Parallel air temperature measurements at the KNMI observatory in De Bilt (the Netherlands) May 2003 - June 2005

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Foreword

From May 2003 through June 2005 a field experiment has been carried out at the observatory of KNMI in De Bilt, as part of the KNMI-program 'Hisklim' (HIStorical CLIMate). The original objectives of the experiment were: (1) to study the representativeness of the current operational air temperature measurement site, and (2) to explore the possibility of using present-day parallel measurements to correct for inhomogeneities, caused by changes in the surroundings and a relocation of the thermometer screen in 1951. At five sites, including the operational site, temperature and wind speed were measured at a height of 1.5 m, using identical instruments and set-up. The temperature differences between the sites have been studied in connection with the local wind speed and other weather variables. Initial results for the period May 2003-April 2004 have already been published in an interim report (Brandsma, 2004).

During the experiment, a significant renovation of the area only 12 m west of the operational temperature screen took place in September/October 2004. The renovation introduced an inhomogeneity in the temperature measurements at the operational site, which was used as the reference site for the interim report. As a result, in this final report another reference site (Test4) has been chosen and the end date of the experiment was extended from April 2005 to June 2005 to have sufficient overlap time. This report presents the results of the whole period of the experiment (May 2003 - June 2005).

In September 2008 the operational site DB260 (06260) was relocated to the Test4 site (the reference site in this report). Both sites are considered in this report. Although this report is not meant to describe the effect of this relocation, the results presented here do give an indication of the effects of this relocation on the temperature measurements. A detailed study of the effects of the relocation will be described in a separate publication.

Summary

Air temperature measurements at the KNMI-observatory in De Bilt are important mainly because the observatory has a long and relatively homogeneous record and because its observations often serve as an indicator of changes in climate for the Netherlands as a whole. Among others, relocations of the temperature measurement sites and (gradual) changes in surroundings influence the measurements. To improve the homogeneity of the long-term temperature record and to study the representativeness of the current measurements, a parallel experiment was carried out at the observatory of KNMI in De Bilt from May 2003 through June 2005.

Five sites at the KNMI-observatory, including the (at that time) operational site WMO 06 260 (further denoted as DB260), were equipped with identical (operational) instruments for measuring temperature and wind speed at a height of 1.5 m (see for an overview of the sites Figure 1.1). The instruments were calibrated each half-year and the calibrations curves were used to correct the data to minimize instrumental errors. With the measurements at the Test4 site (operational site since 25 September 2008) as a reference, the temperature differences between the sites were studied in connection with the local wind speed and its differences and operationally measured weather variables at the KNMI-observatory. In September/October 2004 the area west of the operational site DB260 was renovated and made into a landscaped park. From 1999 onwards that area slowly transformed from grassland into a neglected area with bushes (wasteland). The parallel measurements provided the opportunity to study the impact of this new inhomogeneity in detail.

The results show that changes in surroundings complicate or impede the use of present-day parallel measurements for correcting for site changes in the past. For instance, the (vertical) growth of the bushes in the wasteland area west of DB260, caused increasing temperature differences between the operational site DB260 and four neighboring stations. The effects were most clearly visible in the dry summer of 2003, when the mean monthly maximum temperatures at DB260 were up to about 0.4°C larger than those at the reference Test4. This increase was more than counteracted by a decrease in the mean monthly minimum temperature of up to 0.6°C. After the renovation of the wasteland area, the temperature differences between DB260 and Test4 became close to zero (< 0.1°C). The comparison of DB260 with four neighboring stations showed that the renovation restored to some extent the temperatures of the old situation of before the year 1999. However, the land use west of the DB260 has been changed permanently (no longer grassland as in the period 1951–1999, but landscaped park land with ponds). Therefore, operational measurements at DB260 became problematic and KNMI decided to move the operational site to the Test4 site in September 2008. The Test4 site is the most open of five sites studied in the report.

The results increase our understanding of inter-site temperature differences. One of the most important causes of these differences is the difference in sheltering between sites. Sheltering stimulates the build up of a night-time stable boundary layer, decreases the outgoing long-wave radiation, causes a screen to be in the shade in the hours just after sunrise and before sunset, and increases the radiation error of screens due to decreased natural ventilation. Depending on the degree and nature of the sheltering, the net effect of sheltering on temperatures may be a temperature increase or decrease. DB260 is a sheltered site where the net effect is a decrease of the mean temperature (before the renovation). The former historical site Test1 is an example of a site where the net effect is a temperature increase. The

monthly mean minimum temperature at Test1 is up to 1.2°C higher than the reference and the maximum temperature is up to 0.5°C higher than that at Test4. The mean temperature at Test1 is, however, only slightly higher than the mean at Test4. This is caused by the relatively low temperatures in the hours after sunrise and before sunset, when the screen at Test1 is in the shade. Both the Test1 and Test4 location are probably not affected by the renovation.

The renovation of the wasteland area causes not only a shift of the location of the pdf of the daily temperature differences but also a change in the shape. This means that for the homogenization of daily temperature series it is not sufficient to correct only the mean.

We showed that the magnitude of the inter-site temperature differences strongly depends on wind speed and cloudiness. In general the temperature differences increase with decreasing wind speed and decreasing cloudiness. Site changes directly affect wind speed because they are usually accompanied by changes in sheltering. Some effects, like the built up and (partly) breaking down of the stable boundary layer near the surface, are highly non-linear processes and therefore difficult to model. The fact that these processes are mostly active at low wind speeds (< 1.0 m/s at 1.5 m) further complicates the modeling. Regular cup anemometers are not really suited to measure low wind speeds. Operationally these anemometers have a threshold wind speed of about 0.5 m/s and this threshold wind speed often increases with the time during which the anemometer is in the field. In addition, anemometers are mostly situated at a height of 10 m. During night-time stable conditions the correlation between wind speed at 10 m and wind speed at screen height is weak. This complicates the homogenization of daily temperature series.

1 Introduction

In this chapter we describe the problems that have led to the parallel measurements at the KNMI-observatory. Furthermore, the scope and objectives of the report are stated.

1.1 Problem description

Temperature measurements are often a subject of debate. Questions arise whether the measurements are representative of the area in which the stations are situated, or whether the temperature time series are homogeneous[1] enough to allow studies of climate trends and climate variability. Meteorologists mostly emphasize the first question while climatologists are generally more concerned about the second question. Here both questions will be addressed.

The meteorological measurements in De Bilt are important for several reasons. They are part of the worldwide synoptical measurement network and are used in weather prediction models. In the Netherlands, the measurements are often used as an indicator of changes in weather and climate of the whole country because De Bilt has a long measurement record and is situated in the center of the country. The time series of the De Bilt also constitutes the modern-day part of the Zwanenburg/De Bilt time series (1706-present). This is one of the very few long time series in the world with sub-daily weather observations. It is thus important to assess the representativeness and the homogeneity of the temperature series.

Concerning thermometer exposure and siting, WMO (2008) states: "In order to achieve representative results when comparing thermometer readings at different places and at different times, a standardized exposure of the screen and, hence, of the thermometer itself is also indispensable. For general meteorological work, the observed temperature should be representative of the free air conditions surrounding the stations over as large an area as possible, at a height of between 1.25 and 2 m above ground level. The height above the ground level is specified because large vertical temperature gradients may exist in the lowest layers of the atmosphere. The best site for the measurements is, therefore, over level ground, freely exposed to sun-shine and wind and not shielded by, or close to, trees, buildings and other obstructions." From this statement it is obvious that sheltering, and changes in sheltering due to e.g. growth of trees or relocation are undesirable for air temperature measurements.

