

Urban climate station site selection through combined digital surface model and sun angle calculations

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ABSTRACT: Meteorological measurements within urban areas are becoming increasingly important due to the accentuating effects of climate change upon the Urban Heat Island (UHI). However, ensuring that such measurements are representative of the local area is often difficult due to the diversity of the urban environment. The evaluation of sites is important for both new sites and for the relocation of established sites to ensure that long term changes in the meteorological and climatological conditions continue to be faithfully recorded. Site selection is traditionally carried out in the field using both local knowledge and visual inspection. This paper exploits and assesses the use of lidar-derived digital surface models (DSMs) to quantitatively aid the site selection process. This is achieved by combining the DSM with a solar model, first to generate spatial maps of sky view factors and sun-hour potential and second, to generate site-specific views of the horizon. The results show that such a technique is a useful first-step approach to identify key sites that may be further evaluated for the location of meteorological stations within urban areas.

KEY WORDS digital surface model; lidar; sun angles; site selection

Received 14 September 2011; Revised 24 October 2011; Accepted 31 January 2012

1. Introduction

The measurement of meteorological variables across the urban environment is of great value to both research and society. The identification and subsequent investigation of Urban Heat Islands (UHI) has been extensively studied (Arnfield, 2003; Stewart, 2010), together with impacts upon the local environment and population (e.g. Tomlinson *et al.*, 2011). Unfortunately, the number of long-term meteorological and climatological stations across urban areas is often inadequate to capture the magnitude and extent of the UHI fully over any significant period. Critically, the number of climate stations across the United Kingdom has nearly halved between 1990 and 2009, with a similar decline in the number of rain gauges over the same period (Eden, 2009). This period also coincides with a growing awareness of the need to assess the accentuated impact of climate change upon the urban environment, not least since urban areas are the principal centres of population across the developed world.

Urban areas themselves present a challenging environment for the meteorological observations due to the variable nature of the local environment. Variations, such as land use, density of the built-form and surface properties, all affect the local radiation budget which impacts upon the temperatures of the locality. Methods to calculate such factors over areas of potential sites exist (e.g. Kljun *et al.*, 2004) which should ideally be conducted at each site before installation to ensure any potential siting issues are addressed. The extent of turbulence sources affecting the different heights of the sensors also needs to be considered, although as urban areas tend towards neutral stability, the distance influencing screen level sensors is most likely

to be of the order 10–50 m – i.e. the local (neighbourhood) scale (Oke, 2004). In addition to temperature, other variables such as wind and precipitation are also affected by urban areas.

Ultimately it is necessary to ensure that sufficient observations are available across an urban area to ensure that the UHI is adequately captured. In particular, the loss of any existing sites should be adverted while any resiting, and siting of new, meteorological stations should be carefully evaluated. Overall, no set protocol presently exists for the siting of urban weather stations (Oke, 2004; Stewart & Oke, 2009). Hence, a common sense approach is required, taking into account as much information as possible is required pertaining to site characteristics.

This study focuses upon the relocation of the University of Birmingham's Winterbourne climatological station (operated on the present site since April 1979), due to redevelopment in the locality. To aid in the selection of the new site for the station, a digital surface model (DSM) of the University was obtained and combined with a solar angle model to provide spatial maps of sky view factors (SVF) and the number of potential sun hours across an area of 8 km², helping to identify a number of viable locations for the new site. Although relocating any meteorological station is not ideal in this instance, the opportunity was taken to follow best practice for the site selection and layout (WMO, 2008) while fully upgrading the site with new instrumentation.

2. Siting of meteorological enclosures

Strangeways (1995) describes the basis of the meteorological enclosure, identifying three basic requirements: the site for the enclosure should be as representative of the local area as possible; the site and the surroundings should change as little as possible over time, and it should be accessible, particularly if traditional instrumentation is to be used. Meteorological observations in urban areas pose a problem for the first two

