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A critical analysis of the representation of extreme air temperatures measured at Gravesend-Broadness.

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Abstract

The objective of this project is to analyse the representation of extreme air temperatures recorded by the Gravesend-Broadness meteorological station which has recorded numerous surface air temperature records since it commenced operation in 1996. Clarification of the meaning of extreme air temperatures allows better control of the subsequent data entering climatic models. Between 2009 and 2016, Gravesend-Broadness was the warmest station by daily maximum temperature on 24 of the 50 warmest days of 6 studied sites in the south-east of England. The discrepancy between Gravesend-Broadness daily maximum temperature and the mean of 5 surrounding sites increases from +0.6 degC over all summer days to +1.4 degC over the warmest 10 dates since the beginning of 2009. The spatial variability in air temperatures of the studied sites increases in warmer conditions as temperature differences caused by variable elevation are exaggerated by super adiabatic conditions on the hottest days. 1-minute resolution data reveals that Gravesend-Broadness is susceptible to an intermittent and cooling estuary breeze not detected at surrounding sites. Non-conformity to representative measuring standards permits warmer afternoon air temperatures and corresponding maxima at the measuring station. The measuring station is susceptible to a microclimate and unique site characteristics that combine to generate the warmest air temperatures in the south-east of England on the warmest days.

Abbreviations

AWS – Automated Weather Station(s)

MODIS - Moderate Resolution Imaging Spectrometer

MSL – Mean Sea Level

RUAO – Reading University Atmospheric Observatory

T_{max} – Daily Maximum Air Temperature

UKMO – United Kingdom Met Office

WMO – World Meteorological Organisation

Thames stations – The term used to describe the synoptic stations surrounding Gravesend-Broadness collectively; East Malling, Kew Gardens, St. James's Park, Shoeburyness and Faversham.

1: Introduction

Since records commenced in 1996, the Gravesend-Broadness measuring station has frequently recorded the warmest daily maximum air temperature (T_{max}) during heatwave and extreme air temperature conditions. Inherently this has attracted much media attention and the town of Gravesend is frequently labelled the 'warmest in the UK' as shown in figure 1.

Figure 1: BBC News article reporting the warmest day of year at the town of Gravesend, 24 August 2016 (BBC News, 2016).

Notably it is common for the town of Gravesend itself to be labelled as the warmest place although measurements are made at the Gravesend-Broadness site approximately 3km north-west of the town centre, on the Swanscombe Peninsula, see figure 2.b. This has stirred speculation amongst the meteorological community that air temperatures recorded at the Gravesend-Broadness site are enhanced by site specific features and not representative of the area they are provided for during extreme heat periods (Burt, 2004).

This project investigated how air temperatures recorded at Gravesend-Broadness compared to surrounding sites on the warmest days in the south-east of England from 2009 to 2016, quantifying if Gravesend-Broadness was the warmest station in the south-east. This project will help us to improve our understanding of the prerequisite weather conditions associated with the lead up to an extreme air temperature recording at UK Met Office (UKMO) measuring stations in the south-east of England. The study of extreme air temperature is important as it can have major impacts on human health.

A homogenous climate time series is defined as one where variations are caused only by variations in weather and climate (Conrad and Pollak, 1950). The possibility that Gravesend-Broadness records non-representative air temperatures posed a concern over the reliability of the raw data and the resultant effect on the homogeneity of climate records. It was decided if measurements of extreme air temperatures at Gravesend-Broadness were representative. Contributing factors at the observatory site and physical features within its fetch were discovered on a field visit, referencing to guidelines set out by the World Meteorological Organisation (WMO) (2017). Awareness of non-representative extreme air temperature measurements allows for better quality control of data entering climatic models. For example, the UKCP09 model and its 5 x 5 km gridded datasets described by Perry and Hollis (2005) which include Gravesend-Broadness measurements. More accurate UKCP09 gridded datasets can more accurately verify larger global scale models such as the CRUTEM3 model (Brohan et al., 2006). Although this project focused on the potentially non-representative measurements of just one station, a similar method can be applied to detect non-representative measurements on a wider scale in the future.

1.1: Literature

Spatial variation in air temperature on the warmest days has been well documented (Thornes, 2005; Oke, 1981). The study of urban heat island intensities by Oke (1981) reported intra-urban air temperature differences of up to 9 degC. Urban heat island air temperature enhancements of up to 3.72 degC overnight at Birmingham New Street Station were discovered when compared to countryside around the city of Birmingham during a heatwave of 2006 (Basset et al., 2013, cited in Thornes, 2015, p.1). Thornes (2015) describes that no clear correlation between wind speed and air temperature could be found from measurements at Birmingham New Street Station during the heatwave of July 2013, although anticyclonic winds within the enclosed station were less than 0.8 m s^{-1} and deemed typical of UK heatwaves. Thornes (2015) also measured air temperature differences on a 1-minute basis between the station and Paradise circus, finding that the greatest absolute difference in air temperature was 6.2 degC which occurred on 11 July 2013, the coolest day of the heatwave. Taha et al. (1988) similarly discovered that an urban heat island can raise air temperature by up to 5 degC in a mid-latitude metropolitan area on a mid-summers day. During the heatwave of 2003, Burt (2004) believed the T_{max} recorded on 10 August 2003 at Gravesend-Broadness and Faversham were up to 0.5 degC too warm due to site irregularities. A study of the same heatwave over Europe by Krähenmann et al. (2011) found that T_{max} data is less normally distributed than mean air temperature values, showing that the T_{max} between individual sites is more varied and they tend to occur at different times. Several studies are consistent in their belief that the warmest surface air temperatures in the UK are preceded by stationary high pressure systems over northern Europe, permitting persistent southerly airstreams over the UK (Prior and Beswick, 2007; Burt, 2004; Karl and Nicholls, 1999; Burt, 1992).

1.2: Project aims

This project seeks to address the hypothesis that Gravesend air temperatures are influenced by a local microclimate. This enables several scientific questions to be answered;

- Is Gravesend-Broadness truly the warmest place in the south-east of England or is this anecdotal?
- What determines 1-minute fluctuations in air temperature leading up to and during the hottest days recorded at Gravesend-Broadness?
- Does Gravesend-Broadness have a microclimate and what factors contribute to it?
- How do microclimatic effects influence homogeneity of climate records?

The methods taken to assess these questions are detailed in section 2.

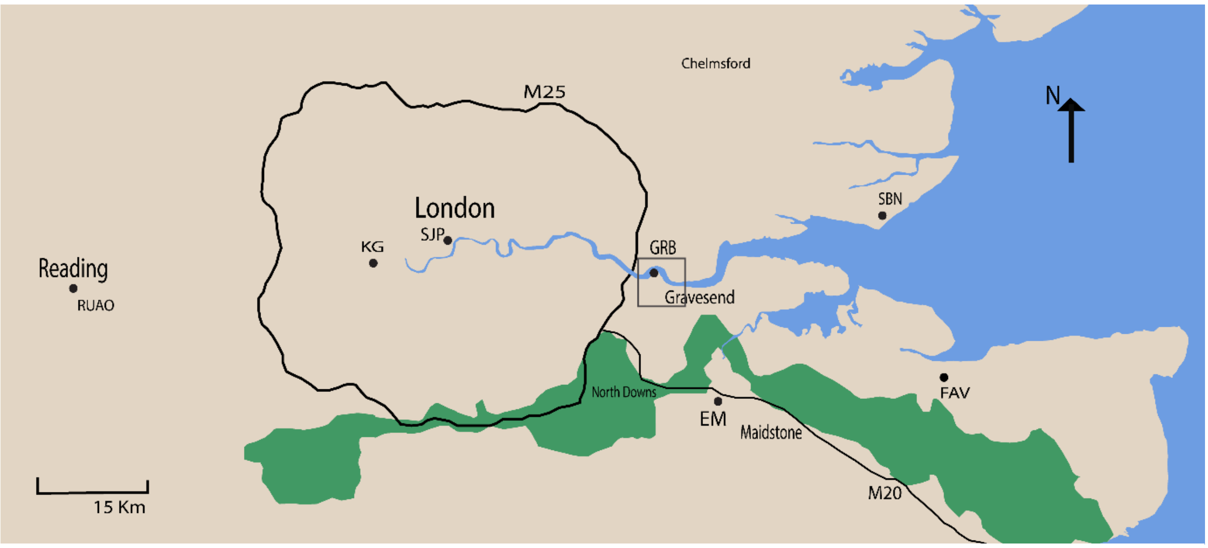

Figure 2.a: Location map of the Reading University Atmospheric Observatory (RUAO), Thames stations; Kew Gardens (KG), St. James's Park (SJP), East Malling (EM), Shoeburyness (SBN), Faversham (FAV) and Gravesend-Broadness (GRB) within the south-east of England. A rectangle shows the area covered by 2.b. The North Downs are highlighted in green and Thames Estuary in blue.

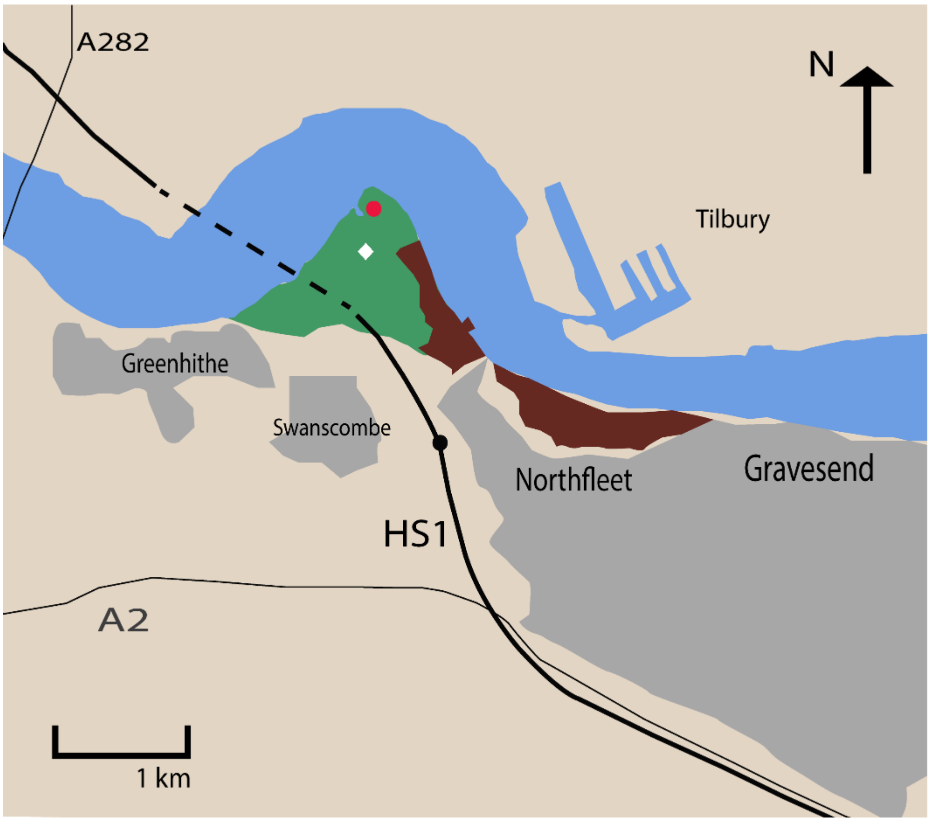

Figure 2.b: Closer scale position of the Gravesend-Broadness site (red) at the tip of the Swanscombe Peninsula marshland (green) within North-West Kent, bordered by the River Thames which flows from west to east. Urban areas are highlighted in grey and industrial works including the Britannia Metals Refinery are highlighted in maroon. The position at which the images in figures 4 and 5 were taken is represented by a white diamond. HS1 denotes the high-speed-1 rail link.

2: Methods and Data

Main meteorological data sources for this project were provided by the UKMO and the Reading University Atmospheric Observatory (RUAO). Archived UKMO synoptic charts and satellite images from the Moderate Resolution Imaging Spectrometer (MODIS) satellite were used to provide a comparison of in-situ wind direction measurements to the wider synoptic scale on case study dates.

2.1: Field Site visit

The author conducted a field site visit to the Gravesend-Broadness automatic weather station (AWS) to assess its exact nature and the land use characteristics with influencing air temperature recorded there. This allowed an understanding of recorded air temperature enhancements by upwind physical features present on case study dates to be understood. Photographs were taken of the measuring station and any upwind land features of potential influence, see figures 3,4 and 5.