The exposure of the sites in De Bilt is illustrated in Figure 1.1. The figure shows the position of the DB260 site, which was the operational site from 27 August 1951 until 25 September 2008. The first problem originates from the lines of trees that run from south of DB260 to north-northeast. The present height of the trees varies from about 20 to 30 meters. Because the thermometer screen at DB260 is amply within the range of 8–12 times the obstacle height, this may affect the temperature measurements. The predominant southwesterly flow further attributes to this problem. In addition, since the year 1999, before the start of the parallel measurements, the area west of DB260 (the green hatched area) had been transformed slowly from grassland[2] into wasteland overgrown with bushes. During

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[1] A numerical series representing the variations of a climatological element is called homogeneous if the variations are caused only by fluctuations in weather and climate (Conrad and Pollak , 1962)

[2] At the end of the nineties of the 20th century there were some years in which the area was planted with maize. Photographs show maize in 1996 and 1999

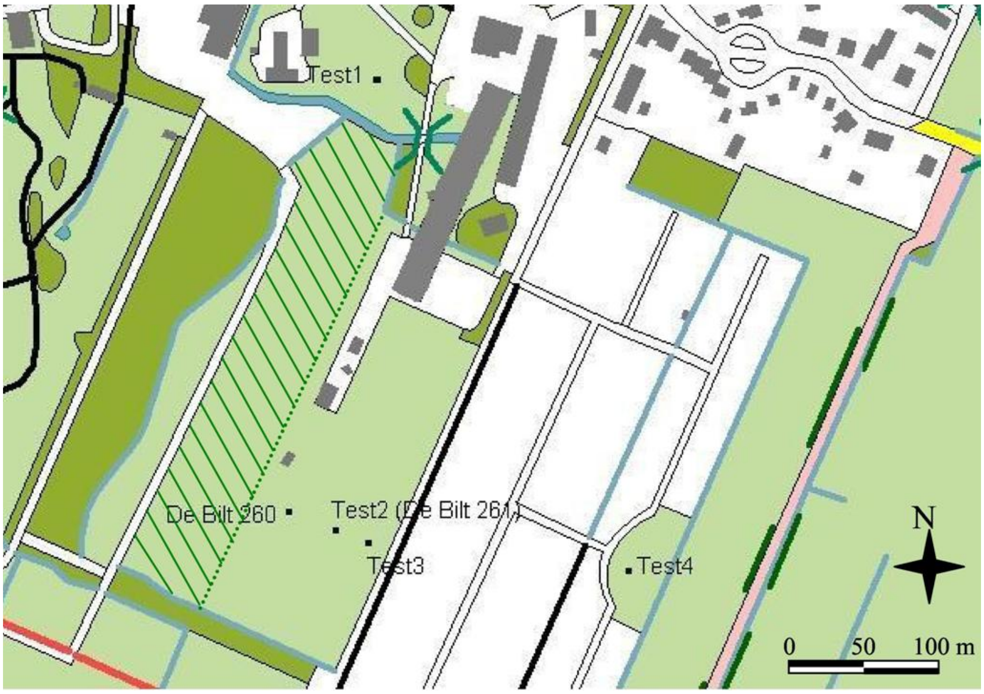

Figure 1.1: Location of the De Bilt 260 (DB260) and the 4 parallel sites (Test1 - Test4) at the KNMI observatory in De Bilt. Light green indicates grass cover and dark green trees. The white area that runs from mid bottom to top right consists mainly of allotments. The KNMI buildings are in gray (on the left of the allotments). The green hatched area represents the former grassland area that since the year 1999 transformed into wasteland. The area was completely renovated in September/October 2004 during the experiment (see also Figure 2.4).

the period May 2003 - September 2004 the bushes in that area had heights up to 2 to 3 m at a distance of only 12 m from DB260, thus creating an additional shelter effect. In September/October 2004 the wasteland area has been renovated and made into a landscaped park, introducing an inhomogeneity in the measurements during the experiment (see Chapter 2).

The second problem deals with long-term homogeneity. On 27 August 1951 the operational thermometer screen was moved from the Test1 site to the DB260 location. It is known that this relocation, combined with a change in screen type and a minor relocation on 16 September 1950, caused a jump downwards in the maximum temperatures, especially in the summer (KNMI, 1999). The change in screen type was accompanied by parallel measurements. We digitized and analyzed these data and found that the screen transition explains about half (0.37°C of the downward jump in summer (April-September) maximum temperature. Unfortunately, no parallel measurements were performed for the relocation, making it difficult to correct for the jump, especially for the daily series. Moreover, since the relocation in 1951 the height of the line of trees increased considerably. Figure 1.2 shows e.g. the situation in 1960, when the height of the line of trees varied between 5 and 25 m. Especially the line of trees south of DB260 experienced a gradual growth in the period 1951 till present.

1.2 Scope and objectives of the report

The parallel measurements at the KNMI-observatory address the above-mentioned problems. This final report presents the results of the experiment for the whole

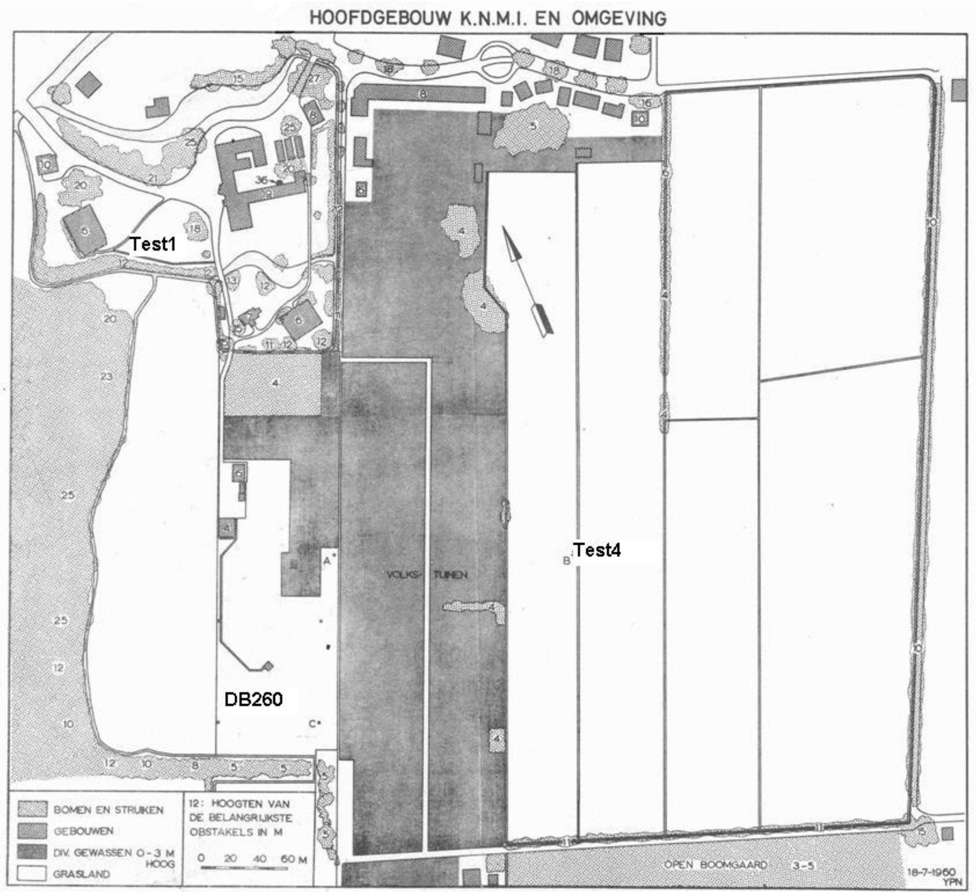

Figure 1.2: Plan of the KNMI observatory in 1960 indicating the tree height around the observation field. For comparison purposes the locations DB260, Test1 and Test4 are depicted on the map.

measurement period (May 2003 - June 2005). The experiment is part of a comprehensive study addressing the homogeneity of the meteorological time series of the so-called Zwanenburg/De Bilt time series (1706-present).

The report describes the temperature differences between 5 different sites at the KNMI-observatory. An analysis of the first year of data in Brandsma (2004) showed that the operational temperature site for the May 2003 - April 2004 period has been affected by local effects. The site could therefore not be considered representative of the larger surrounding area of the KNMI-observatory. In addition to Brandsma (2004), this final report also focuses on the effects of the renovation of the wasteland area in September/October 2004 on the measurements. On 25 September 2008 the operational thermometer screen at DB260 was relocated to the Test4 site. The impact of this relocation on the long-term temperature trend in De Bilt has to be estimated by comparison with neighboring stations and will be dealt with in a separate publication. The current parallel measurements cannot be used for that purpose because: (1) at the start of the measurements in May 2003, the DB260 site was no longer representative of the pre-1999 conditions at that site, and (2) after the renovation of the wasteland area in September/October 2004, the DB260 site cannot be considered representative of the pre-1999 conditions.

The present study deals with local effects on the scale of the KNMI-observatory.

Effects of e.g. urbanization and reclamation of land are not taken into account. In case of the former, Brandsma *et al.* (2003) discussed that effect on the De Bilt series.

Chapter 2 describes the setup of the measurements and discusses the potential sources of air temperature differences. Chapter 3 presents the results of the comparison between the 5 sites and Chapters 4 and 5 present a discussion and conclusions and recommendations.

2 Data and methods

This chapter first describes the setup of the experiment (site, instrumentation). In the second part of this chapter we present the mechanisms that may cause temperature differences between the sites and we further explain our approach. Details about the sites, data collection and calibration, can be found in Appendix A.