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criteria. In particular, the representativeness of a particular site to the locality is often less than ideal on two accounts. Firstly, the heterogeneous nature of the urban environment means that the scale-length of any meteorological variable will be very short (i.e. a measurement at one location will undoubtedly be dissimilar to one close by). Secondly, the location of the site will be very much dependent upon the parameter being investigated. For example, to capture the microclimate of an urban canyon fully it would be necessary to instrument the whole canyon, not just one location within the canyon. For climatological applications, the best location is arguably as close to the average conditions of the area that the station will represent. However, as the second criterion notes, changes to the site and surrounding environment should be kept to a minimum, which is often difficult to determine with an urban setting. The third criterion, access, is rarely an issue with modern automatic weather stations. The example site in this study includes traditional instruments that are used to check the electronic instrumentation and which are also used for teaching and research. It should be noted that, while access is useful, too much access, or visibility, might attract unwanted attention both from vandals and planners. Indeed, vandalism is often a major problem of locating instrumentation in urban areas (Oke, 2006), which often leads to further compromises. Finally, one additional criterion should also be noted. If the site is to be relocated it should be placed as close to the original site as possible with similar conditions: this is particularly important to ensure continuity of climate records for the selected area.

Careful attention needs to be made to selected sites to limit any shadows or shade while not being overly exposed. This is particularly important for the measurement of solar radiation, wind and rainfall. For example, for rainfall it is recommended that the gauges are sited at a distance of at least twice the height of the nearest obstacle (Meteorological Office, 1982), while radiation and sunshine hours need a clear view of the sky that allows the Sun to be visible as often as possible throughout the year. While the siting of enclosures outside urban areas is not necessarily straightforward, there are certainly more potential sites available in rural areas that match these conventional requirements.

3. Lidar, surface models and sky view factors

Sky view factors (SVFs) are a measure of the openness of the sky and are an important measure for both incoming and outgoing radiation. As such, SVF maps can be usefully employed to determine suitable locations for meteorological sites, particularly if used in conjunction with maps of potential sunshine hours. Traditionally, SVF calculations have relied upon manual measurements of the elevation of the horizon around a particular site. Typically, this has been done through the use of photographic techniques (e.g. Chapman *et al.*, 2001; Grimmond *et al.*, 2001). However, such techniques are limited by the number of locations that can be measured and assessed. When considering potential sites for a new meteorological station, a broad area will often need investigating. Potential sites will initially be identified from a map, and subsequent site visits conducted to assess the exposure.

The growing need to provide detailed elevation measurements has led to the exploitation of lidar technology. Lidar (light detection and ranging) is similar to radar, except it uses pulses of light from a laser to illuminate the landscape below a sensor, usually mounted on board an aircraft. The time taken for

the pulse of light to travel to the ground and back is measured, and the distance calculated. Detailed lidar data sets have been used extensively to study surface features for archaeological (e.g. Bewley *et al.*, 2005; Devereux *et al.*, 2008) and climatological investigations (e.g. Hammond *et al.*, 2011). However, care is needed when encountering semi-permeable features such as trees and vegetation; some data will represent the top of the objects, while adjacent data might represent the surface (see Priestnall *et al.*, 2000).

The acquired lidar data can be processed to provide a digital surface model (DSM) that is essentially the height of the surface (elevation) together with any object upon it. This information can be usefully employed to map SVFs over large regions rather than at point locations. Gal *et al.* (2009) used high resolution raster and vector databases to calculate SVFs in urban areas, while Lindberg (2007) used SVF and daily averages of solar radiation from a 1 m digital elevation model correlated against surface temperatures. Recently, Lindberg and Grimmond (2010) described the generation of SVFs using a DEM and a shadow casting algorithm over central London, while Kidd and Chapman (2011) showed that lidar-derived SVF and photographically-derived SVF produced comparable results.

In this study the lidar derived DSM is used to generate maps of both SVF and the maximum potential sunshine hours.

4. Methodology

The area of study is centred on the University of Birmingham in Edgbaston, Birmingham, U.K. The region covers an area of 2 km by 2 km, subsetting from a larger region covering 2 km (east–west) and 4 km (north–south). Figure 1 shows the area covered by the study region together with an image of the lidar-derived DSM. The latter shows both the general topography of the study area and the form and structure of the buildings in this area. The lidar data were collected by the UK Environment Agency which provides samples every 1 m with the height data quantized in 10 mm increments. Figure 2 illustrates the level of detail that can be attained from such data. In Figure 2(a) differences in the height between footpaths and the surrounding grass can be observed in the centre of the image, while in Figure 2(b) the Stevenson screen at the Winterbourne Climatological Station can be discerned (highlighted by the arrow). Although the instrument noise level inherent in the lidar data is relatively small, each grid cell from which the ray tracing took place was deemed to be 50 cm above the surrounding area, thus avoiding any localized variations caused by instrument noise.