Figure 3: (Image looks toward the north-north-east) The Gravesend-Broadness AWS enclosure at the northern tip of the Swanscombe Peninsula, bordered by steel fencing, radar masts operated by the PLA are also present within the enclosure. A Stevenson screen and 10m wind measuring mast are in the south-east corner of the enclosure (taken by the author).

Figure 4, 5: Both images taken 150m directly south of the Gravesend-Broadness site. Left, figure 4 looks to east-south-east, overhead powerlines and Industrial areas including Britannia Metals refinery are visible. Right, figure 5 looks directly south where chalk cliffs +28m above mean sea level (MSL) are visible (Dartford Borough Council, 2004). Urban areas of Gravesend, Northfleet and Swanscombe are atop (taken by the author). Exact position of capture relative to site noted in figure 2.b.

2.2: Met Office meteorological data

Data recorded by 5 Automated Weather Stations (AWS) including Gravesend-Broadness and 1 manual station in the south-east of England was collated by T_{max}. Additionally, more detailed 1-minute resolution air temperature, wind speed and direction data for three of those stations was collected for Gravesend-Broadness, East Malling and Kew Gardens. The 5 stations surrounding Gravesend-Broadness will be referred to as the Thames stations as a collective, see table 1.

Station	Type	Straight-line distance from Gravesend-Broadness (km)	Geolocation (Decimal degrees)	Altitude above mean sea level (MSL) (m)
Gravesend-Broadness	AWS	-	51.464, 0.313	3
East Malling	AWS	17.8 to south-east	51.287, 0.450	33
Shoeburyness	AWS	31.1 to north-east	51.554, 0.828	2
St. James's Park	AWS	35.6 to west	51.504, -0.129	5
Faversham	Manual	38.8 to east	51.296, 0.879	46
Kew Gardens	AWS	46.3 to west	51.481, -0.292	6

Table 1: The Thames stations in order of straight-line distance from Gravesend-Broadness, exact positions of Stevenson screen enclosures are provided in geographical coordinates. Shaded stations are additionally analysed in finer 1-minute resolution (section 3.2.2).

AWS make observations collected in real time by the Exeter based headquarters, while Faversham observations of T_{max} are recorded by manual observation each day, compiled on site and transferred to the Exeter based headquarters monthly. During a heatwave in the south-east this often leads to delays in Faversham declaring the warmest T_{max}. As was the case on 10 August 2003 when Gravesend-Broadness (38.1°C) was initially awarded the all time T_{max} record, however this was retrospectively transferred to Faversham (38.5°) the following month (Burt, 2004; BBC News, 2017).

The Thames stations and Gravesend-Broadness form part of a larger UK wide network of more than 200 synoptic stations operated by the Met Office (2016), these provide continual observation of meteorological variables which are assimilated by climate models such as the UKCP09 (Perry and Hollis, 2005). The AWS record air temperature via platinum resistance thermometer housed within a Stevenson screen 1.25m above its observatory surface. Measurements of air temperature every 15 seconds are averaged to form 1-minute measurements, the AWS T_{max} is defined as the extreme 1-minute value recorded within the 24-hour period up until 2100UTC. In the case of Faversham, a mercury based self-registering maximum and minimum thermometer is mounted within the Stevenson screen and is read at 0900UTC instead of the evening, further details on this collection difference are provided in section 2.2.1. The AWS also record wind speed and direction via cup anemometer and vane respectively, both are mounted atop a 10m mast within the observatory enclosure, measurements are taken in 0.25s intervals and averaged to provide a 1-minute value (Met Office, 2017). Thornes (2015) recorded a discrepancy between analogue and digital measurements of air temperature however the standard error in the mean of analogue and digital measurements was considered small, less than 1 degC in heatwave conditions.

2.2.1: Daily maximum temperature

Before a Thames station and Gravesend-Broadness mean T_{max} could be calculated, it was discovered that separate methods are used to generate a T_{max} at Faversham in comparison to the 5 AWS. The T_{max} at Faversham is defined by the warmest air temperature recorded by mercury thermometer within the 24 hours leading up until 0900UTC on the *morning* of the measurement day. On the other hand, the T_{max} at the 5 AWS are generated by the extreme 1-minute air temperature recorded within the 24 hours leading up to 2100UTC in the *evening* of the measurement day.

It will be assumed that any date stamped T_{max} recorded at Faversham infers the warmest temperature from the previous afternoon when compared with the 5 AWS (Table 1). To confirm this, two correlations were performed between T_{max} in Faversham and mean T_{max} values of the 5 AWS. The first was between the two datasets with the same date stamp (0.16) and the second with Faversham date stamps 1 day ahead of the 5 AWS (0.83). This was performed over the warmest 50 days which in this correlation only, were defined by the rank of mean T_{max} at the 5 AWS recording T_{max}, up until 2100UTC in the evening of the measurement day. The correlation coefficient in the two datasets with Faversham date stamps 1 day ahead (0.83) is much closer to 1 which confirms that date stamped measurements at Faversham are 1 day ahead of the other 5 sites when comparing T_{max} in summertime.

As there is not a uniform method for calculating T_{max} between all Thames stations and Gravesend-Broadness, data comparisons may be less reliable against Faversham. During summertime in the UK, it is unlikely but not impossible for T_{max} to be recorded between 21:00 and 09:00 overnight, as air temperature in summer months is controlled mostly by the amount of solar heating (Karl and Nicholls, 1999). For example, on 1 July 2015, the air temperature at Kew Gardens was already 33.0°C at 0900UTC, 2.7 degC lower than its 35.7°C T_{max} on this day. By relying upon the assumption that the highest temperatures at Faversham were not recorded overnight, this method is not portable to assess wintertime T_{max} between Faversham and the other 5 sites, when overnight T_{max} are frequent.

Between January 2009 and November 2016, T_{max} from the Thames stations and Gravesend-Broadness were collected to provide a quantitative assessment of the warmest days in the past 8 years. The Thames stations were chosen for their proximity in terms of physical distance to Gravesend-Broadness and the Thames Estuary, 84km was the farthest separation of a site pair, Kew Gardens and Faversham (Figure 2.a). Due to time constraints, it was not possible to include more stations within this analysis, which may limit the comparability of any results from this south-east location with the wider UK climate. T_{max} from each day of the 7 summers (1 July – 31 August inclusive) between 2009 and 2016 were averaged to derive a mean summertime T_{max} at each of the Thames stations and Gravesend-Broadness.

Next, the 50 and 10 warmest days in the south-east of England were derived by first calculating a mean T_{max} of all Thames stations and Gravesend-Broadness on each day between 1 January 2009 and 1 November 2016 to generate a ranked order of T_{max}. This reveals the warmest days in the south-east wholly. This method was preferred over generating the warmest dates by order of the highest T_{max} at Gravesend-Broadness independently. This secondary option will have generated a bias towards the warmest days at Gravesend only. However, the comparability of the summertime and warmest 50 and 10 day datasets will be limited. This is because some of the warmest days between January 2009 and November 2011 occurred outside of the summer season, such as the 13 September 2016, on which a 34.4°C T_{max} was recorded at Gravesend-Broadness. The 10 warmest days were additionally analysed in 1-minute resolution data at Gravesend-Broadness, East Malling and Kew Gardens on a synoptic case study basis described in section 2.2.2.

2.2.2: 1-Minute resolution

The 10 warmest days defined by the ranked order of Thames stations and Gravesend-Broadness T_{max} were additionally assessed on a synoptic basis with the addition of finer resolution data in 1-minute form. Due to project time constraints and lack of wind data at some Thames stations, only Gravesend-Broadness, East Malling and Kew Gardens were analysed in this detail. Burt and Eden (2004) describe East Malling and Kew Gardens as more reliable and representative sites in comparison to Gravesend-Broadness and Faversham. Air temperature, wind direction and wind speed were analysed between the three sites to provide insight into air temperature fluctuation on 1-minute scales during an extreme air temperature event. Differences in timing between the maximum temperatures at each site on case studies were compared, along with related wind characteristics to understand if any common factors lead to Gravesend-Broadness becoming the warmest station. When combined with the knowledge of upwind surface characteristics discovered during the field site visit, any correlation between air temperature and wind directions at Gravesend-

Broadness can be assessed to understand whether the site is exposed to microclimate factors.

The mean and standard deviation of 1-minute air temperatures recorded between the warmest midday periods of 1000-1800UTC on each of the ten case study dates will be compared at each site to their respective T_{max} values. This will reveal the uniformity of air temperatures recorded at Gravesend-Broadness, East Malling and Kew Gardens and how the rank of station temperatures compares when considering temperatures throughout the daytime in comparison to a single 1-minute extreme associated with T_{max}.

An anomaly regarding wind direction was calculated by subtracting each of the 4800 1-minute air temperature measurements recorded between 1000-1800UTC over the 10 warmest days at Gravesend-Broadness from the respective 1-minute mean values of East Malling and Kew Gardens (480 samples). If the wind speed at the time of each of the 4800 anomaly values measured greater than $0.2\ m\ s^{-1}$ the 1-minute anomaly value is binned against its wind direction in 10° increments. The air temperature anomalies in each 10° increment of wind direction were averaged to form an air temperature anomaly considering wind direction. The minimum wind speed was required to confirm that there was a wind blowing and that the wind vane has not stalled in position. Where the number of samples contributing to a wind direction bin mean air temperature anomaly was less than 30, this wind direction bin was considered unreliable and removed from the analysis.

A second anomaly of Gravesend-Broadness 1-minute air temperatures between 1000-1800UTC over the 10 warmest days from 1-minute mean measurements at East Malling and Kew Gardens was created. This would reveal if Gravesend-Broadness air temperature tends to differ from regional conditions, especially at the warmest 1500UTC period. As there were just 20 contributing samples to each of the 480 1-minute mean values between 1000-1800UTC, the statistical robustness of this anomaly was limited by a small number of station days that it considers. Nevertheless, it is still useful in identifying departures of Gravesend-Broadness air temperature from the mean regional diurnal cycle, especially at the warmest 1500UTC period when T_{max} is usually recorded. The 10 days considered were not consecutive therefore variable synoptic conditions such as cloud cover on these days would further decrease the statistical significance. Identification of the synoptic situation and cloud cover presence on the 10 case study dates is detailed in section 2.3, anomaly data corresponding to days on which the air temperature was heavily influenced by cloud cover would be removed from the dataset as cloud cover is not a variable which this project otherwise controls, see section 3.2.

2.3: Synoptic charts and satellite imagery

UKMO synoptic charts at 0000UTC on each of the case study dates along with MODIS satellite imagery of south-east England were analysed, to reveal the synoptic wind direction and cloud presence respectively (University of Dundee, 2017). Knowledge of cloud position on the case study dates can reveal the nature of any unexpected fluctuation or decrease in temperature. In addition, the synoptic wind direction can be compared to those recorded at Gravesend-Broadness, East Malling and Kew Gardens to confirm the presence of microclimate effects at Gravesend-Broadness and whether wind direction changes are consistent with the synoptic case or a sea-breeze effect from the River Thames estuary exists. Importantly, the MODIS satellite tends to pass the south-east of England on no more than two occasions during daylight hours on any of the case study dates. Although this is enough to reveal general location and development of cloud cover, this imagery is only useful as supporting evidence and is not considered a primary data source for this investigation. A synoptic chart from 1200UTC on each case study day would be more accurate but is not archived, the synoptic situation assessed at 0000UTC will change somewhat by the warmest daytime period we are interested in. Thus, these charts may not be used to infer precise wind speeds or local directions in the afternoon. On the other hand, heatwave conditions leading to an extreme T_{max} in the UK commonly require hot anticyclonic conditions in the days prior (Burt, 2004). Stationary anticyclones persist and evolve relatively slowly in comparison to cyclones (Lyall, 1974), therefore the 0000UTC chart is still useful to show the direction from which air masses in the south-east have advected.

2.4: Reading University Atmospheric Observatory

The RUAO is 91km west of Gravesend-Broadness, therefore the two stations will experience different meteorological influences. However, this distance places the two stations within the same mesoscale, defined by Oke (1987) as greater than 10^4 km, meaning that synoptic influences experienced at Gravesend-Broadness will still apply at the RUAO. The wide array of radiation data at the RUAO is beneficial to understand the influence of cloud cover upon air temperature on warm summer days in the south of England. The downward shortwave radiation component was compared with air temperature on two consecutive days, one known to be clear and the next, overcast. This meant that the incident radiation would otherwise be the same at the measuring station under the same atmospheric conditions. The influence of cloud cover on the diurnal cycle of air temperature can be related to that at Gravesend-Broadness on case study dates known to have experienced passing cloud cover.