2.1 Site description and instrumentation

2.1.1 Site description

The observatory of of KNMI in De Bilt is situated at 52°06′N and 05°11′E. The KNMI-observatory is surrounded by three towns: De Bilt (33,000 inhabitants) extending from KNMI to the north, Utrecht (234,000 inh.) town border at about 2 km west, and Zeist (60,000 inh.), town border at about 3 km southeast. Extending from De Bilt, there is a forested area in directions between north-northeast and southeast and mainly pastures in the other directions. The observatory is flat with ground surface at 2 m above mean sea level and a clay/sand soil type. Groundwater levels in summer are generally from 50–80 cm below ground surface and in winter < 40 cm below ground surface.

Figure 1.1 shows the position of DB260 and the four selected parallel sites indicated by Test$N$ ($N = 1, \ldots, 4$). Test1 is located near the historical operational site; Test2 (the current test site) is situated 30 m from DB260 at 118°, and Test3 at 50 m from DB260 at 118°. Test4 is situated about 220 m east of DB260 near the operational wind mast, which measures wind direction and speed at 20 m height.

Besides the large barrier of trees that runs from south of DB260 to north-northeast, there is also a shallow barrier between the allotments and the KNMI observatory (see the straight black bold line in Figure 1.1). The distance of Test3 to the barrier equals 23 m (perpendicular to the barrier). The barrier consists of a 2 m high permeable fence. Behind the fence, there are garden houses with a height of 2–3 m scattered over the allotments gardens.

Figure 2.1 shows the obstacle altitude for each site. The figure clearly shows that

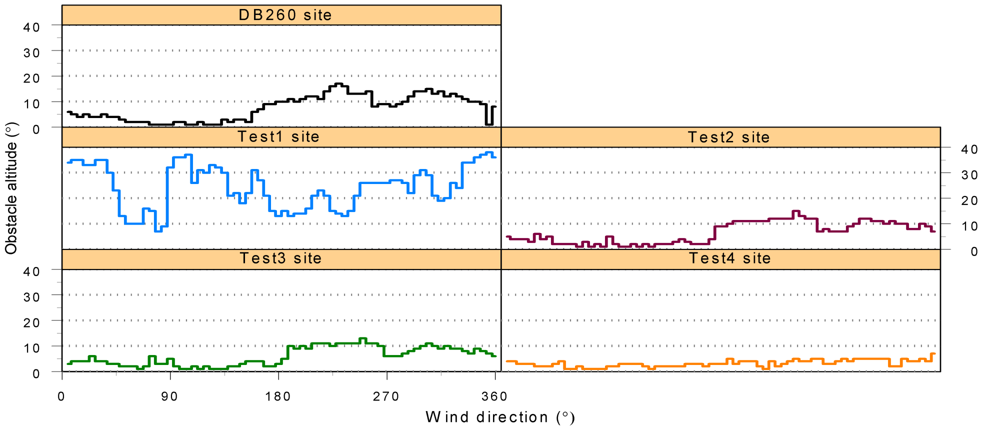

Figure 2.1: Obstacle altitude as a function of wind direction at DB260 and the 4 parallel sites.

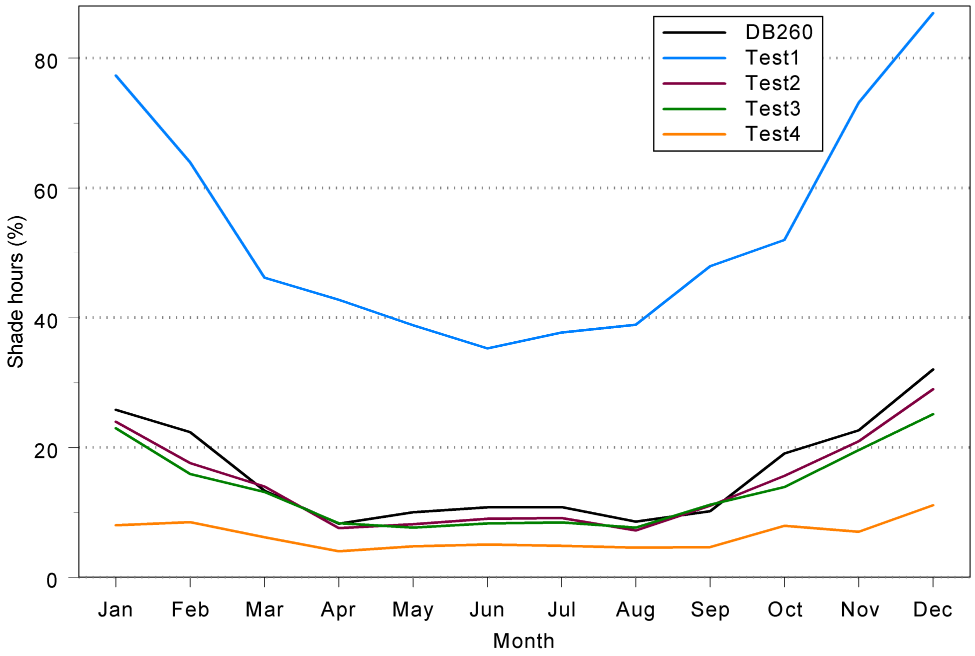

Figure 2.2: Annual cycle of the percentage of shade hours at the DB260 and the 4 parallel locations.

Test1 is the most enclosed site and Test4 the most open site. This is also reflected in the annual cycle of the percentage of shade hours in Figure 2.2. The figure shows that during winter, Test1 is in the shade for almost the whole day, while for Test4 this only happens for a small fraction (< 13%) of the day. The panorama photos in Figure 2.3 give an impression of the type of obstacles for each site.

During the experiment the following irregularities with respect to the terrain have been noted:

1. In the dry summer of 2003, on August 12, 18, 21 and 26, the gardener irrigated the Test1 field. We found that this caused a small temperature drop on those days at the Test1 site.
2. In that same year, on 11 September 2003 the pasture east of the Test4 site was ploughed by the owner and re-sown with grass. We have no indication that this affected the measurements.
3. On behalf of the 150-year jubilee of KNMI large tents were placed in between the KNMI building and the measuring field on 6 May 2004. The tents were removed on 17 May 2004. The effect of the placement of the tents is briefly discussed in Appendix B.
4. The renovation of the wasteland area (Sandwijck) started on 9 September 2004. Immediately a long strip of land of about 20 m width was cleared of bushes close to the operational screen. As a result, the operational site was no longer affected by the bushes. Around the end of October 2004 the renovation was completed. Figure 2.4 gives an aerial photo of the terrain after the renovation of the wasteland area. Note the bodies of water that have been created close to the operational site. The effects of the renovation on the measurements are discussed in this report.
5. On 21 February 2005 a tree was cut down at a distance of about 50 m northwest from the Test1 site. There is no indication that this affected the temperatures of Test1.

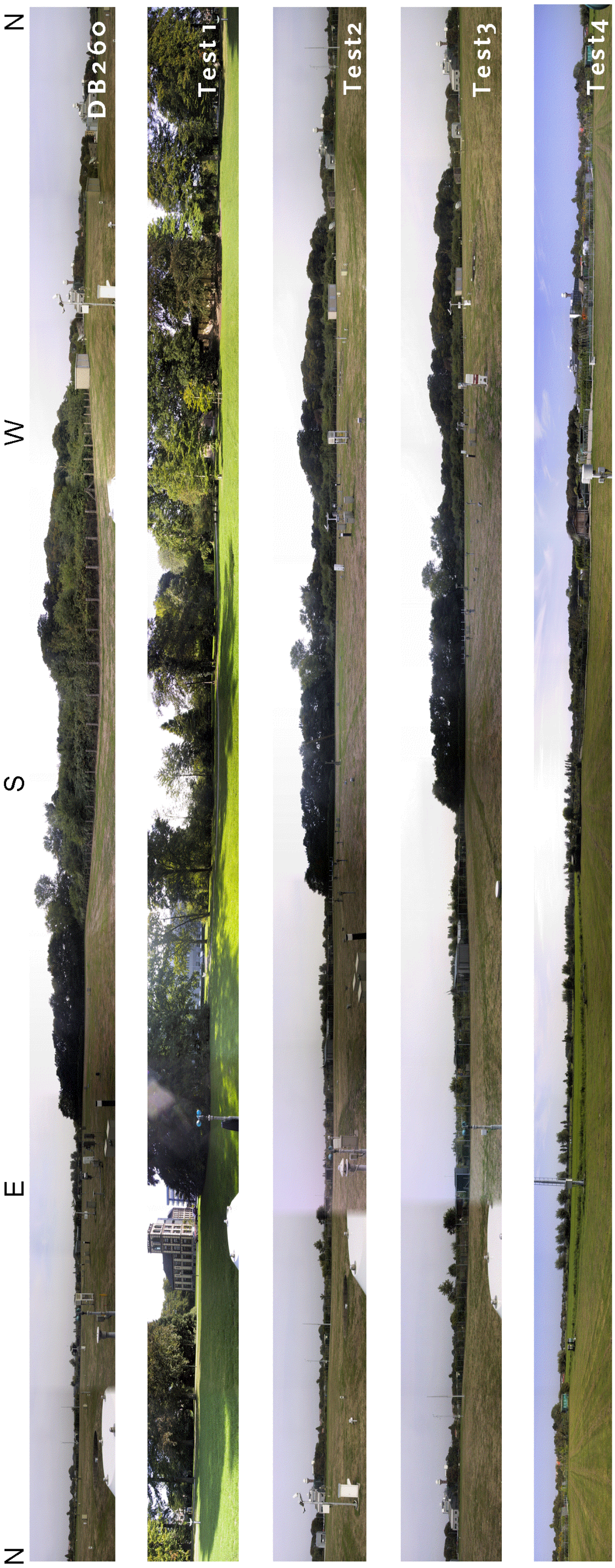

Figure 2.3: Panorama photos at the operational site DB260 and the 4 parallel sites (September 2003).