4.1. Sky-view factor calculations

The calculation of the SVF is important since it regulates the maximum possible outgoing longwave radiation, and can be calculated from the DSM data set alone (Kidd and Chapman, 2011). For each 1 m grid square on the DSM all the surrounding points were scanned and the elevation angle between the current location and a distant point was calculated. This approach requires two user-defined inputs about the level of detail required; the scan angles and distance contributing to the analysis. In this analysis these were both derived subjectively; azimuth angles run from 0° to <360° in increments of 0.1°, while points up to a distance of 1000 m were considered. The choice of this maximum distance within an urban/suburban

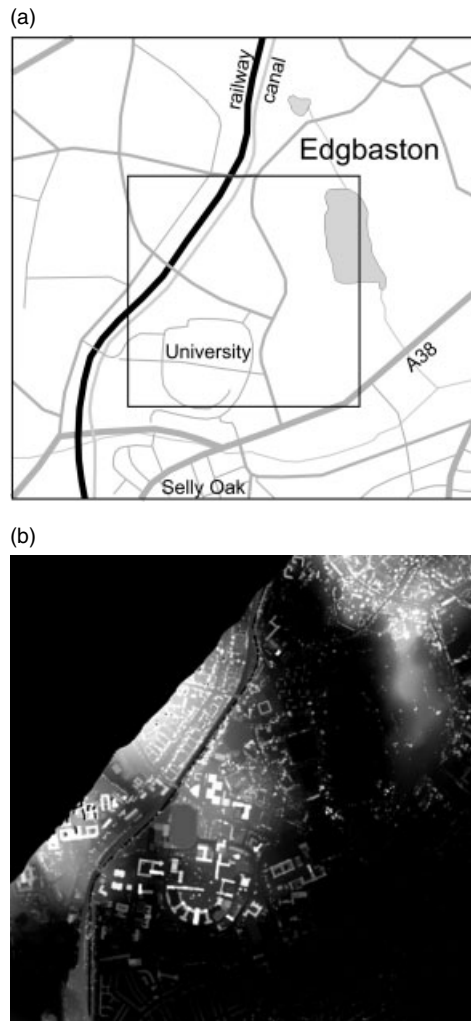


Figure 1. Location map (a) of the University of Birmingham covering a region 2 km by 2 km with the 1 km by 1 km study region identified by the box and (b), the lidar-derived digital surface model; the dark region in the upper left is outside the lidar coverage in this study.

environment was deemed adequate in the absence of any significant topographical relief. A tall building 100 m high at a range of 1000 m would produce an elevation angle of $< 6^\circ$, and would contribute little to obscuring the sky. The greatest elevation angle *per* azimuth angle was recorded and used to calculate the SVF as a fraction of the maximum possible SVF defined as a clear hemisphere of the sky.

4.2. Sun angle calculations

The key solar angle calculations relate to the declination of the Sun for a particular day and the time of day. The current maximum declination varies slightly, but currently stands at $23^\circ 26'$ (23.44°). Therefore, the declination of the Sun for any particular day of the year may be approximated as:

$$\delta = -23.44^\circ \times \cos[360^\circ/365^\circ \times (N + 10)] \quad (1)$$

where N = year day number

and the solar elevation angle at a particular local time and latitude as:

$$\sin \theta_s = \cos h \times \cos \delta \times \cos \Phi + \sin \delta \times \sin \Phi \quad (2)$$