3: Results

3.1: Is Gravesend the warmest station in the south-east by mean air temperature?

Gravesend-Broadness recorded the highest mean T_{max} in each of the three T_{max} categories measured between 2009 and 2016 (Table 2). On summer days, mean Gravesend-Broadness T_{max} was 0.6 degC higher than the Thames station mean. Mean summertime T_{max} at Gravesend-Broadness was 0.3 degC and 0.4 degC above Kew Gardens and St. James's Park. The difference In Gravesend T_{max} from the Thames station mean increases from +0.6 degC in mean T_{max} of all summers between 2009 and 2016 to +1.2 degC and +1.4 degC in the 50 and 10 warmest days respectively. This shows that as heat wave conditions in the south-east of England become more extreme, Gravesend-Broadness air temperatures are propelled farther above the regional mean. Galvin (2005) and Tinn (1938) similarly recorded increases in summertime surface air temperature range as conditions became warmer, dryer and clearer in the Hertfordshire and Nottingham districts respectively.

Stronger convection conditions make the atmosphere more unstable above the south-east, super-adiabatic conditions will exist. Galvin (2007) documents that on a warm sunny day in the UK, temperature can decrease as much as 4 degC in the first 50m of elevation. Table 1 shows that the Gravesend-Broadness AWS is just 3m above mean sea level (MSL). The land immediately south is elevated on top of a chalk cliff (Figure 5) +28m above MSL (Dartford Borough Council, 2004). Air flows tend to be southerly on the warmest days (Burt, 1990). Air parcels travelling on a southerly flow in the lee of the North Downs toward Gravesend-Broadness will therefore sink (Figure 2.a) from 122m elevation 15km south (Wilson, 2002).

As they compress, the air parcels warm super adiabatically on the warmest days, allowing warmer surface air temperatures to be recorded at Gravesend-Broadness relative to higher elevated and flatter sites. The warmer the conditions the greater air temperature changes in an air parcel per m of elevation as the surface heats much faster than the air directly above in clear conditions. Therefore clearer, warmer and more unstable the conditions allow greater spatial variation in air temperature.

Air Temperature Category	(1) (°C)	(2) (°C)	(3) (°C)	(4) (°C)
Gravesend-Broadness	22.5	29.9	32.8	30.3
East Malling	21.5	28.6	31.4	29.6
Kew Gardens	22.2	29.5	32.4	30.3
St. James's Park	22.1	29.6	32.5	-
Shoeburyness	21.5	26.7	28.3	-
Faversham	22.0	29.1	32.6	-
Thames station mean	21.9	28.7	31.4	-
Gravesend-Broadness difference from Thames station mean	+0.6	+1.2	+1.4	-
All 6 stations mean	22.0	28.9	31.6	-
Gravesend-Broadness difference from all stations mean	+0.5	+1.0	+1.1	-
East Malling and Kew Gardens mean	21.9	29.1	31.9	30.0
Gravesend-Broadness difference from mean of East Malling and Kew Gardens	+0.6	+0.8	+0.9	+0.3

Table 2: Summary of Thames stations and Gravesend-Broadness air temperatures between 2009 and 2016 including T_{max} and 1-minute resolution data sets, shaded cells represent the difference in Gravesend-Broadness air temperature from the regional mean in each category (degC). Blank cells indicate non-applicable fields. Mean T_{max} of June, July, August 2009-2016 (1). Mean T_{max} of warmest 50 days of all between 2009-2016 (2). Mean T_{max} of warmest 10 days of all between 2009-2016 (3). Mean of 1-minute air temperatures between 1000-1800UTC on 10 warmest days of all between 2009-2016 (4).

The 50 warmest Thames station days do not include air temperature measurements from sites farther afield. Thus, these warmest dates may not be homogenous with the rest of the UK, therefore statement of the 'warmest dates' truly refers to the south-east of England and the region covered by the six sites in question only. Figure 2.12b of Jenkins et al. (2009) shows the area covered by the sites in this project to be warmest of any UK region by mean summertime T_{max} of the UKCP09 model from 1961-1990. Figure 2.5b of Jenkins et al. (2009) gives the same result in mean summertime air temperature from 1971-2000. This means that the warmest of the studied stations within this project is likely the warmest in the UK.

Gravesend-Broadness recorded the warmest T_{max} on 24 of 50 occasions (Table 3). Shoeburyness recorded the lowest individual mean T_{max} over the 50 warmest days, 2.0 degC lower than the Thames station mean despite its 2m elevation above MSL. This is explainable by the coastal location of Shoeburyness along the mouth of the Thames Estuary, see Figure 2.a. A common prerequisite for the hottest days in the south-east of England is the presence of an anticyclone permitting southerly air flow (Prior and Beswick, 2007; Burt, 2004; Karl and Nicholls, 1999; Burt, 1992). The south and south-easterly fetch at Shoeburyness is the English Channel, sensible heat flux (Q_H) is reduced above water bodies, thus the diurnal range in temperature for an air mass arriving from the water in the south or south-east will be suppressed (Oke, 1987).

Station	Gravesend	East Malling	Kew Gardens	St. James's Park	Shoeburyness	Faversham
Highest T_{max} frequency	24	1	9	9	1	10

Table 3: Summary of the frequency at which each station recorded the highest T_{max} of any station over the 50 warmest days, on 4 days, the warmest T_{max} was tied between a pair of sites.

Tinn (1938) and Smith (1976) also document that T_{max} varied most between coastal located screens and those farther inland during fine, anticyclonic conditions. The temperature of an air mass arriving at inland stations will be relatively warmer having undergone surface heating in the presence of Q_H while advecting dry land surfaces of Kent when moving from the south or south-east. It is therefore surprising that St. James's Park and Kew Gardens are also cooler than Gravesend-Broadness on average by 0.3 degC and 0.4 degC respectively over the 50 warmest days, see appendix A. This was not expected considering that urban heat island effects associated with metropolitan areas such as those in London have been known to raise the air temperature by up to 5 degC during a mid-latitude summer's day (Taha et al., 1988). Study of the August 2003 heatwave by Burt (2004) excluded the highest T_{max} values recorded by Gravesend-Broadness and Faversham on 10 August 2003 because they were considered both misrepresentative of the locality and excessively influenced by local site influences. In this case, St. James's Park and Kew Gardens were the warmest locations. Between 2009 and 2016, Gravesend-Broadness and Faversham similarly have also consistently recorded the warmest mean T_{max} values whose removal would also constitute St. James's Park and Kew Gardens being the warmest location in the south-east. Importantly the summer T_{max} category does not include all 50 of the warmest dates since 2009. Other events outside June, July and August will not be included in the summertime T_{max} category, this limits comparability between summertime measurements and the warmest days while summertime measurements only include data from 3 months in each year.

Date	Gravesend		East Malling		Kew Gardens		St. Jp	Sbn	Fav	All sites mean T_{max}
	T_{max}	Mean 10-18 (UTC)	T_{max}	Mean 10-18 (UTC)	T_{max}	Mean 10-18 (UTC)	T_{max}	T_{max}	T_{max}	
01/07/2015	34.7	32.0 ± 1.8	33.5	31.0 ± 1.7	35.7	33.6 ± 1.3	34.7	26.3	35.2	33.4
24/08/2016	33.9	31.0 ± 1.4	32.1	30.0 ± 1.4	33.0	30.4 ± 1.6	33.0	30.0	34.1	32.7
01/08/2013	33.2	31.3 ± 1.2	31.6	29.6 ± 1.6	33.0	31.2 ± 1.3	33.0	30.4	32.6	32.3
13/09/2016	34.4	30.6 ± 2.2	31.3	30.1 ± 1.0	33.5	30.5 ± 1.9	32.5	26.5	32.7	31.8
27/06/2011	33.1	30.7 ± 1.6	31.2	28.8 ± 1.5	31.4	28.5 ± 1.4	32.0	30.7	31.1	31.6
09/07/2010	31.7	29.4 ± 1.9	30.3	28.6 ± 1.3	31.0	28.4 ± 2.3	31.2	29.8	32.7	31.1
22/07/2013	30.7	28.4 ± 1.3	32.1	30.6 ± 1.2	33.2	30.9 ± 1.8	33.3	24.8	32.4	31.1
18/07/2014	32.3	29.5 ± 2.3	30.7	29.2 ± 0.9	31.2	29.5 ± 1.0	31.8	27.8	31.5	30.9
18/08/2012	31.5	29.6 ± 1.2	30.1	28.8 ± 1.1	29.6	28.5 ± 0.8	30.8	30.8	32.1	30.8
19/07/2016	32.1	30.0 ± 1.8	30.7	29.7 ± 0.7	32.5	31.4 ± 0.7	32.3	25.5	31.4	30.8
Mean	32.8	30.3 ± 1.7	31.4	29.6 ± 1.2	32.4	30.3 ± 1.4	32.5	28.3	32.6	31.7

Table 4: Summary of the 10 warmest days in the south-east between 2009 and 2016, calculated by the ranked mean T_{max} on each day since 2009, between East Malling, Kew Gardens, St. James's Park ('St. Jp'), Shoeburyness ('Sbn'), Faversham ('Fav') and Gravesend-Broadness. The T_{max} at station is shown, as well as the mean of 1-minute air temperatures between 1000-1800UTC ('Mean 10-18 (UTC)') on each of the 10 warmest days in East Malling, Kew Gardens and Gravesend-Broadness. The standard deviation is displayed as error.

The warmest station rank can also be influenced by the method used to calculate the statistic. When comparing, Gravesend-Broadness, East Malling and Kew Gardens only; Gravesend-Broadness and Kew Gardens recorded the same mean of 1-minute air temperatures between 1000-1800UTC over the 10 warmest days (30.3°C) as shown in table 4. However, the mean T_{max} over the 10 warmest days was 0.4 degC higher in Gravesend-Broadness than East Malling. Gravesend-Broadness remains warmer than the mean 1-minute daytime air temperatures of East Malling and Kew Gardens by a smaller margin of +0.3 degC compared to +0.9 degC in T_{max}. Krähenmann et al. (2011) similarly found that T_{max} data was more varied than mean air temperature values in heatwave conditions. This is because surface air temperature range increases as conditions become warmer (Galvin, 2005; Tinn, 1938), therefore at the time of recording extreme values, air temperatures will vary more.

Table 4 also shows that Gravesend-Broadness recorded the warmest T_{max} of the 6 stations on 4/10 occasions and at least the second warmest T_{max} on 7/10 occasions. The warmest T_{max} since 2009 was recorded by Kew Gardens on 1 July 2015. Gravesend T_{max} was 1.0 degC lower than the Kew Gardens 35.7°C record, section 3.2 details that passing cloud cover had interrupted the diurnal cycle of air temperature most significantly at Gravesend-Broadness and East Malling on this day and therefore limited the T_{max} recorded there.

3.2: Lead up to an extreme air temperature recording

Initial motivations for this investigation were launched by the apparent correlation between wind direction and air temperature during the mid-afternoon of 13 September 2016 at Gravesend-Broadness (Figure 6). On this afternoon, a sharp increase of nearly 3 degC in air temperature between 1300-1320UTC led to Gravesend-Broadness recording the warmest T_{max} of 2016 In the UK (34.4°C). At East Malling and Kew Gardens, the air temperatures at this specific mid-afternoon period were less variable, despite East Malling being situated just 18km south-east of Gravesend-Broadness. The T_{max} at East Malling and Kew Gardens was 31.3°C and 33.5°C respectively. The abrupt mid-afternoon fluctuations in wind direction from the east-north-easterly and south-easterly directions in less than 15 minutes at Gravesend-Broadness were not replicated by East Malling and Kew Gardens nor predictable from the 0000UTC UKMO synoptic chart (Figure 7). The latter suggested a consistent wind from the south-east as recorded by East Malling (Figure 6) and Kew Gardens (not shown). The 0000UTC UKMO synoptic chart is the closest available to the midday period and is susceptible to changes as the weather system will have evolved by midday. However, heat wave conditions associated with the warmest days studied in this project require persistent stationary anticyclonic presence over Britain (Lyall, 1974). By midday the anticyclone is unlikely to have undergone significant changes meaning that the 0000UTC synoptic chart will still be relevant for the warmest afternoon period. The attribution of air temperature fluctuations to changes in wind direction would ignore the influence of other meteorological variables such as daytime cloud cover which causes cooling in the Northern Hemisphere during the summer (Groisman et al., 2000). This is because, incident solar radiation is limited which in turn reduces the available energy at the surface, lowering sensible heat flux.