Figure 2.4: Aerial photo of the measurement field after the renovation of the wasteland area west of DB260 in September/October 2004. The arrows point to two new bodies of water.

2.1.2 Instrumentation

All five sites were equipped with identical instruments and sensors. Figure 2.5 shows the instruments at DB260. Air temperature was measured at 1.5 m above ground level in naturally ventilated so-called KNMI multi-plate radiation shields (based on a design from the Meteorological Service of Canada type CCIW) using PT-500 temperature sensors (see KNMI (2000)). The operational measurement uncertainty (uncertainty always refers to the end of a calibration term) of the sensors is 0.1°C and the resolution of the 1-minute averages is 0.1°C. For the present experiment, we obtained much higher accuracies by (1) correcting the measurements afterwards with high resolution (0.01°C) calibration curves, and (2) by re-calibrating the instruments every half year instead of the standard 36 months. The 1-minute average temperatures were stored in the database and later averaged to obtain 10-minute temperatures. Appendix A presents more details on the calibration. Figure 2.5 shows two radiation shields on the pole, directed west-east. The easterly shields contain the PT-500 sensors. For DB260, Test2 and Test4, the westerly radiation shield contained a humidity sensor, for Test1 and Test3 the corresponding shield is empty. Humidity measurements are only briefly addressed in this report.

Wind speed was measured at each site with a cup anemometer on top of a pole (see Figure 2.5) at the same height as the air temperature measurements (1.5 m). The anemometers were situated at a distance of 4 m northeast of the thermometer screens. The standard uncertainty of the sensors is 0.5 m/s and the resolution of the 1-minute averages is 0.01 m/s. As for temperature, we obtained higher accuracies by (1) correcting the measurements afterwards with the calibration data, and (2) by re-calibrating the instruments every half year instead of the standard 26 months. One-minute average wind speeds were stored in the database and later averaged to obtain 10-minute averages. For more details on the calibration see Appendix A.

Figure 2.5: Instruments at DB260. The left side shows the KNMI multi-plate radiation shields for measuring temperature and relative humidity. The right side shows the cup anemometer. Both instruments operate at 1.5 m above ground level. The 4 parallel sites are equipped with the same instruments and have an identical set-up.

Besides the experimental temperature and wind speed measurements also the following operational 10-minute measurements at the KNMI terrain were stored: wind direction, cloud cover (with ceilometer at the DB260 site), air pressure reduced to mean sea level, precipitation duration, mean precipitation intensity, direct radiation, diffuse radiation, global radiation, grass minimum temperature at 10 cm, and horizontal visibility. Details about the corresponding observation methods can be found in KNMI (2000).

2.2 Methodology

The differences between the 5 sites are studied by comparing the air temperature differences $\Delta T = T(\mathrm{site}X) - T(\mathrm{Test4})$, where site$X$ stands for the Test1, Test2, Test3 and DB260 sites. Test4 is used as the reference site. In Brandsma (2004) we used DB260 as the reference site, but that site is likely affected by the renovation of the wasteland area.

The possible causes of observed temperature differences between the sites are:

1. Advection of warm/cold air
2. Local stability differences
3. Screen ventilation differences (radiation error)
4. Sky-view factor/horizon differences (shading or direct sun light)
5. Radiation by surrounding objects
6. Local soil type and groundwater level and albedo differences
7. Instrumental errors.

Brandsma (2004) showed the importance of daytime advection, resulting from the non-uniformity of the KNMI-terrain. Especially the allotments seem to have energy balances different from those of the surrounding grassland. This results in different Bowen ratios (sensible heat flux/latent heat flux). Local stability differences are most important during nighttime stable conditions (clear sky, small wind speeds) when inversions develop, causing low temperatures near the ground. In those situations, small differences in wind speed between the sites may cause different strengths of the inversion, resulting in higher temperatures at the site with the larger wind speed.

Screen ventilation differences are especially important during the day when radiation errors increase with decreasing wind speed. The effect of a small sky-view factor is mainly the reduction of nighttime outgoing long-wave radiation and the reduction of day-time incoming short-wave radiation. This is mainly important at the Test1 site. Also a restricted horizon is most important at this site (see Figure 2.2). Local differences in soil type and groundwater levels between the sites may affect the energy balance and may cause differences in observed temperatures. It is known that at the Test4 site groundwater levels are shallower than at the other sites. Especially in dry summers this may result in local differences in the Bowen ratio. Finally, instrumental errors may play a role, though these are minimized here by the calibration procedures outlined in Section 2.1.2.

In this report we focus on the temperature differences between the 5 sites from May 2003-June 2005. The differences are discussed in connection with wind direction and with speed differences, because these are strongly related to most of the afore-mentioned causes of temperature differences. Special attention is given to the impact of the renovation of the wasteland area.

3 Results

In this chapter, we first present the mean climate conditions during the experiment. The remainder of the results focuses on the effects of the renovation on the inter-site temperature differences. The monthly and daily temperature differences are discussed followed by a discussion of the diurnal cycle of these temperature differences and its relation to wind speed and cloudiness. Diurnal wind speed cycle differences are discussed thereafter. Then we discuss the dependence of the temperature and wind speed differences on wind direction. For DB260 and Test2 we also discuss the vapor pressure differences. For the calculation of all differences, the Test4 site always serves as the reference. Finally, the temperature data of the operational site DB260 are compared with the mean of four neighboring stations to estimate the effect of the growth of the bushes in the wasteland area.

3.1 Climatic conditions during the experiment

Figure 3.1 presents the time series of monthly mean values of daily maximum temperature (T_{x}), daily minimum temperature (T_{n}). daily mean temperature (T_{mean}), wind speed at 1.5 m (W_s), cloud cover (nc), and the monthly precipitation amount (r) in De Bilt. T_{x}, T_{n}, T_{mean} and W_s are measured at the reference site Test4. The variables nc and r are measured near DB260. Note the dry and warm summer (JJA) of the year 2003.

3.2 Monthly mean temperature differences

Figures 3.2–3.4 present the time series of the monthly mean differences $\Delta T = T(\mathrm{site}X) - T(\mathrm{Test4})$ for T_{x}, T_{n} and mean T_{mean}. For each day T_{x}, T_{n} and T_{mean} values were calculated as the maximum, minimum and mean of the 144 10-minute average temperatures[3], respectively.

The results for T_{x} in Figure 3.2 show the largest temperature differences in the summer half of the year, amounting to 0.4-0.5°C for Test1 and DB260 (summer 2003). Before the renovation of the wasteland area (September/October 2004), ΔT for DB260 and Test 1 are comparable, while after the renovation DB260 is close to Test2 and Test3. Keep in mind that the temperatures at Test1 and the reference Test4 are probably not affected by the renovation of the wasteland area. It is noteworthy that for all sites ΔT_{x} values for July/August of 2003 are large. These two months were relatively dry and warm with only 28% of the 30-year average rainfall amount and with T_{x} 2.2°C (July 2003) and 3.0°C (August 2003) higher than the 30-year average for these months.

Figure 3.3 shows for the ΔT of T_{n} an opposite sign compared to the results for T_{x}, except for Test1. Test1 is warmer than Test4, both in the maximum and minimum temperature, where the relative warmth is largest for the minimum temperature. After the renovation of the wasteland area, ΔT for DB260, Test2 and Test3 are all close to zero. This suggests that the renovation had the larges impact on DB260 but also affected Test2 and Test3.

The results for T_{mean} in Figure 3.4 show that on average Test2, Test3 and DB260 are somewhat colder than Test4 with the largest values in the summer half of the year. After the renovation all values are close to zero. As expected, T_{mean} of Test1 is larger

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[3] Operationally, KNMI determines T_{x} and T_{n} from 1-minute running averages and T_{mean} from the means of the 1-minute average of the 10-minute intervals; the 10-minute averages used here, produce a less noisy estimate than the operational values.