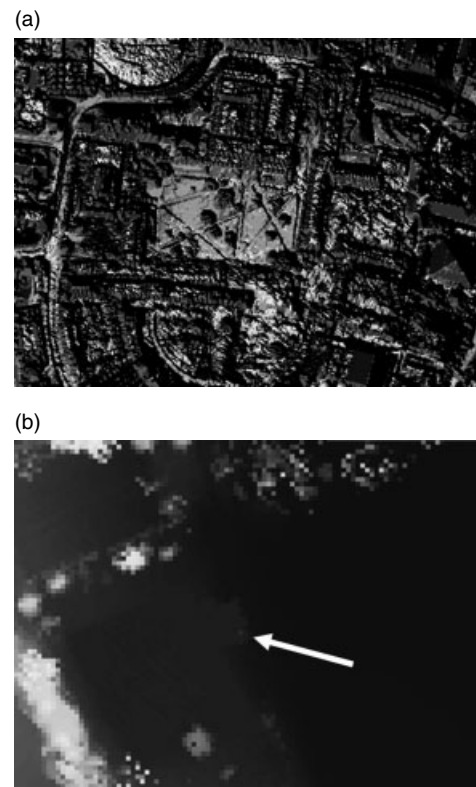


Figure 2. Detailed imagery of the lidar data. (a) is a 'sunlit' scene to highlight the relief showing in the centre of the image footpaths across an area of grass with differences in height of a few centimetres and; (b) is the current Winterbourne meteorological site (centre), the Stevenson Screen is discernable as the single higher elevation pixel (arrowed).

where:

θ_s = solar elevation angle (degrees)

h = hour angle (local solar time as fraction of day)

δ = solar declination (degrees)

Φ = latitude (degrees).

The azimuth and elevation of the Sun was calculated using the location of the University of Birmingham's Winterbourne Climate Site, 52.455°N 1.924°W , for each minute of the day over 1 year.

4.3. Combined sky-view factors and Sun angles

The calculation of the maximum number of sun hours a particular location receives is important as excessive shading of a climatological site at any time of year should be avoided. The calculation of the maximum theoretical number of sun hours on any particular day requires the calculation of the Sun's azimuth and elevation over a period of time. A straightforward approach is to calculate these angles for each time increment, and then compare the azimuth and elevation to the data in the DSM to determine whether the sun angle is below that of the horizon for that particular azimuth. It was determined that the solar angles would need to be calculated on a minute-by-minute basis to enable an acceptable level of detail to be resolved. This calculation is somewhat tedious for generating a value of annual sun hours since it would require 365 (number of days) \times 24 (number of hours) \times 60 (number of minutes)

$\times 1000$ (the number of data points to the maximum distance), resulting in potentially in excess of 500 million calculations *per* grid cell on the DSM. However, the process was optimized since the horizon from any one point will remain the same throughout the year, only the cumulative number of sun hours above a certain elevation angle for a certain azimuth is required. Therefore, a database of the number of sun hours for each azimuth (0° to $<360^\circ$) and each elevation ($0-90^\circ$) over an entire year was generated. This database was matched with the elevation data at each location and the total number of hours where the Sun was above the horizon was calculated. This process reduces the number of calculations *per* point to <250000 *per* location assuming 0.1° azimuth increments and the same maximum distance of 1000 m. In addition, the calculation of the x/y offsets (dx and dy) for each azimuth is pre-calculated to reduce the number of sine and cosine calculations required. Limiting the azimuth to the range of

5. Results

A number of products was generated from the analysis above including the SVF and number of potential sun hours for the winter solstice, equinoxes and summer solstice. In addition 360° horizon panoramas with solar tracks were generated to visualize the horizon view from potential sites.

Figure 3 shows the spatial map of SVF over the study area; the dark areas represent regions with low SVF, while the lighter regions are areas with high SVF. It should be noted that the lidar sensor does not provide any data over water bodies. Hence the lake (Figure 3, upper right) and the canal running from upper centre to left centre have no data. The pattern of the SVF is as expected: low values are observed close to the sides of buildings, while the highest values are found on the roofs of the buildings. It can also be observed that there is a number of large areas devoid of buildings where the SVF values



Figure 3. Spatial map of the sky view factor over the University of Birmingham study site. Note that the lidar data are not obtainable over water bodies, such as the lake in the upper right. The top left of the region is outside the coverage of the digital surface model (DSM) data.

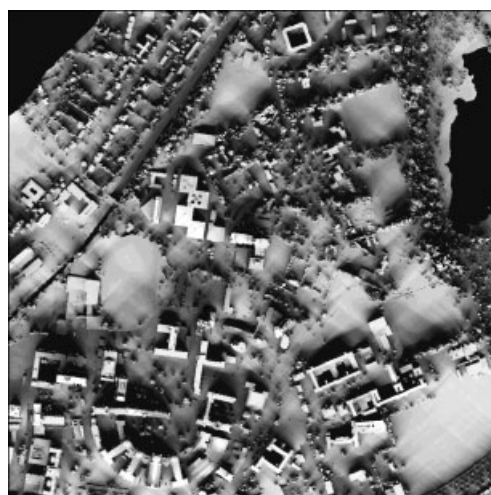


Figure 5. Map of the potential daily sun hours at the winter solstice, showing significant shading on the northern side of buildings.



