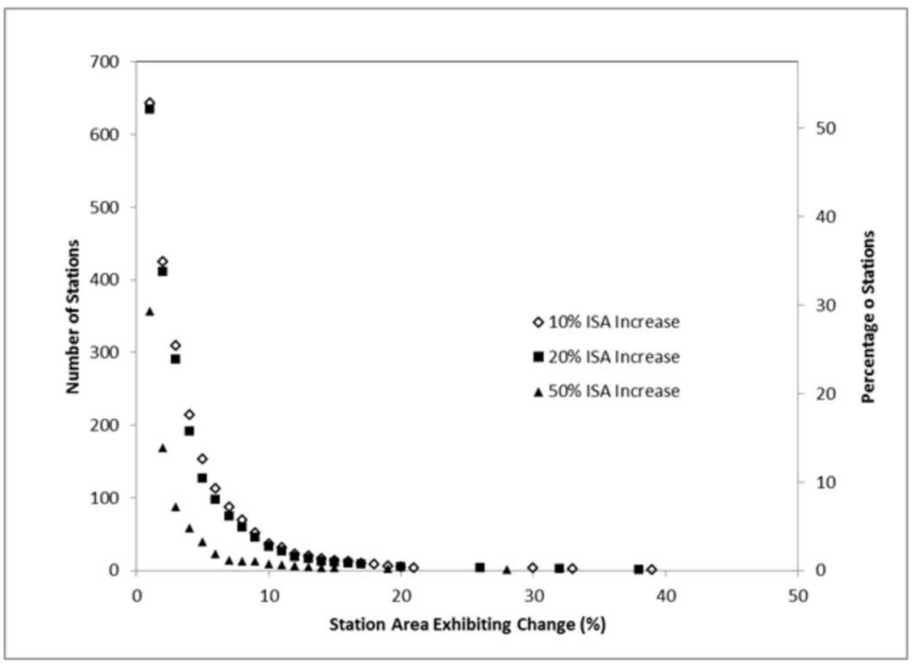

Figure 5. Number of stations, and percentage of area within 1000 m radius of stations, that exhibits an increased change in ISA of 10, 20, and 50% between 2001 and 2011. Includes stations with a minimum of >1% area exhibiting increased ISA.

Several thresholds of ISA have been used in previous analyses to quantify urbanization of settlements (Imhoff et al 2010, Potere et al 2009, Zhang et al 2010) or climate stations (Hausfather et al 2013). Imhoff et al (2010) defined five zones associated with cities included in an analysis of urban heat islands, with a minimum ISA value of 25% used to separate the urban zone from a suburban zone. Potere et al. (2009) utilized an ISA value of 20% to distinguish urban and non-urban areas. ISA was one of four measures of urbanity utilized by Hausfather et al (2013) in an assessment of urbanization on temperature trends of the USHCN stations. ISA was evaluated within a 1 km area surrounding the USHCN station. All of these studies used a single (static) ISA dataset in their analyses, compared to the analysis of change in ISA included within this study.

Hausfather et al (2013) identified 357 USHCN stations as urban based on use of a 1000 m grid cell static ISA dataset (nominally 2001) developed from nighttime lights and population data (Elvidge et al 2007). A threshold of 10% ISA was used to distinguish rural (ISA < 10%) and urban (ISA ≥10%) stations based on the ISA value within the 1000 m grid cell in which the USHCN station was located.

The 1000 m analysis of ISA change (2001 to 2011) within this study indicates that as many as 1067 stations (87% of stations) exhibited at least one 30 x 30 m grid cell within a 1000 m radius of the station that displayed an ISA change of ≥10%. When a minimum of 1% of the area within a 1000 m radius of the station location was required to exhibit an ISA change of ≥10%, 652 stations were observed to meet this criterion. Only 37 stations exhibited an ISA change of ≥10% over more than 10% of the area within a 1000 m radius of the station.

CONCLUSIONS

The availability of gridded impervious surface area (ISA) data presents a consistently measured indicator of a surface feature that may influence the environment near a climate observation station. The level and spatial extent of changes in ISA were evaluated within 100 m and 1000 m buffer radiuses of USHCN stations. Over 32% of the USHCN stations exhibited an increase in ISA of ≥ 20% between 2001 and 2011 for at least 1% of the grid cells within a 100 m radius of the station. However, as the required area associated with ISA change was increased from ≥1% to ≥10%, the number of stations that were observed with a ≥20% increase in ISA between 2001 and 2011 decreased to 113 (9%). When the 1000 m radius associated with each station was examined, over 52% (over 600) of the stations exhibited an increase in ISA of ≥ 20% within at least 1% of the grid cells within that radius. However, as the required area associated with ISA change was increased to ≥10% the number of stations that were observed with a ≥20% increase in ISA between 2001 and 2011 decreased to 35 (less than 3% of the stations).

The datasets utilized within this study could potentially permit a more detailed spatial assessment of the relative proximity of grid cells with increased ISA to the station locations. Additionally, an assessment of the impact of the spatial distribution of ISA associated with stations on observed temperatures would be recommended. Comparisons of the ISA data with temperature observations should include a thorough assessment of the location of temperature sensors at each station. The availability of increasingly higher resolution remotely sensed data, and the validity of comparisons of this data with in situ observations, will ultimately rely on accurate location information for the data observed by the satellite (or airborne) sensors as well as the ground-based sensors.

Minimally, a periodic evaluation of changes in the ISA near the USHCN and other network stations is recommended to assure the local environment around the stations has not significantly changed such that observations at the stations may be impacted.

Acknowledgements

The authors acknowledge the assistance of Shelley McNeill and Russell Vose of NOAA's National Centers for Environmental Information (NCEI) with providing detailed USHCN station sensor location information. This manuscript was partially supported by the NOAA/NESDIS Center for Satellite Applications and Research and US Geological Survey. The manuscript contents do not constitute a statement of endorsement, policy, decision, or position on behalf of NOAA or the U.S. Government.

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