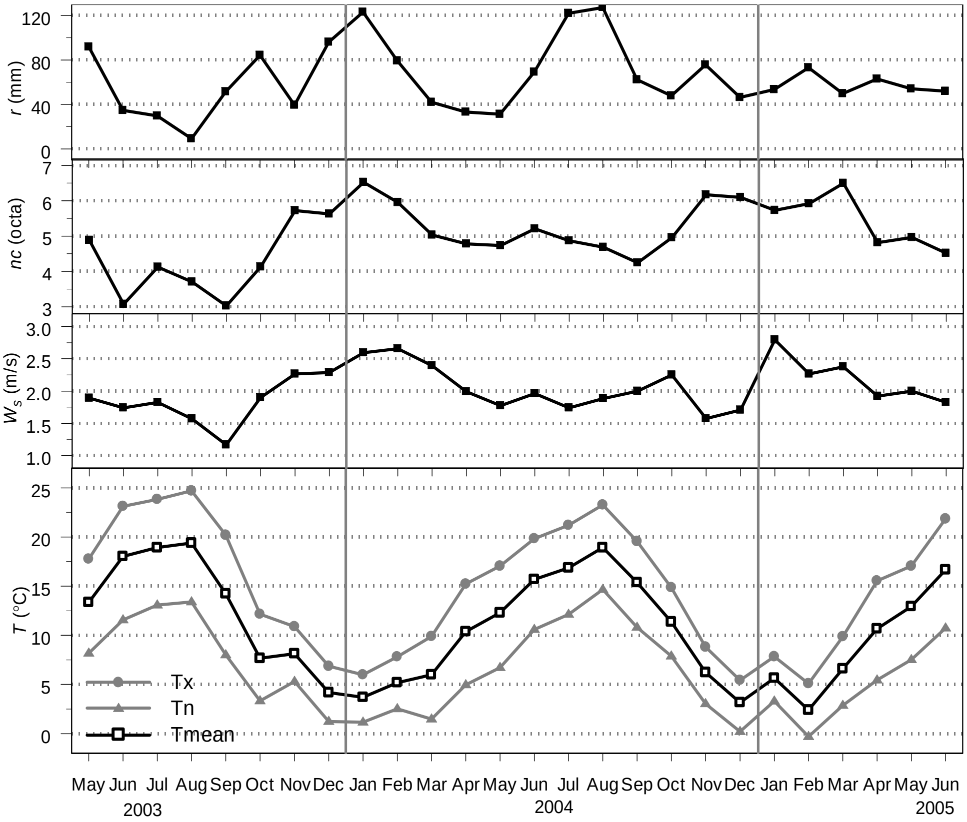

Figure 3.1: Monthly means of the daily maximum, minimum and mean temperatures, wind speed (at 1.5 m), cloudiness and monthly precipitation amount for the period May 2003-June 2005.

than the reference most of the year and is not affected by the renovation. However, the values are much smaller than the mean of the ΔT values for T_n and T_x. Later we will show that this is the result of the shape of the daily cycle differences.

Note that in general, all the absolute temperature differences for DB260, Test2 and Test3 increase with increasing distance to the bushes in the wasteland area.

The ΔT values for T_x, T_n and T_mean are quantified in Table 1. The table is constructed to facilitate the comparison between periods before and after the renovation. For instance, the May-June summer periods of 2003 and 2004 represent the situation before and that of 2005 after the renovation. The results for the July-August period are only available for the period before the renovation and illustrate the year to year variation. Most notable is the large rise of T_n of Test2, Test3, and DB260 in the May-June period (compare the May-June average ΔT_n values of 2003 and 2004 with those of 2005) and amounts about 0.3-0.5°C on average. The rise of T_n in the winter half year is smaller than for the May-June period but still discernible.

3.3 Daily temperature differences

In addition to looking at the monthly mean temperature differences, it may be of interest to look at the distribution of the daily temperature differences.
Figures 3.5–3.6 present boxplots of the daily temperature differences ΔT for T_x, T_n and T_mean before and after the renovation of the wasteland area.

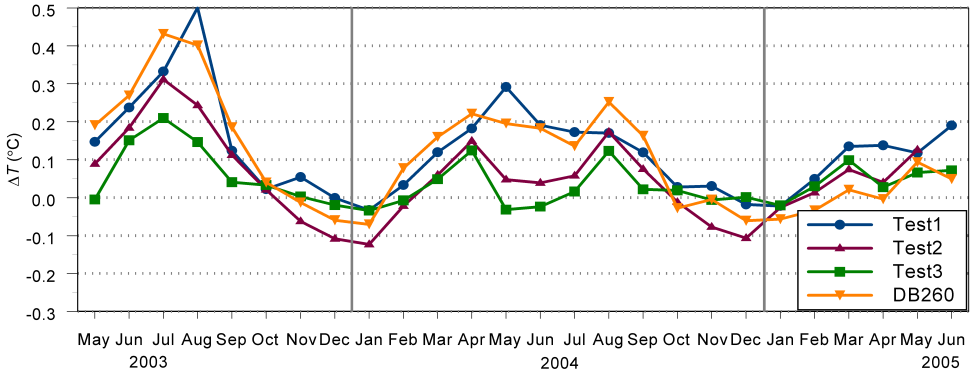

Figure 3.2: Monthly means of daily temperature differences $\Delta T = T(\mathrm{site}X) - T(\mathrm{Test4})$ *for the period May 2003-June 2005 for the maximum temperature.*

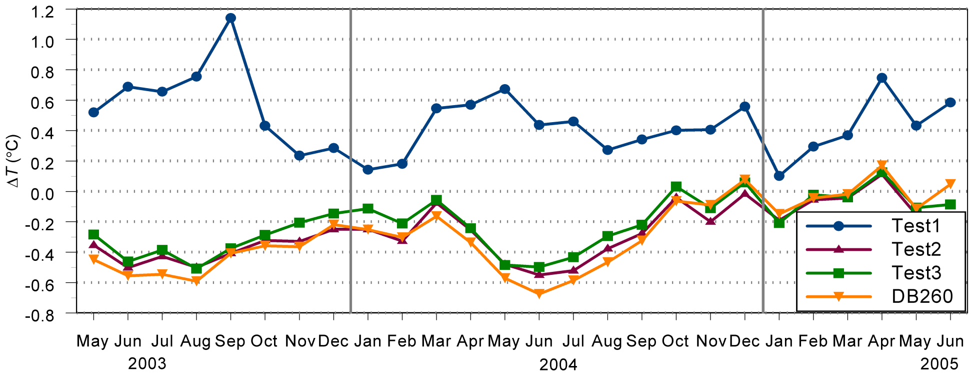

Figure 3.3: Same as Figure 3.2 but now for the daily minimum temperature. Note the different vertical scale.

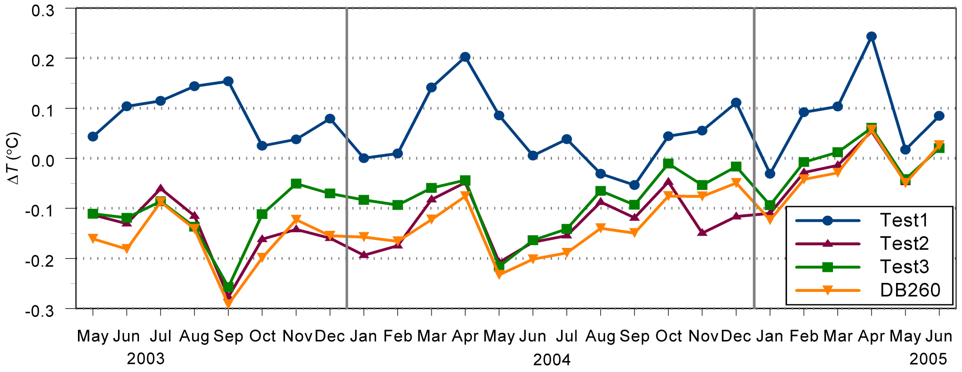

Figure 3.4: Same as Figure 3.2 but now for the daily mean temperature. Note the different vertical scale.