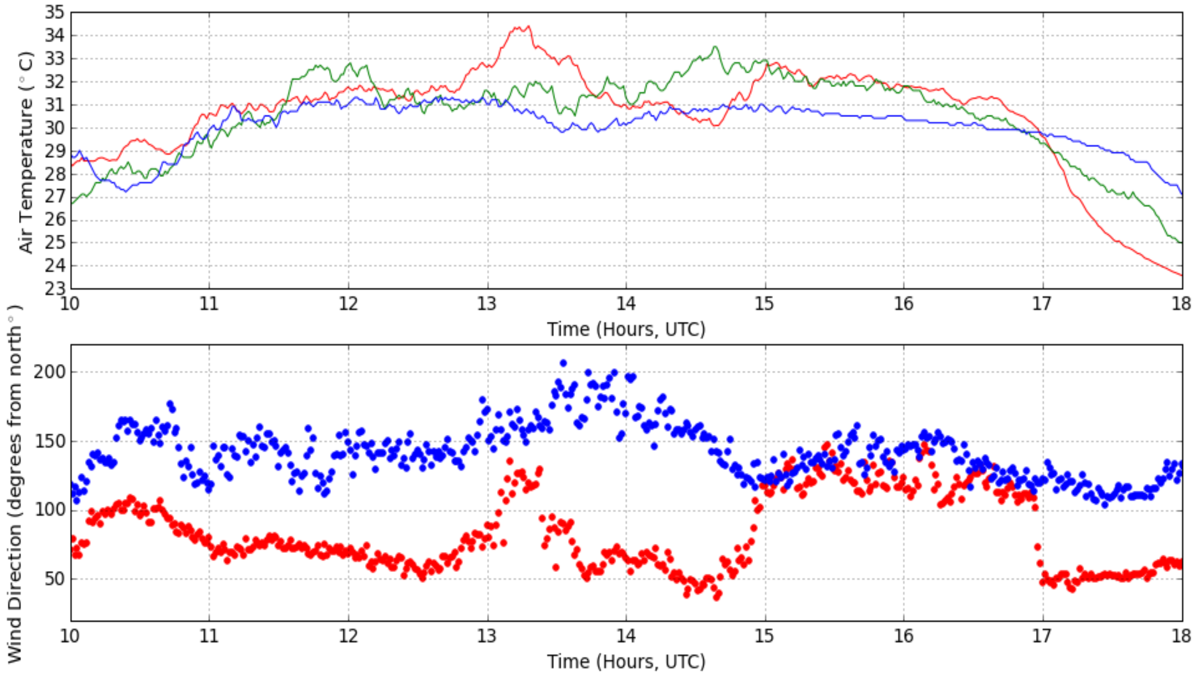

Figure 6: 1-minute air temperature and wind directions at Gravesend-Broadness (red), East Malling (blue) and Kew Gardens (green) between 1000-1800UTC 13 September 2016. 1-minute wind directions at Kew Gardens not shown for clarity.

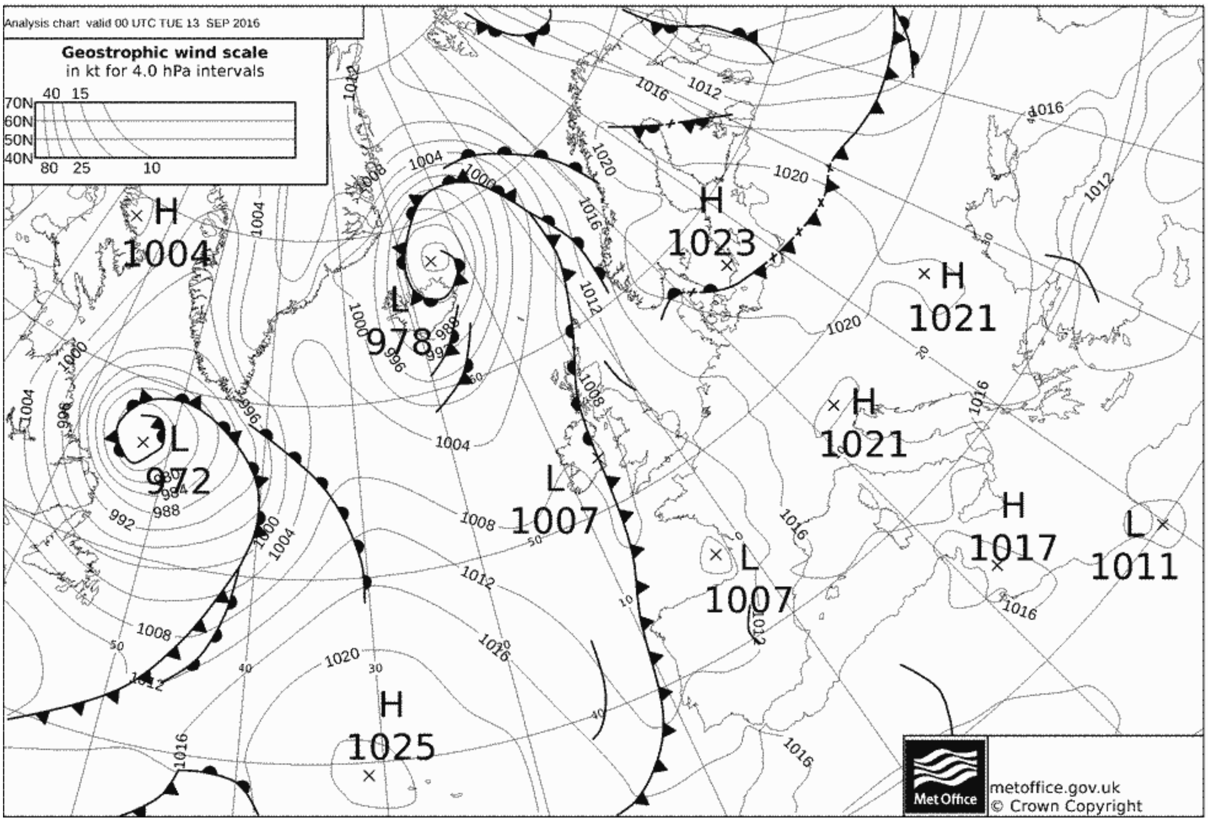

Figure 7: 0000UTC UKMO synoptic chart for 13 September 2016

MODIS satellite imagery on 13 September 2016 indicates that morning cloud cover had almost cleared by 1333UTC over the south-east of England, see figure 8. This means that cloud cover at Gravesend-Broadness on this day was unlikely to influence in the sharp mid-afternoon temperature fluctuations. Nevertheless, it is not possible to confirm whether convective cloud formation in the south-east did not occur due to lack of both further satellite passes and an archived 1200UTC UKMO synoptic chart on the case study.

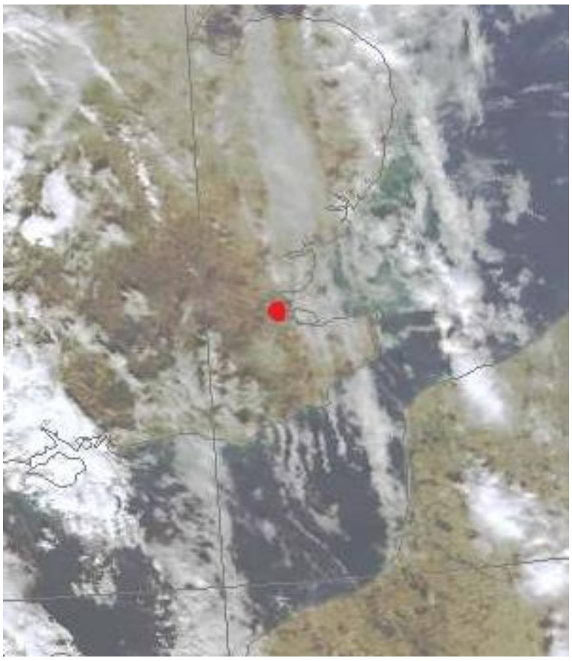

Figure 8: MODIS satellite high resolution composite image of south-east England, 13 September 2016, 1333UTC. Position of Gravesend-Broadness is marked in red.

The position of the Gravesend-Broadness AWS (Figure 2.b) at the tip of the Swanscombe Peninsula means that winds between the directional bin 110°-260° (southerly) deliver air masses via the neighbouring towns of Gravesend, Northfleet, Greenhithe and Dartford less than 1.5km inland. Additionally, the North Downs lies 15km beyond in this direction. Winds from the west have travelled along the tidal section of the river Thames from the direction of the 5km distant Queen Elizabeth II bridge and London City airport beyond, but easterly winds leave the AWS downwind of the Thames Estuary. To the north is a 300m stretch of open water bordering the county of Essex.

Table 4 shows that 1 July 2015 was the warmest day between 2009 and 2016. The mean T_{max} of the 6 stations was 33.4°C. Kew Gardens recorded the absolute highest Individual

T_{max} on this day (35.7°C), while Gravesend-Broadness recorded a T_{max} of 34.7°C. Despite East Malling positioning just 18km south-east of Gravesend-Broadness, the T_{max} there was 33.5°C, 1.2 degC lower than Gravesend-Broadness. 1-minute air temperature measurements and MODIS satellite imagery show that air temperatures were likely influenced by sustained passing cloud cover on this day, see figures 9 and 10. 1 July 2015 was the only day of the warmest 10 with pronounced cloud cover passing over Kent and the south-east, this prolonged enough to cause a significant cooling in air temperature between 1130UTC and 1315UTC. The air temperature at all stations fell during this period, initially at Kew Gardens before Gravesend-Broadness and East Malling. Air temperature at Gravesend-Broadness fell from 33.7°C at 1115UTC a temperature near its 34.7°C maximum during what is usually the warmest time of day. At 1315UTC air temperature at Gravesend-Broadness and East Malling begins to recover and the air temperature at Gravesend-Broadness rapidly increases by 3 degC in a 10-minute period. A wind direction fluctuation between 100-150° (from north) coincides with the temperature increase at 1315UTC but not a similar wind fluctuation at 1215UTC (Figure 9). Thus, current data cannot confirm that a wind direction change at 1315UTC contributed to the rapid increase in air temperature, instead this was likely due to cloud clearing as seen at 1245UTC in figure 10.b.

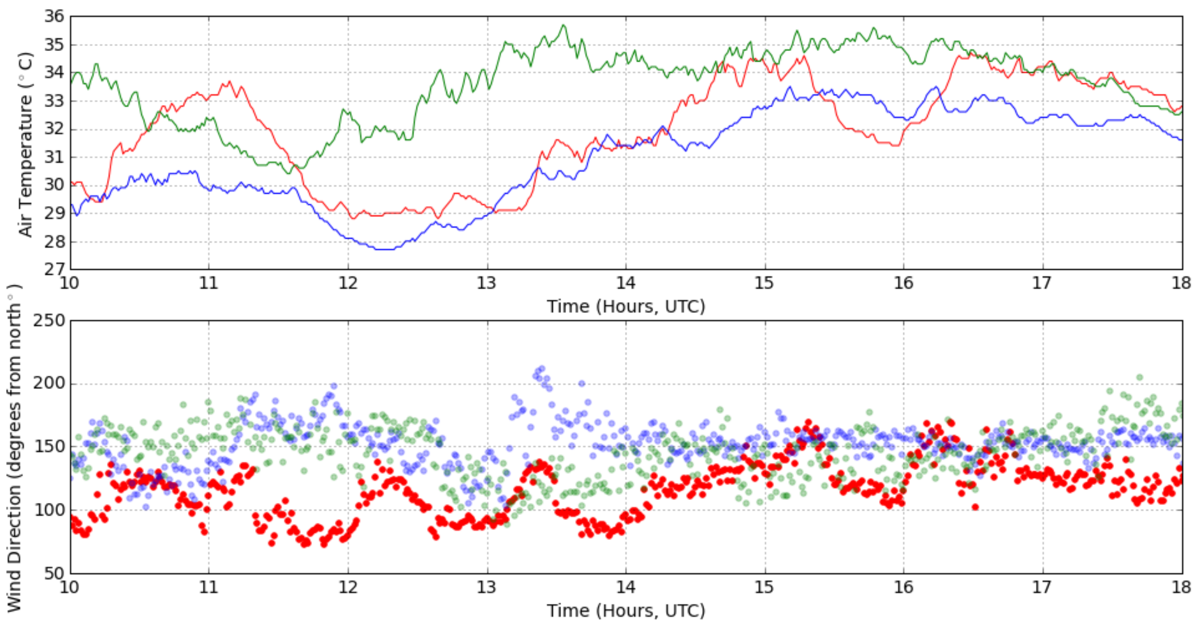

Figure 9: 1-minute air temperature and wind directions at Gravesend-Broadness (red), East Malling (blue) and Kew Gardens (green) between 1000-1800UTC 01 July 2015.