Figure 4. Map of maximum potential sun hours at the summer solstice, showing high values on roof tops and in the open areas. angles between the solstices (about $50-310^\circ$) allowed the total analysis of 260 000 million calculations to be performed for a $1\text{ km} \times 1\text{ km}$ area in just under 8 h on a 2 GHz laptop.

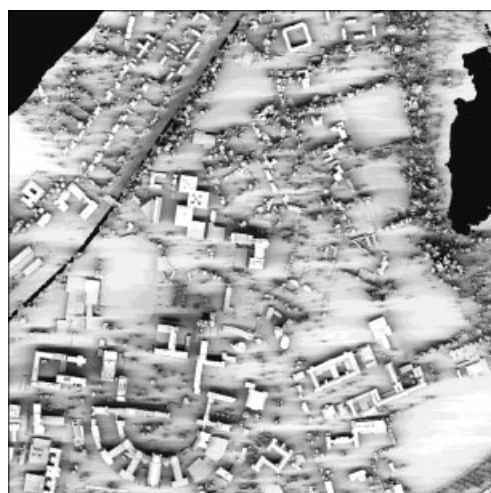


Figure 6. Map of the potential mean daily sun hours at the equinoxes.

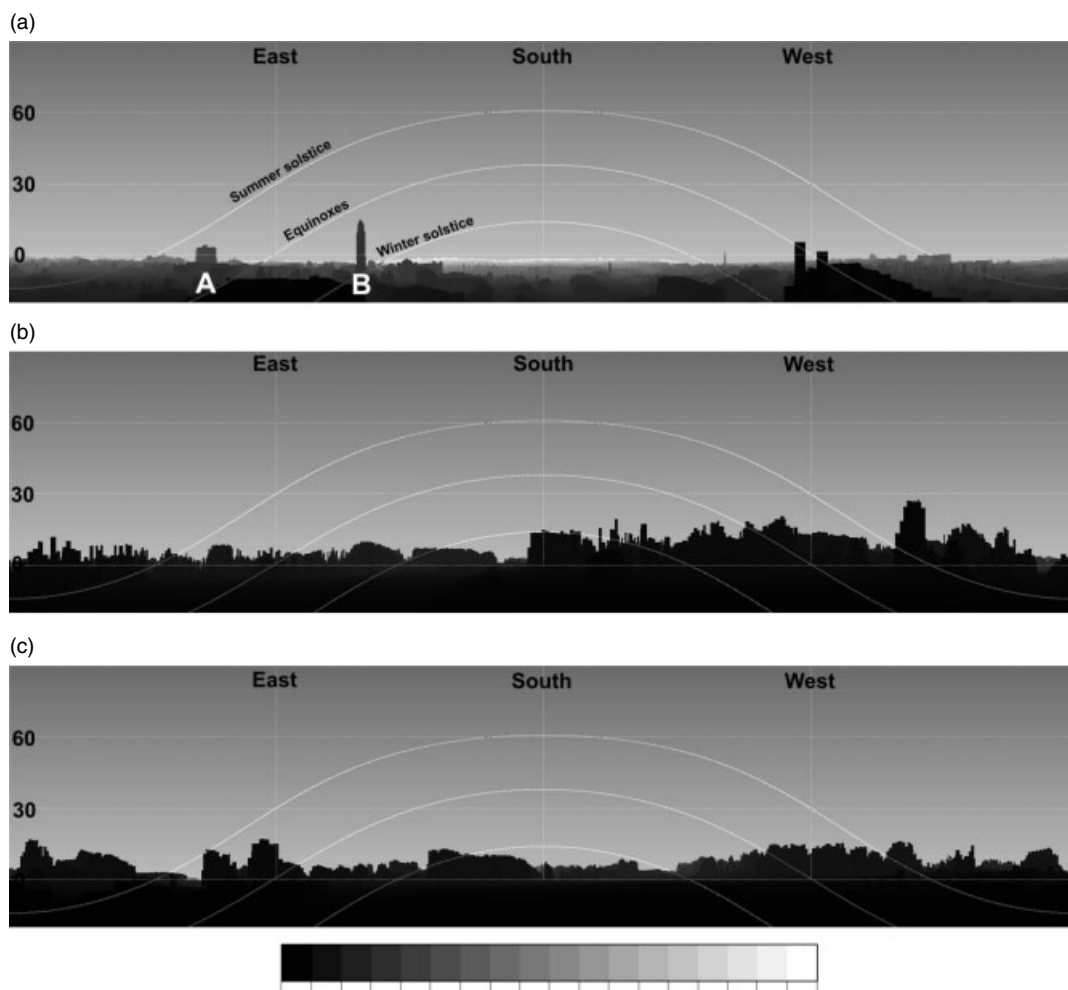


Figure 7. (a) Example of site-specific horizon panorama for a location on the roof of the Biosciences Tower at the University of Birmingham. The faint horizontal lines indicate the 0, 30 and 60° elevation angles, while the faint vertical lines relate to 90° compass points, east, south, west (north is at both extreme left and right). The curved lines represent the solar paths at the summer solstice (top), the equinoxes (middle) and the winter solstice (bottom). The landscape has been shaded according to distance from the location, where black is close and light grey is far. The Muirhead Tower (A) and the Chamberlain Tower (B) of the University can be clearly seen either side of the east compass point. (b) Horizon panorama for the University of Birmingham Winterbourne climatological station (details as in Figure 7(a)). Much of the obstruction of the horizon is relative close to the site caused by shrubs and trees, particularly affecting the wintertime solar view. (c) Horizon panorama for the new University of Birmingham Winterbourne climatological station (details as in Figure 7(a)). The obstruction of the horizon is similar to that of the old site, although blockage of the wintertime solar view tends to be later in the day (being west of south) than at the old site.

increase toward the centres of the areas; these are open areas such as running tracks and playing fields. This map provides the basis for an initial site selection, avoiding the low SVF around buildings and identifying more open sites.

In addition to SVF data, maps of sunshine hours were generated to ensure that potential sites could receive the maximum potential incoming solar radiation. The maps of sunshine hours are shown in Figures 4–6. Figure 4 shows the number of sun hours that could be expected on the summer solstice: only areas close to the northern side of buildings exhibit very low sun hours, while more open areas receive as much as 16 h sun. The opposite extreme, the winter solstice, is shown in Figure 5. Here there is significant shadowing on the northern side of the buildings with some notable shadowing also caused by trees and vegetation. It should be noted, however, that the DSM does not take into account the seasonal variations in vegetation. Finally, Figure 6 shows the number of sun hours at the equinoxes, highlighting shading caused by the low east-west sun angles.