Table 3.1: Means of the daily temperature differences $\Delta T = T(\mathrm{site}X) - T(\mathrm{Test4})$ *for* T_x*,* T_n *and* T_mean *for periods before (May-June 2003 and 2004; July-August 2003 and 2004; October-March 2003/4) and after the renovation of the wasteland area (May-June 2005; October-March 2004/5).*

	May-June			July-August		October-March	
	2003	2004	2005	2003	2004	2003/4	2004/5
T_x							
Test1	0.192	0.242	0.155	0.417	0.172	0.033	0.036
Test2	0.136	0.044*	0.126^{1}	0.277	0.116	−0.039	−0.020*
Test3	0.072	−0.028*	0.069*	0.178	0.070	0.004*	0.022
DB260	0.230	0.189	0.071	0.416	0.194	0.022*	−0.026
T_n							
Test1	0.603	0.557	0.510	0.706	0.366	0.306	0.354
Test2	−0.426	−0.514	−0.154^{1}	−0.464	−0.448	−0.257	−0.090
Test3	−0.371	−0.490	−0.096	−0.447	−0.363	−0.169	−0.048
DB260	−0.501	−0.622	−0.031*	−0.568	−0.525	−0.275	−0.048*
T_mean							
Test1	0.073	0.046	0.055	0.129	0.004*	0.050	0.064
Test2	−0.121	−0.188	−0.047^{1}	−0.088	−0.120	−0.152	−0.076
Test3	−0.115	−0.190	−0.010*	−0.111	−0.103	−0.078	−0.027
DB260	−0.170	−0.217	−0.010*	−0.114	−0.164	−0.153	−0.066

^{1} May only; * values differ less than 2 times the standard error from zero

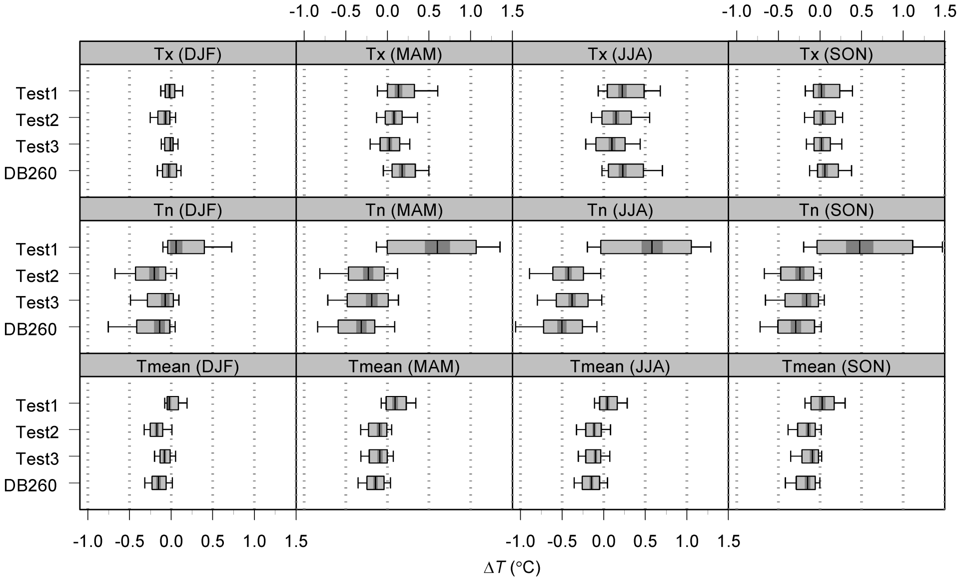

Figure 3.5: Boxplots of the individual daily temperature differences $\Delta T = T(\mathrm{site}X) - T(\mathrm{Test4})$ *for winter (DJF), spring (MAM), summer (JJA) and autumn (SON) for daily minimum, maximum, and mean temperature before the renovation of the wasteland area (≤ September 2004). The left and right limits of the box represent the 25th/75th percentiles (quartiles); the vertical line within the box represents the 50th percentile (median) with 95% confidence interval (dark gray); and the whiskers mark the 10th/90th percentiles.*

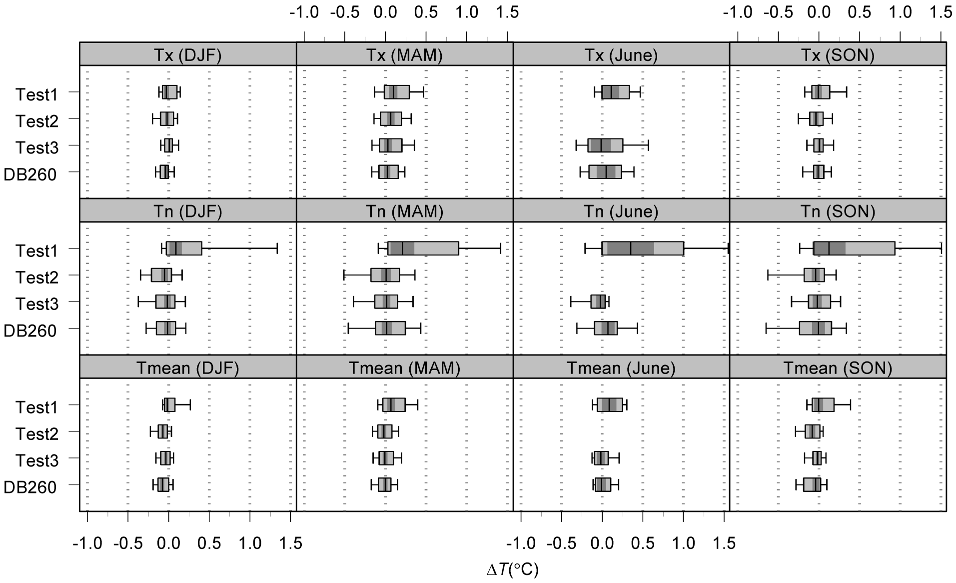

Figure 3.6: Same as Figure 3.5 but now after the renovation of the wasteland area (> September 2004). The summer season in this figure consists only of the month of June and the values for Test2 in that season are missing.

Figure 3.5 for instance shows that in the March-May (MAM) and June-August (JJA) periods in 10% of the days T_{n} of Test1 is more than 1.3° higher than T_{n} of the reference site Test4. Both figures show that the distribution of ΔT values is widest for T_{n} and smallest for T_{mean}. At first sight, the shapes of the distributions before and after the renovation look about the same. The changes in the ΔT values as presented previously are mainly manifested in a shift of the ΔT distributions.

The most extreme daily ΔT values are far outside the 10th and 90th percentiles shown in the figures. For instance, for T_{x} the ΔT values range between −0.75 (DB260, September 24, 2003) and 1.23°C (Test1, July 14, 2003). For T_{n} the values range between −2.58 (DB260, July 14, 2004) and 2.36°C (Test1, September 18, 2003). For T_{mean} the values range between −0.81 (DB260, August 31, 2003) and 0.95°C (Test1, April 2, 2005). As in the boxplots, the range for T_{n} is much larger than the range for T_{x} and T_{mean}.

To study the shape of the distribution somewhat further, we compared the probability density functions (pdf) of the daily ΔT values before and after the renovation. Values are only presented for the operational site DB260 and for Test1.

Figures 3.7–3.9 present the pdfs of ΔT for T_{x}, T_{n} and mean T_{mean}, respectively. Figure 3.7 shows that the location and shape of the pdfs of the ΔT values for Test1 are about the same before and after the renovation. This was expected because Test1 and the reference site Test4 are probably not affected by the renovation. For DB260 the renovation resulted in a change in the shape and a shift of the location of the pdf except for winter. Note that both for Test1 and DB260 the distributions are positively skewed except for winter and that for DB260 the skewness decreases as a result of the renovation.

The results for T_{n} in Figure 3.8 also show that the location and shape of the pdfs of the ΔT values for Test1 are about the same before and after the renovation. For DB260 the renovation resulted in a change in shape and location of the pdf in all

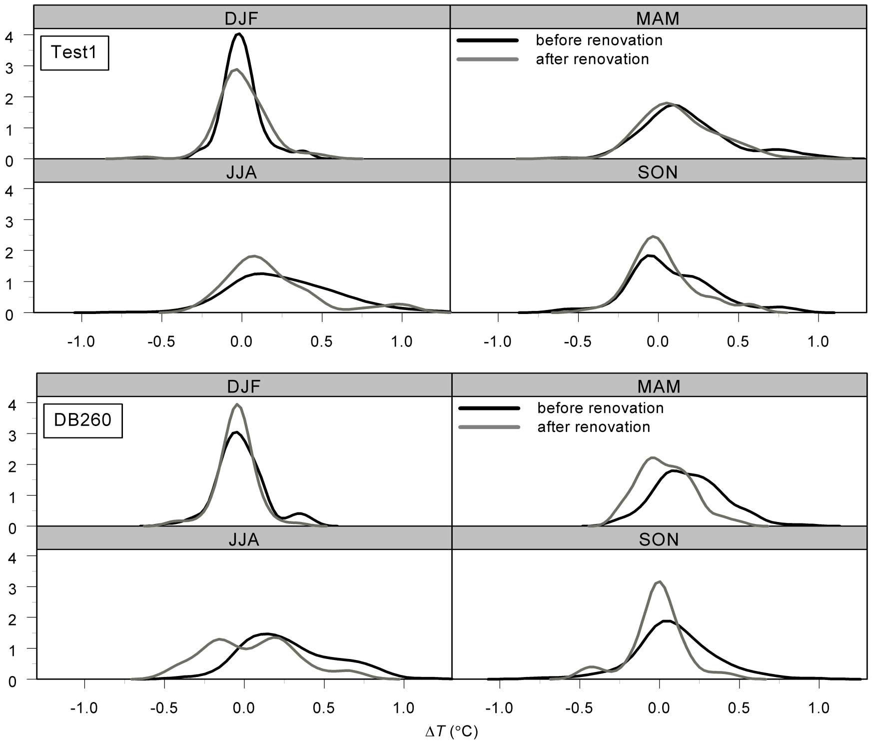

Figure 3.7: Probability density functions of the individual daily temperature differences $\Delta T = T(\mathrm{site}X) - T(\mathrm{Test4})$ before and after the renovation of the wasteland area in September/October 2004) for daily maximum temperature for winter (DJF), spring (MAM), summer (JJA) and autumn (SON). The upper four panels consider the temperature difference between Test1 and the reference site Test4 and the lower four panels the differences between DB260 and Test4. The Unit along the vertical axis is $^{\circ}C^{-1}$.