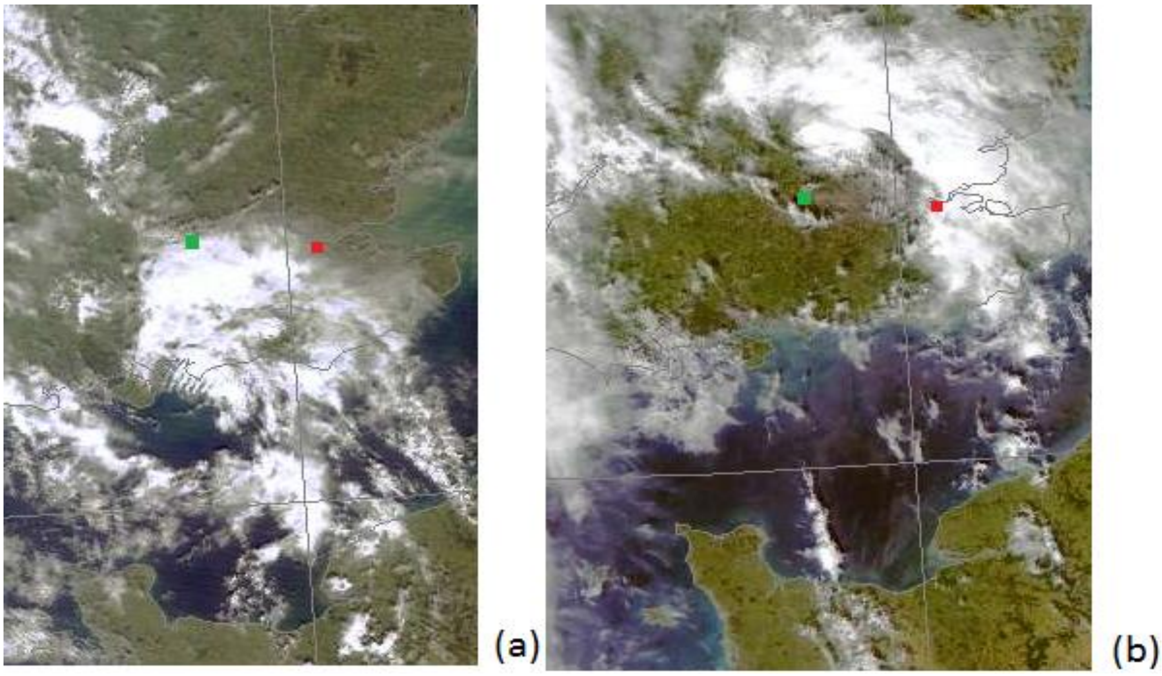

Figure 10: MODIS imagery of passing cloud system over south-east England 1 July 2015, position of RUAO (green) and Gravesend-Broadness (red) are marked, two passes were made at 1057UTC (a) and 1245UTC (b).

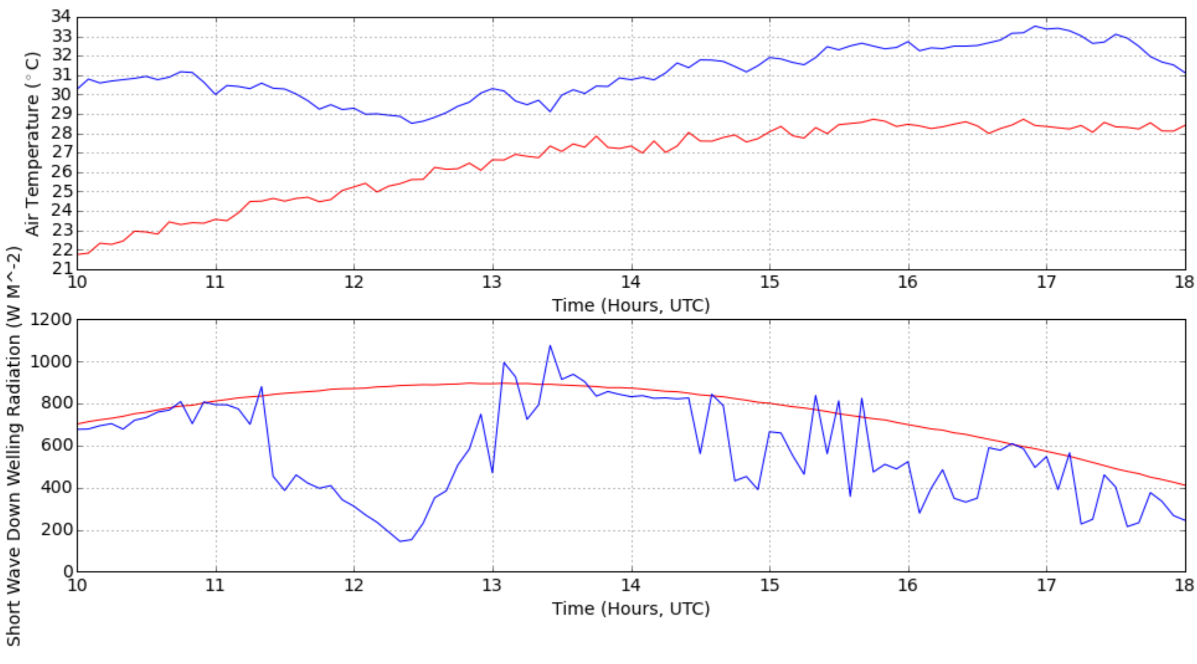

Figure 11: RUAO air temperature and downwelling component of shortwave radiation (inferring cloud cover) on 30 June 2015 (red) and 01 July 2015 (blue) between 1000-1800UTC.

Figure 11 shows that this midday cloud cover on 1 July 2015 prolonged more than 20 minutes and caused shortwave radiation fluctuations of up to 250 $W\ m^{-2}$ at the RUAO, leading to a decrease of 2 degC in air temperature. Shorter periods of cloud cover were not enough to disrupt the diurnal cycle of air temperature. This is because the heat capacity of air allows the heat to be maintained for short periods in which solar heating is removed. When compared to 30 June 2015 (previous day), a clear day with similar shortwave downwelling radiation, air temperature fluctuations at the RUAO of 0.5 degC on 5 minute scales were still possible even in the absence of cloud cover, see figure 11.

As Gravesend-Broadness and the RUAO experienced the same synoptic effects, physical principles from the RUAO data can be applied to suggest that cloud cover at Gravesend-Broadness was not responsible for fluctuations of up to 0.5 degC in a 5-minute period but it may be attributed to the prolonged disruption of the traditional bell-shaped curve expected for air temperature over the diurnal cycle as witnessed on 1 July 2015 between 1130UTC and 1315UTC at both Reading and the Thames stations. The T_{max} could have been higher at all three sites on this day but especially Gravesend-Broadness and East Malling considering that temperature disruption occurred slightly later at a normally warmer time of day. Otherwise lack of sufficient cloud cover on the other 9 warmest days suggest that severe fluctuations in temperature such as the one witnessed at Gravesend-Broadness on 13 September 2016 are not a result of cloud cover interference.

The 1 July 2015 was removed from the dataset contributing to the anomalies described in section 3.3. This was because cloud cover was not an otherwise controlled variable in this project and the disruption to air temperature would alter the anomaly distribution considering that Gravesend-Broadness, East Malling and Kew Gardens air temperatures were influenced differently by this passing cloud cover system (Figure 10).

3.3: Influence of wind direction on air temperature at Gravesend-Broadness

Figure 12 shows that from the 10 warmest days during 2009-2016, winds via the direction of the river Thames in the west or east coincide with a negative temperature anomaly, while southerly breezes from the direction of the North Downs and local urban areas coincide with a positive anomaly at Gravesend-Broadness. Northerly winds were rare during the 10 warmest dates, northerly wind direction bins between 310° and 40° from North had less than 30 contributing samples to each average temperature anomaly bin and therefore were removed from the data set, this was expected as northerly breezes are rare in the UK on warm days (Karl and Nicholls, 1999).

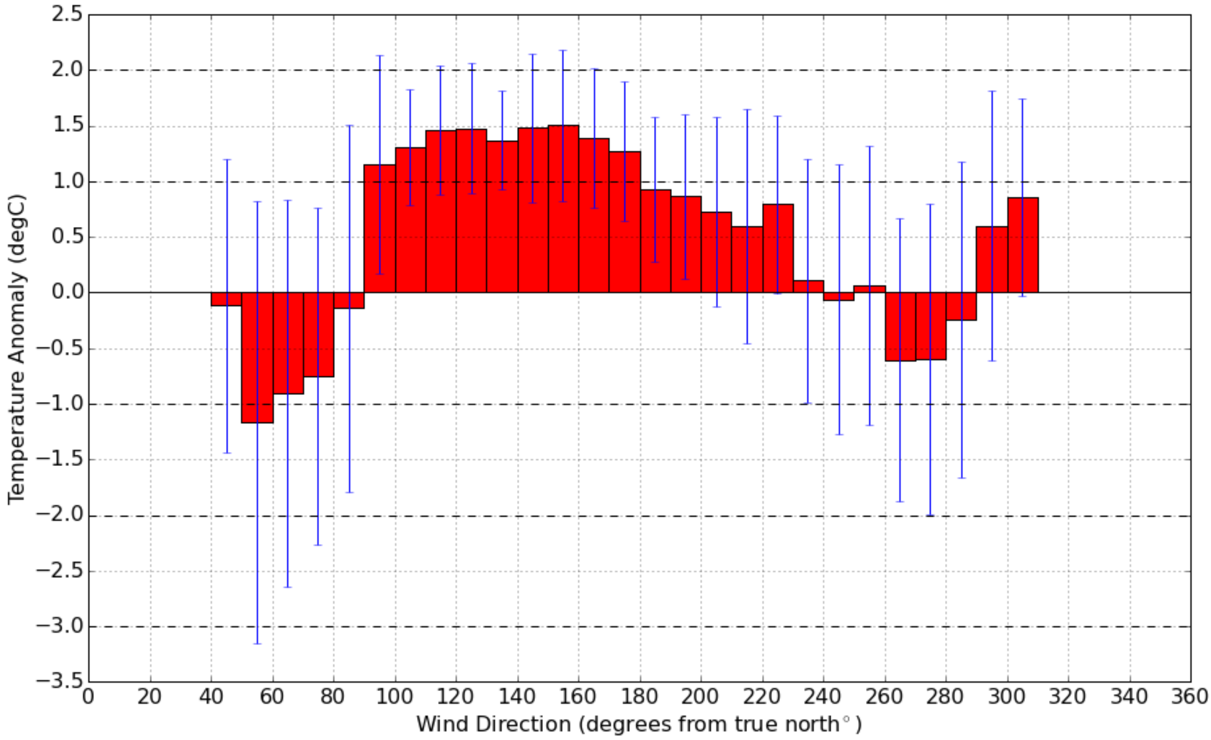

Figure 12: Mean Gravesend-Broadness air temperature anomaly from the East Malling and Kew Gardens mean between 1000-1800UTC, within ten degree increment wind direction bins. Error bars of standard deviation are plotted, temperature anomaly with wind speeds less than 0.2 $m\ s^{-1}$ are removed from average temperature anomaly calculation, wind direction bins with less than 30 samples contributing to temperature anomaly average have been removed. Air temperatures from the 1 July 2015 have been removed due to diurnal air temperature disruption by cloud cover presence. See figure 15 for an overlay of this data over figure 2.b.