These spatial maps identified a number of potential sites on the ground for the new climatological station. For each of these sites a 360° panorama was generated using the DSM together with the solar trajectories at the solstices and equinoxes; examples of these are shown in Figure 7. Figure 7(a), by way of an extreme example, shows the virtual horizon view from the top of the Biosciences Tower at the University of Birmingham. Since the tower is one of the highest points in the area it can be seen that it has a very clear aspect, only interrupted by two other buildings on campus; the Chamberlain Clock Tower and the Muirhead Tower. Although ideal for radiation studies, its exposed location is less ideal for other measurements. Figure 7(b) shows the horizon panorama for the existing Winterbourne climate site: it can be observed that at the winter solstice the Sun is only visible between south-southeast and south, with vegetation blocking the rest of the trajectory. Each of the potential sites were investigated for planning requirements and access, resulting in the final selection of a site about 300 m to the northwest of the existing climate

site. The horizon panorama for this site is shown in Figure 7(c), and while not ideal it is at least comparable to that of the existing site.

6. Conclusions

This study has shown the utility of combining digital surface model (DSM) and solar angle information to find potential locations of meteorological/climatological sites within an urban environment. Although the results of the methodology provide an indication of possible sites, additional investigations obviously need to be undertaken to ensure that such sites are suitable. Nevertheless, by combining the DSM and solar angle information it is possible to evaluate sites quantitatively, and if repeat DSMs are available, also over time. The technique also provides the ability to identify sites that would not necessarily be considered, thus expanding the range of potential sites. Once the site has been selected the results can provide metadata with the observations. This enables users of the meteorological observations to assess the measurements and correct, if necessary, for any shading effects.

Acknowledgements

The authors would like to thank the Environment Agency for the provision of the lidar data set for evaluation purposes.

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