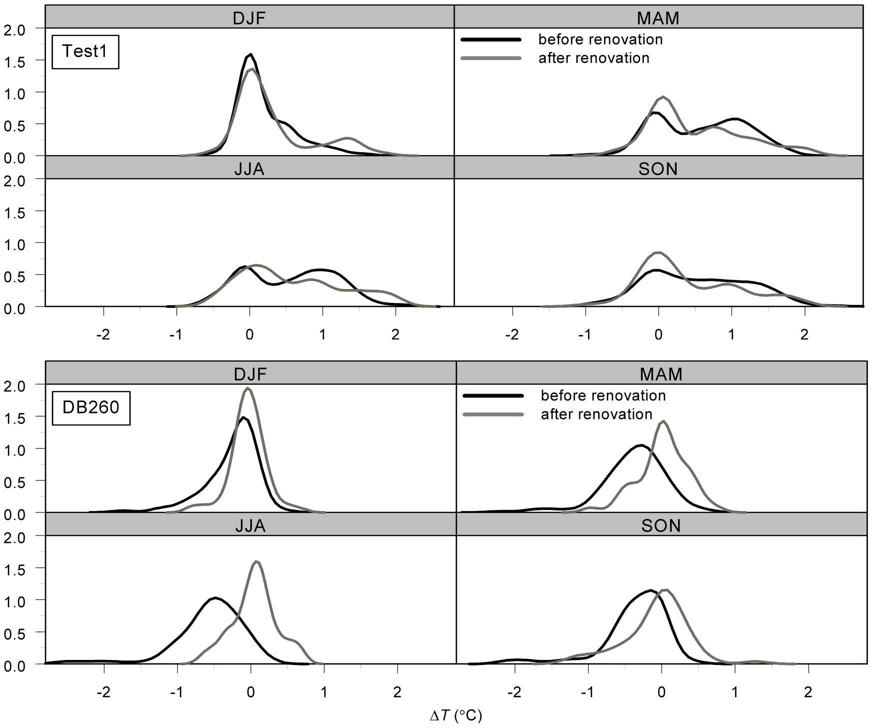

Figure 3.8: Same as Figure 3.7 but now for daily minimum temperature. Note the different scales of the axes.

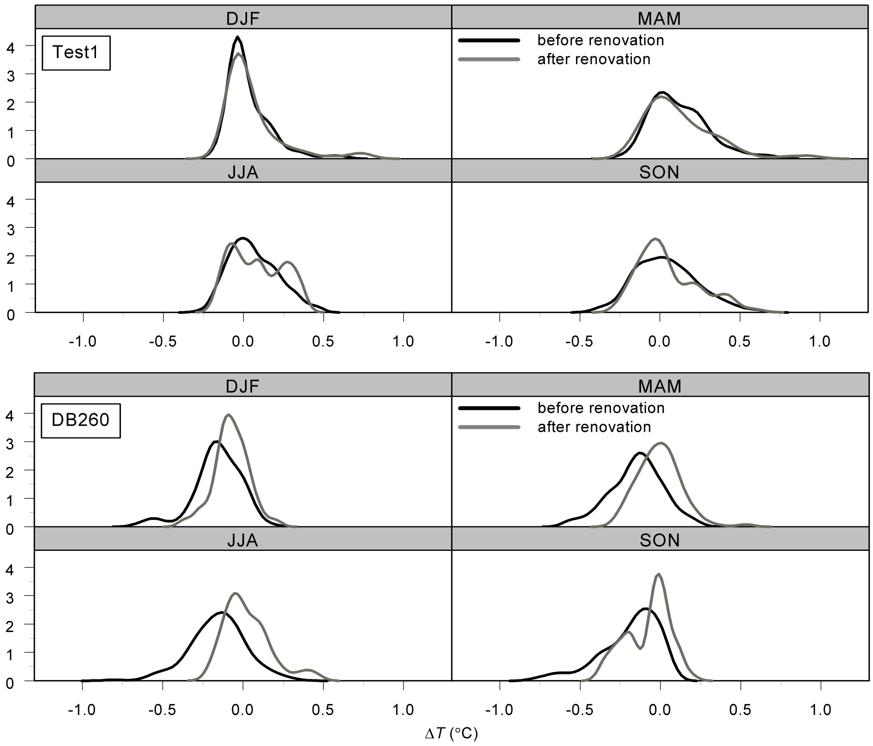

Figure 3.9: Same as Figure 3.7 but now for daily mean temperature.

seasons. Note that the range of the ΔT values is much larger compared to the values for T_{x} and that the distribution of the ΔT values for DB260 is now negatively skewed in a number of cases.

The results for T_{mean} in Figure 3.9 show in general the same pattern as the results for T_{n} except that the absolute ΔT values values are smaller here.

The results illustrate that the introduction of an inhomogeneity, like the renovation of the wasteland area, causes not only a shift of the location of the pdf of the daily temperature differences but also a change of the shape. This means that for the homogenization of a daily temperature series it may not be sufficient to correct only the mean.

3.4 Diurnal temperature cycle differences

Sheltering affects the diurnal temperature cycles of each site. This is reflected in the results for T_{x} and T_{n} in the previous paragraphs. Diurnal temperature cycle differences may provide extra information on the behavior of sites during during sunrise and sunset. Especially for strongly enclosed sites like Test1 this may be of interest.

Figure 3.10 presents the mean diurnal temperature cycle differences between site*X* and Test4 in a 10-month period before the renovation of the wasteland area and a corresponding period after the renovation. Note the behavior of Test1 during sunrise and sunset. Because the site is in the shade during sunrise and sunset, temperatures at these times are lower than that of the other sites. This also explains that T_{mean} at Test1 is not as large as could be expected from the positive temperature differences of both T_{x} and T_{n}. Note also that the shapes of the curves of Test1 are almost the same before and after the renovation. For the other sites, DB260 most strongly deviates from the reference Test4, especially during nighttime. The deviations seem

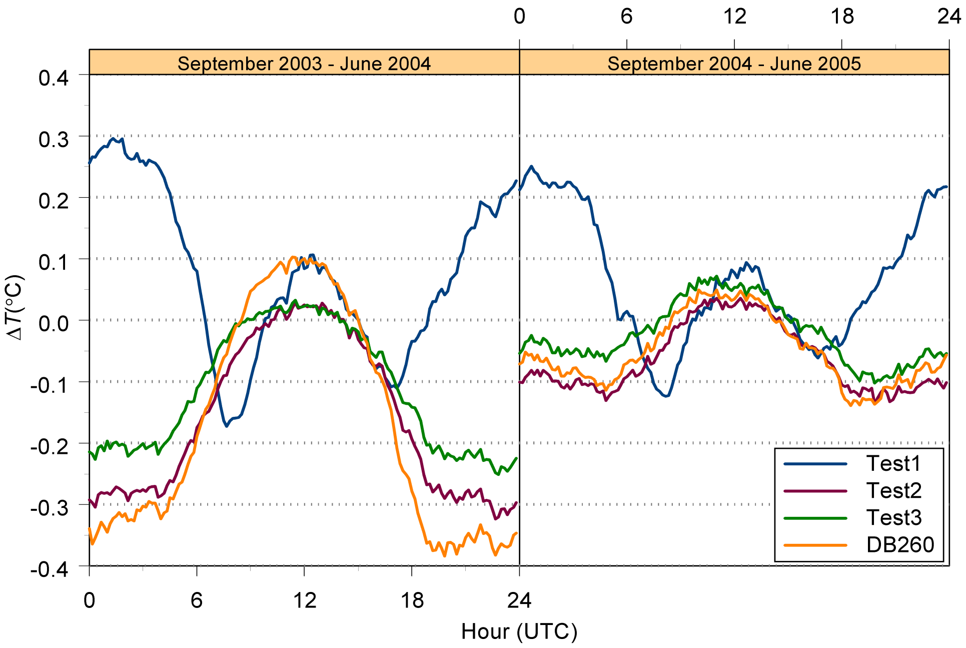

Figure 3.10: Mean diurnal temperature cycle differences between SiteX and Test4 for (a) September 2003 - June2004, (b) September 2004 - June 2005. The second period represents the period after the renovation of the wasteland area.

to decrease with increasing distance to the bushes in the wasteland area. After the renovation the diurnal cycle differences for Test2, Test3 and DB260 become almost negligible (≈ 0.1°C).