Of the 10 warmest days in the south-east during 2009-2016, 22 July 2013 was the only day which provided a consistent and unbroken east-north-easterly estuary breeze at Gravesend-Broadness throughout the daytime measuring period, see fig. 13. Air temperatures at Gravesend-Broadness were also consistently 1 degC or more lower than both East Malling and Kew Gardens throughout the mid-afternoon period. This scenario was not repeated on any other of the 10 warmest days. Figure 13 shows obvious differences between wind directions recorded at Gravesend-Broadness to those at East Malling and Kew Gardens, the estuary breeze at Gravesend-Broadness was exceptional to south-south-easterly winds recorded at Kew Gardens and East Malling which agreed with the 0000UTC UKMO synoptic chart shown in figure 14. Figure 13 also shows that there was less variation in wind direction at Gravesend-Broadness on 22 July 2013 compared to East Malling and Kew Gardens. This is due to stronger mean winds experienced at Gravesend-Broadness between 1000-1800UTC of 8.9 m s^{-1}, while at East Malling and Kew Gardens, this measured 6.4 m s^{-1} and 4.8 m s^{-1} respectively. This is very windy for a warm day in comparison to Thornes (2015) who measured much lighter mean winds of 0.8 m s^{-1} during a heatwave In the previous week at Birmingham New Street Station. Additionally, the smooth estuary water body will have induced less turbulence compared to air parcels traversing the convective surface layer and landforms at East Malling and Kew Gardens.

The east-north-easterly estuary breeze (between 60° and 80°) at Gravesend-Broadness formed the most consistent wind direction bin of the anomaly, involving 17.8% of the 4320 anomaly samples over the warmest 10 days. The lowest average temperature anomalies at Gravesend-Broadness also relate to this wind direction, see figure 12. This shows that Gravesend-Broadness is susceptible to a sea breeze type effect in which the estuary breeze encourages cooler moist air directly from the North-Sea. Surface air temperature is restricted in comparison to East Malling and Kew Gardens while cool air advection from the sea limits convection and sensible heating (Smith, 1976). Without this estuary breeze, the air temperature at Gravesend-Broadness may have been higher, as greater sensible heat flux achievable from the land surface allows greater diurnal maxima to be reached (Oke, 1987). Westerly winds at Gravesend-Broadness also provide a negative average temperature anomaly, but wind direction bins from this inland river breeze are not less than -1.0 degC unlike the Estuary breezes, see figure 9. This is likely resultant of the narrowing river width inland, to the west, reducing the water surface influence in addition to urban heating associated with the London metropolitan area 20km beyond as shown in figure 2.a.

East-south-easterly winds (between 110° and 130°) occurred in 10.5% of the 4320 samples, the temperature was up to +2 degC higher than the East Malling and Kew Gardens mean in this direction. This shows that air temperatures recorded at Gravesend-Broadness are very sensitive to wind direction. Table 4 shows that the average standard deviation of all 1-minute air temperatures recorded between 1000-1800UTC over the 10 warmest Thames station days during 2009-2016 at Gravesend-Broadness (1.7 degC) was higher than either East Malling (1.2 degC) or Kew Gardens (1.4 degC). This means that air temperature at Gravesend-Broadness was more variable on hot summer days although this may somewhat owe to the higher temperatures recorded there as described in section 3.1. Further normalization of this data is required to remove biases in higher standard deviations associated with warmer air temperatures recorded at Gravesend-Broadness.

It was expected that southerly air flows would form the prevailing wind direction at Gravesend-Broadness on the 10 warmest days (Prior and Beswick, 2007; Burt, 2004; Karl and Nicholls, 1999; Burt, 1992). East-south-easterly breezes were not as common as those from the east-north-east (10.5% vs 17.8%), this is due to higher wind speeds associated with the east-north-easterly breeze and therefore more consistent wind flow, non-estuary breeze days allow very light winds and thus wind direction to be more changeable (Thornes, 2015).

Figure 12 shows that the standard deviation is smallest in wind direction bins between 110° and 170° in the south easterly direction, its range was entirely positive, this gives robust evidence that air temperature at Gravesend-Broadness were consistently higher than the mean air temperature at East Malling and Kew Gardens while the wind flows from urban areas, see figure 15. Although the mean air temperature anomaly is negative whilst winds blow from the river Thames in the west or east (Figure 2.b) the standard deviation is spread across the mean value (0 anomaly). This removes robustness from the conclusion that air temperatures are limited whilst the wind flows from water bodies surrounding the Gravesend-Broadness site. However, the standard deviations in wind direction bins between 110° and 170° support the statement that air temperature at Gravesend-Broadness is increased by air flows from surrounding urban areas.

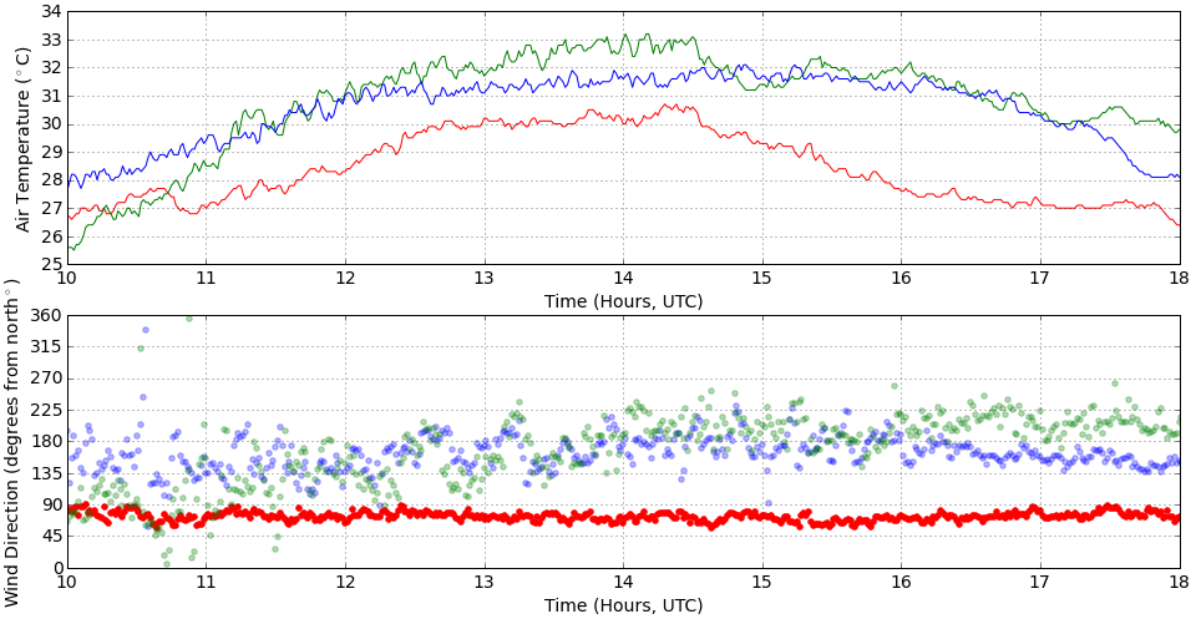

Figure 13: 1-minute air temperature and wind directions at Gravesend-Broadness (red), East Malling (blue) and Kew Gardens (green) between 1000-1800UTC 22 July 2013.

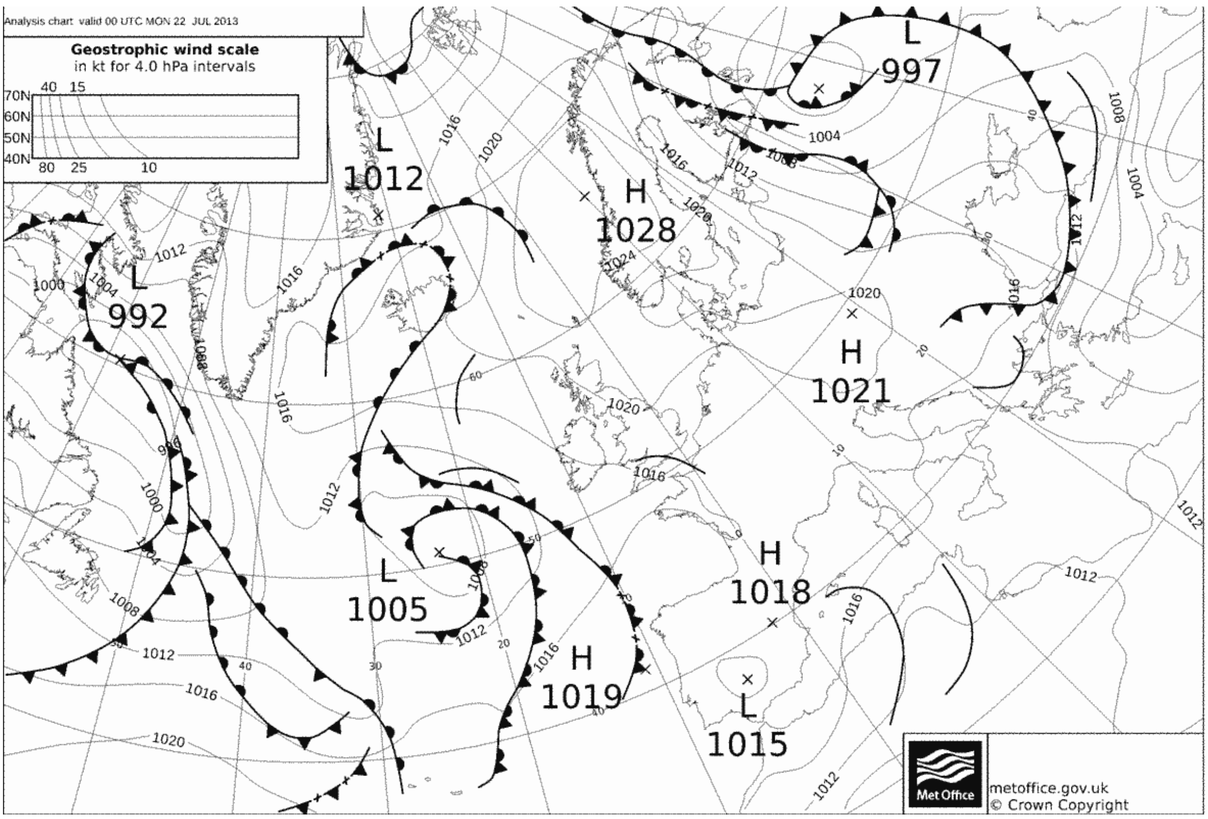

Figure 14: 0000UTC UKMO synoptic chart 22 July 2013.

3.4: What factors contribute to a microclimate at Gravesend-Broadness?

The Gravesend-Broadness AWS is at the tip of the Swanscombe Peninsula of North-West Kent, figure 15 shows that air masses arriving at the Stevenson screen from the south and south-east are up to 1.5 degC warmer than the regional mean. Breezes from the inland or estuary directions of the river Thames generate air temperatures up to 0.7 and 1.2 degC cooler than the East Malling and Kew Gardens mean respectively.

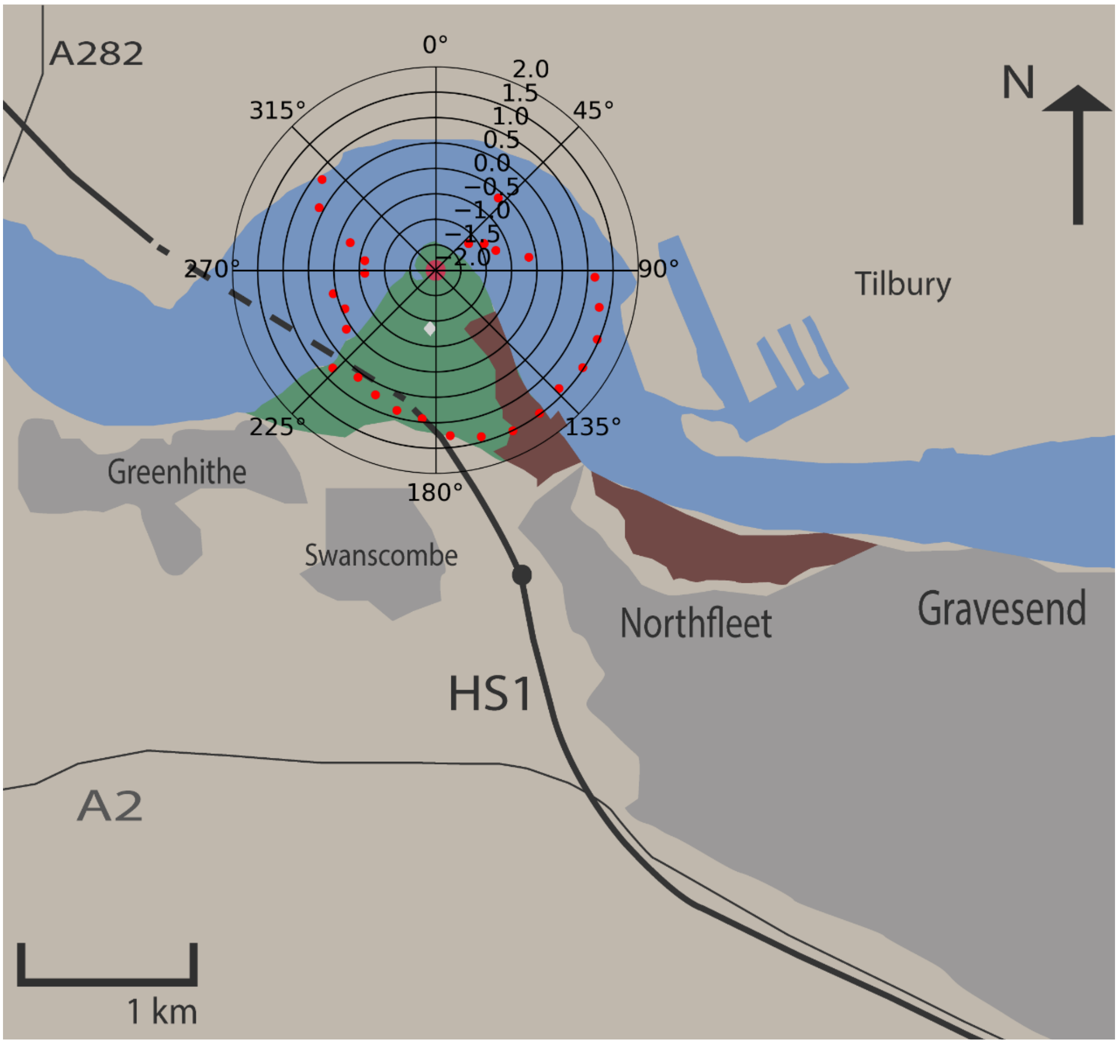

Figure 15: Overlay of data from Figure 12 over figure 2.b; Mean Gravesend-Broadness air temperature anomaly from the East Malling and Kew Gardens mean between 1000-1800UTC, within ten degree increment wind direction bins. Temperature anomaly with wind speeds less than 0.2 $m\ s^{-1}$ are removed from average temperature anomaly calculation, wind direction bins with less than 30 samples contributing to temperature anomaly average have been removed. Air temperatures from the 1 July 2015 have been removed due to diurnal air temperature disruption by cloud cover presence.

As mentioned in section 3.1 the relatively low altitude of the Gravesend-Broadness AWS (3m above MSL) allows air parcels travelling on a southerly flow in the lee of the north downs (Figure 2.a) to sink. As they compress, the air parcels warm super adiabatically on the warmest days, allowing warmer surface air temperatures to be recorded at Gravesend-Broadness relative to higher elevated land and sites. This contributes to the positive air temperature anomaly at Gravesend-Broadness during southerly winds (Figure 15). The magnitude of this factor is not quantifiable without placement of extra Stevenson screens in the transect between East Malling and Gravesend-Broadness (Figure 2.a).

Urban heating of air masses arriving at the Gravesend-Broadness AWS from the south-east is likely. The urban areas of Gravesend and Northfleet less than 3km to the south-east (Figure 15) contribute urban heating in addition to waste heat flux from the Britannia Metals refinery just 300m south-east of the AWS when in operation (Figure 4). The positive 1.5 degC anomaly from the south-east at Gravesend-Broadness (Figure 12) coincides with findings of Taha et al. (1988) in which urban heat island effects were also found to raise air temperature by up to 5 degC. The urban heat island influence may not be as large in this project due to measurements being made 3km downwind of the main urban area in comparison to direct measurements by Taha et al. (1988).

Burt (2004) described that T_{max} at Gravesend-Broadness during the August 2003 were raised by site irregularities. The field site visit has enabled a detailed analysis of any irregularities that exist. A grass banking is present at Gravesend-Broadness (Figure 3) standing 2m in height, surrounding the enclosure on the east and north sides within 4m of the Stevenson screen. This undulating topography between -2m and +6m MSL is repeated for 300m in the southerly direction (Figure 5), across the Swanscombe Peninsula which originates from cement works waste tipping in the last 50 years and excavations for the construction of the HS1 rail link (Dartford Borough Council, 2004). Oke (1987) refers to this topography as Ridge and Furrow in type which encourages shelter to the Stevenson screen from ventilation as well as a radiation trapping effect. The coarse sandy and quarried soil on the Swanscombe Peninsula described by Dartford Borough Council (2004) gains and loses heat more rapidly than finer clay soils. This is because of the relatively large amount of air space between particles giving the ground a high heat flux (Johnson and Davies, 1927).

Figure 3 and appendix B show the west and south facing banks immediately surrounding the enclosure are angled such that the radiation trapping effect will be most influential at the warmest time of day considering the solar azimuth at 1500UTC is between 240° and 250° in summer months. When angled perpendicular to the incident radiation, the soil temperature of these banks increases by day and outgoing longwave radiation losses overnight are limited (Oke, 1987). This is replicated by an air temperature anomaly response at Gravesend-Broadness which increases as the afternoon progresses until 1500UTC (Figure 16). Jones (1976) agrees that ground sloping toward the south and east is favourably warmed by the sun which is at a greater angle, permitting a higher T_{max} to be achieved. Observations by Black et al. (2004) at the RUAO of the 2003 heatwave have shown that the ground plays an important role in the accumulation of heat during an extremely hot day, as well as the gradual release at night. When long-wave radiation losses were limited overnight, the decrease in air temperature before sunrise was slowed. This helped sustain the heatwave conditions, leading to the warmest ever T_{max} at the RUAO. As the shelter at Gravesend-Broadness acts to retain long wave radiation overnight, higher surface air temperatures in the daytime are achievable relative to surrounding more sites such as East

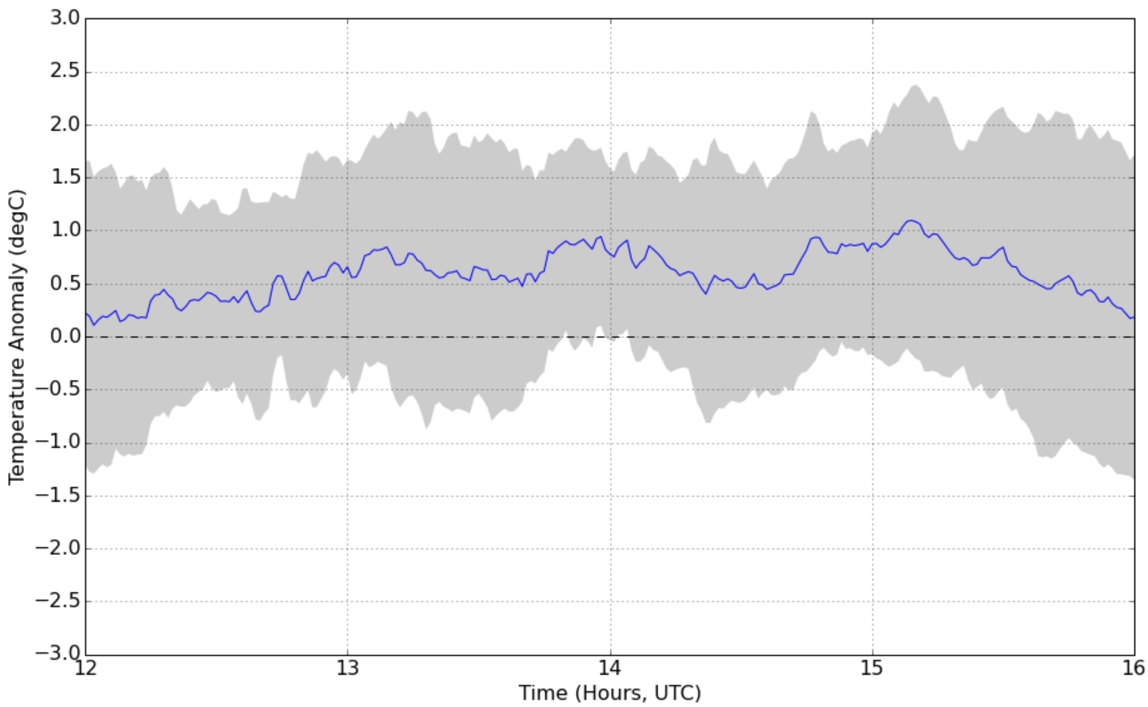

Figure 16: Mean 1-minute Temperature anomaly at Gravesend-Broadness between 1200-1600UTC from the 1-minute temperature mean between East Malling and Kew Gardens over the 10 warmest days of the Thames stations, shaded area represents standard deviation in 1-minute values. Data from the 1 July 2015 has been removed due to diurnal air temperature disruption by cloud cover interference.

Malling and Kew Gardens which Burt and Eden (2004) describe as more exposed and representative.

Of important note is that the wind measurements are made atop a 10m mast and are therefore less likely to be influenced by any sheltering effects relative to those on the Stevenson screen at 1.25m (Met Office, 2017). The diurnal Gravesend-Broadness air temperature anomaly from the mean of East Malling and Kew Gardens over the 10 warmest days in figure 16 should be interpreted with care as only 18 samples (9 days * 2 sites) contributed to each of the 480 1-minute mean air temperature values between 1000-1800UTC once 1 July 2015 was removed. These 9 contributing dates were not consecutive and thus variable synoptic conditions created a wide standard deviation.

3.5: How does Gravesend-Broadness affect the homogeneity of climate records?

The siting of a meteorological station in a truly representative position is not always possible (Burt, 2012). However, the Gravesend-Broadness AWS fails to meet several standards required set by the WMO (2014) for measuring air temperature; To produce useable measurements, a site is deemed representative if exposed to conditions homogenous with an area between 100 and 1000 km^2. Previous quarrying, heavy construction, reclamation and waste tipping detailed by Dartford Borough Council (2004) within 300m of the site in the southerly direction has made the terrain and topography surrounding the Gravesend-Broadness site unique to the Swanscombe Peninsula. Additionally, the surrounding 30m should be flat, with natural vegetation less than 10cm in height and free of temperature enhancing land surfaces or features. However, figure 3 depicts 2m high banking within 4m of the screen as well as long and unmanaged grass in addition to the large water body of the river Thames which contrarily restricts the maximum air temperature with advection of cool air from the water body on a hot day (Smith, 1976). Galvin (2007) describes that the first 50m of elevation at the surface can decrease air temperature by up to 4 degC on a hot summers day and the town of Gravesend itself is more than 30m higher in elevation than the Swanscombe Peninsula and AWS, see figure 5 (Dartford Borough Council, 2004). These factors force Gravesend-Broadness to record non-representative air temperatures on the hottest days. If the Gravesend-Broadness AWS was moved even a few hundred metres the air temperatures recorded would be substantially different considering its current unique position.

If removed from the regional mean of summertime T_{max} during 2009-2016 (all 6 stations), the mean T_{max} is also 0.1 degC lower than when Gravesend-Broadness data is included as shown in Table 2. The enhancement of active climatological records by Gravesend-Broadness data will be less prominent in large-scale models that consider many stations. However, Perry and Hollis (2005) describes the UKCP09 model which includes data from every Met Office site including Gravesend-Broadness to generate 5km x 5km gridded data sets on which scale the influence of Gravesend-Broadness recordings would be much greater. As detailed in section 3.1, the spatial variation in T_{max} grows under warmer, dryer and clearer conditions (Galvin, 2005; Tinn, 1938). Therefore, as summers become warmer due to climate change, the air temperatures recorded at Gravesend-Broadness will range further from those of surrounding sites, enhancing regional mean T_{max} and creating an inhomogeneous record. The detection and control of non-representative data recorded by Met Office stations is therefore important as this climate model alone is used in adaptation planning for future climate change impacts.

4: Conclusions

Gravesend-Broadness is the warmest of the studied stations in climate analysis of T_{max}. The discrepancy between Gravesend-Broadness T_{max} and the mean of Thames stations T_{max} increases from +0.6 degC over all summer days to +1.4 degC over the warmest 10 dates since 2009. This shows that the spatial variability in air temperatures of the studied sites increases in warmer conditions as temperature differences caused by variable elevation are exaggerated by super adiabatic conditions on the hottest days. The UKCP09 model depicts the region covered by the study as the warmest in the UK between 1961-1990 by T_{max}, therefore it likely but not explicit that by T_{max}, Gravesend-Broadness is also the warmest station in the UK.

1 July 2015 was the warmest day between 2009 and 2016 based on the mean T_{max} of all stations. Kew Gardens recorded the absolute highest T_{max} since the beginning of 2009 on this day (35.7°C) while the T_{max} at Gravesend-Broadness and East Malling was 1.0 and 2.2 degC cooler respectively. If cloud cover was not prolonging enough to disrupt the diurnal

cycle of air temperature at midday, the T_{max} at all three sites but especially Gravesend-Broadness and East Malling would have been higher on this day.

Gravesend-Broadness air temperature measurements are susceptible to cooling by an intermittent estuary breeze on the warmest of days. This wind direction was measured in 17.8% of 4320 samples over the 10 warmest days. This wind direction was exceptional to measurements at East Malling and Kew Gardens which remained generally southerly alike the case described by synoptic charts. Gravesend-Broadness air temperatures are up to 1.2 degC cooler than the mean of East Malling and Kew Gardens during east-north-easterly winds and up to 0.7 degC cooler during westerly winds. The lack of urban heating and greater proportion of open water in the east-north-east fetch is deemed reason for limitation of sensible heating and thus relatively cooler temperatures.

Gravesend-Broadness is susceptible to urban heat island warming from urbanised areas less than 3km south and south-east of the AWS. Air temperature was up to 1.5 degC warmer than the mean of East Malling and Kew Gardens during winds from the direction of the Britannia Metals Refinery and Gravesend town. This makes air temperature at Gravesend-Broadness very sensitive to wind direction.

The Gravesend-Broadness AWS is exposed to a microclimate at the Swanscombe Peninsula. Sheltering 2m high banks within 4m of the Stevenson screen enclosing the north and east sides are angled perpendicular to incident radiation on a clear, warm summers day. This enhances air temperatures by up to +1 degC at 1510UTC, the warmest afternoon period. This lead to Gravesend-Broadness recording the highest T_{max} when compared to surrounding sites on 24 of the 50 warmest days.

Extreme air temperatures measured at Gravesend-Broadness are not considered representative of the north-west Kent region. This Is largely due to a +30m altitude difference between the neighbouring towns and the AWS as well as topography surrounding the site that is unique to its current position. Movement of the AWS just a few hundred metres would considerably alter the fetch and terrain surrounding the site, constituting a large difference in temperature readings on the warmest days. The AWS site fails to meet several WMO standards for measuring representative air temperatures.

The UKCP09 climate model is influenced by non-representative measurements of air temperature at Gravesend-Broadness. As the air temperature range between Gravesend-Broadness and surrounding sites increases in warmer, clearer conditions. An inhomogeneous climate record between Gravesend-Broadness and surrounding sites will be introduced by warmer summers experienced due to climate change in the future.

5: Future Work

There are multiple limitations associated with the current data analysis. The standard deviation in the diurnal air temperature anomaly dataset could be reduced by extending beyond the 10 warmest days in addition to adding 1-minute data from more AWS. Sunshine data at Gravesend-Broadness would allow explicit confirmation of cloud cover presence above the measuring site on the warmest days and its influence on air temperature measurements could be directly assessed as they are currently approximate.

Placement of additional AWS between Gravesend-Broadness and the surrounding Thames stations will allow detailed study of the intermittent and currently unpredictable sea-breeze type effect that influences air temperatures recorded at Gravesend-Broadness. This will allow contributing factors and the distance inland which it influences to be better understood. Stevenson screens in the transect between East Malling and Gravesend-Broadness will allow quantification of air temperature enhancement by sinking motions of air parcels in the lee of the Wrotham section of the North Downs.

Radiation instruments of similar richness supplied at the RUAO installed at Gravesend-Broadness will also allow the heating effects of the surrounding grass verges at the observatory to be quantified directly.

Within 30m of the AWS are the tidal waters of the River Thames, Tides therefore considerably alter the fetch surrounding the AWS. Tidal data may provide insight into the effect on measured air temperature.

Current plans for a 'Paramount' theme park to be constructed on the Swanscombe Peninsula and open by 2021 (London Paramount, 2017), will heavily transform the landscape surrounding the Gravesend-Broadness AWS especially in the warm southerly direction and may even require this meteorological site to be relocated. Altering the fabric of this measuring station may inherently change the frequency at which Gravesend-Broadness records the highest T_{max}. This can also be used as an opportunity to provide recommendation for a relocation site that is more representative of the local environment.

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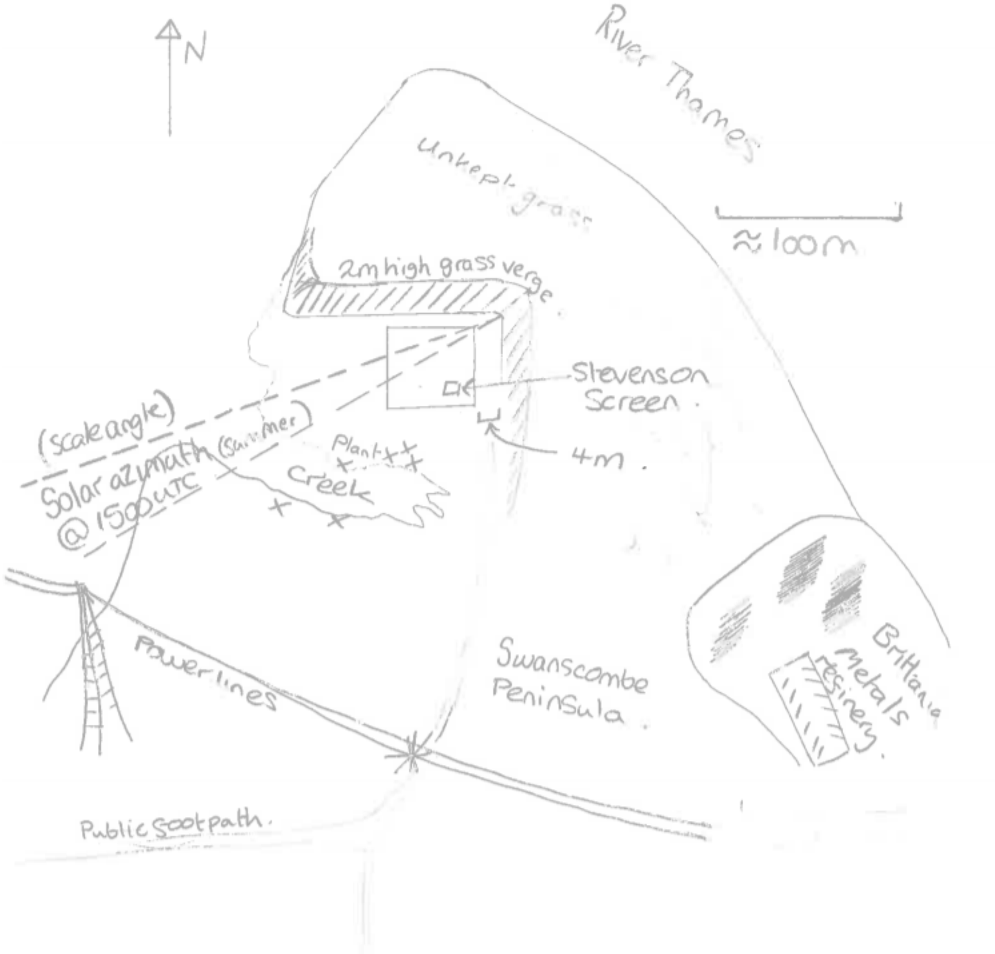
Appendices:

	Gravesend	East Malling	Kew Gardens	St. James's Park	Shoeburyness	Faversham	All sites mean
01/07/2015	34.7	33.5	35.7	34.7	26.3	35.2	33.4
24/08/2016	33.9	32.1	33	33	30	34.1	32.7
01/08/2013	33.2	31.6	33	33	30.4	32.6	32.3
13/09/2016	34.4	31.3	33.5	32.5	26.5	32.7	31.8
27/06/2011	33.1	31.2	31.4	32	30.7	31.1	31.6
09/07/2010	31.7	30.3	31	31.2	29.8	32.7	31.1
22/07/2013	30.7	32.1	33.2	33.3	24.8	32.4	31.1
18/07/2014	32.3	30.7	31.2	31.8	27.8	31.5	30.9
18/08/2012	31.5	30.1	29.6	30.8	30.8	32.1	30.8
19/07/2016	32.1	30.7	32.5	32.3	25.5	31.4	30.8
10/07/2010	30.9	29.3	29.4	29.7	29.2	30	29.8
22/08/2015	30.9	27.9	30.9	30.7	26.8	29.5	29.5
20/07/2016	30.2	28.9	30.2	30.4	29.1	27.4	29.4
27/06/2010	30.9	29.1	30.3	30.1	25.5	30	29.3
19/08/2009	30.3	28.8	29.1	29.1	28.2	29.8	29.2
23/08/2016	30.5	28.4	30.2	30.1	25.9	29.8	29.2
15/07/2013	30	29.5	30.8	30.4	26	28	29.1
17/07/2013	30.1	29.1	31.2	31.2	25.2	27.6	29.1
03/08/2011	30.3	29.4	29.6	29.5	26.4	28.7	29
05/09/2013	29.5	29.7	29.7	29.3	25.7	29.9	29
16/07/2013	30.1	28.3	31.2	30.3	25.3	27.8	28.8
25/07/2012	29.8	28.9	30.1	30.7	25.5	27	28.7
15/09/2016	30.1	27.6	29.8	29.6	25.9	27.9	28.5
09/09/2012	29.1	27.8	27.7	28.6	28.6	28.6	28.4
30/06/2015	27.7	27.7	30.4	30.2	24.1	29.6	28.3
01/10/2011	29.9	27.8	29.2	29.1	24.6	29	28.3
19/08/2012	29.5	27.9	29.3	29.7	24.8	28	28.2
18/07/2016	29.1	28.1	30	30	24.3	27.7	28.2

02/10/2011	29	27.7	28	28.4	28	28	28.2
19/07/2010	29.4	27.7	28.6	28.6	26.7	28	28.2
05/08/2009	28.9	27.7	27.5	27.9	27.8	29	28.1
02/07/2010	29.9	28.4	26.1	26.5	29.2	28.5	28.1
25/08/2016	29.3	29.2	28	28.6	24	29.5	28.1
08/09/2009	28.7	27.4	27.8	28	28.1	28.1	28
07/09/2016	29.3	27.3	28.7	28.3	25.3	29	28
02/08/2011	28.2	28.5	28.2	28.6	24.7	29	27.9
14/09/2016	28.5	26.2	27.9	28.1	27.4	29.1	27.9
14/07/2013	28.5	28.9	29.4	28.9	23.1	28.2	27.8
06/08/2009	28.7	29.2	25.7	27.8	26.1	29.2	27.8
24/07/2012	28.2	27.9	29.1	30.1	24.9	26.4	27.8
13/07/2013	29.4	28.5	30.4	30.5	20.9	25.4	27.5
28/06/2012	28.6	26.6	27.4	28.4	26.9	27.2	27.5
17/08/2012	27.4	26.3	27.8	28.4	27.5	27.2	27.4
23/08/2009	28.1	26.8	27.7	27.5	26.9	27.4	27.4
11/07/2010	28.7	26.3	27.2	27.5	27.1	27	27.3
04/07/2014	27.7	26.5	26.1	26.9	28.4	28.2	27.3
26/08/2016	27.9	27.6	27.5	27.3	27	26.4	27.3
04/07/2015	28.3	25.2	27.2	26.9	27.7	28.1	27.2
12/08/2016	27.3	25.5	27.1	27.4	26.9	27.8	27
26/06/2015	27.8	24.8	26.7	27.2	26.6	26.8	26.7

Appendix A: Summary Table of the 50 warmest days in the south-east between 2009 and 2016 defined by the ranked mean T_{max} on each day since 2009, between all Thames stations and Gravesend-Broadness, green shading highlights the warmest station on each day.



Appendix B: Sketch of the Gravesend-Broadness site at the Swanscombe Peninsula, angles to scale, distance not to scale. 'X' denotes plant machinery within 50m of the site. '*' denotes the position at which images in figures 4 and 5 were captured. The solar azimuth in summer months at 1500UTC (between 240° to 250° from North) the warmest time of day in clear, warm conditions has been traced.