In Figure 3.11 a distinction is made between the winter (DJF) and May/June months. The figure shows that for Test2, Test3 and DB260 in winter the diurnal cycle differences are small and only slightly affected by the renovation. The diurnal cycle differences for Test1 are also small. In the May/June months the diurnal cycle differences are large before the renovation and become small thereafter, with the exception of Test1.

Figure 3.12 shows how the temperature differences are related to wind speed and cloudiness. The figure presents the diurnal cycles of mean temperature differences between site$X$ and Test4 in summer for 4 combinations of wind speed W_s (at DB260) and cloudiness nc (cloud cover fraction). It can be seen that the inter-site temperature differences strongly depend on the prevailing weather conditions. Low wind speed and clear to partly cloudy sky conditions result in large inter-site temperature differences while large wind speed and cloudy conditions minimize the differences. High wind speed implies improved mixing of the air, making a site representative of a large area. Increasing cloudiness implies less disturbance from local differences in outgoing radiation and direct sunlight.

Figure 3.13 shows the relationship between the nighttime (between sunset and sunrise) temperature differences between Test1 and the reference Test4 as a function of wind speed at the Test4 site for the two cloudiness categories. The calculation of the standard error bands does not take into account the autocorrelation of the wind speed values. In reality the width of the standard error bands will therefore be somewhat larger than shown. The figure shows a strong non-linear relationship between wind speed and ΔT with the non-linearity becoming

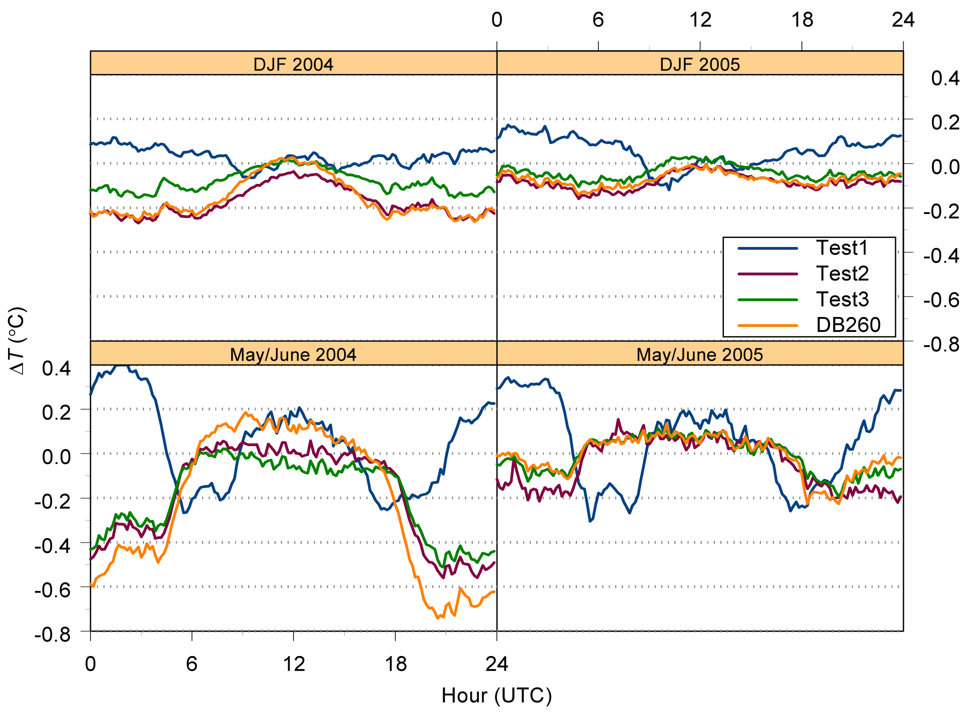

Figure 3.11: Same as Figure 3.10 but for (a) winter (DJF) of 2004 and 2005 and (b) the May-June months of 2004 and 2005. The 2005 values represent the period after the renovation of the wasteland area. Note the different vertical scale compared to Figure 3.10.

stronger with decreasing cloud cover. Note that for wind speeds > 1 m/s $\Delta T \approx 0$. This result stresses the importance of low wind speeds at screen level in homogenisation studies. Operationally wind speed is measured at 10 m with an accuracy of about 0.5-1.0 m/s. During stable nighttime conditions this 10 m wind speed is not or weakly related to the wind speed at screen height.

During the day the temperature differences between Test1 and Test4 are also related to wind speed (not shown). In contrast to the nighttime differences, the daytime temperature differences increase with increasing wind speed.

3.5 Diurnal wind speed cycle differences

Differences in wind speed between the sites may be an important factor explaining the temperature differences. On the one hand, wind speed affects the daytime radiation error of the temperature screen, being larger for low wind speeds. On the other hand, wind speed affects the growth of a nighttime stable layer at screen height.

Figure 3.14 presents the diurnal wind speed differences $\Delta W_s = W_s(\mathrm{site}X) - W_s(\mathrm{Test4})$ (at 1.5 m height). A distinction is made between the winter and May/June months before and after the renovation of the wasteland area. The figure clearly shows that the Test1 site is the most enclosed site and the reference site Test4 the most open. During the day, when the wind speeds are highest, the wind speed differences are also largest. In the May/June months the diurnal cycle differences are most clearly visible. This is related to the fact that in the November-April period there are no leaves on the trees surrounding the sites. The relatively large wind speeds at the reference site Test4, reduce the radiation error during the day (causing lower

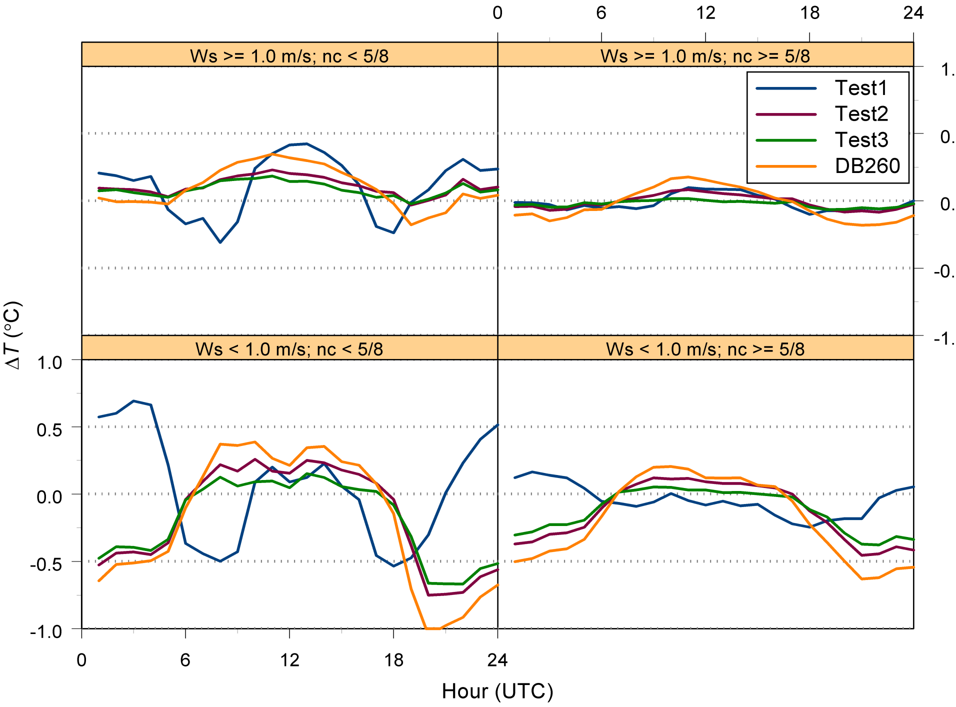

Figure 3.12: Diurnal cycles of the mean temperature differences between SiteX and Test4 for the summers (JJA) of 2003 and 2004 (before the renovation of the wasteland area) for four combinations of wind speed W_s and cloud cover nc (fraction of cloud cover) as indicated on top of each panel. The 10-min values are grouped together in 24 hourly values.

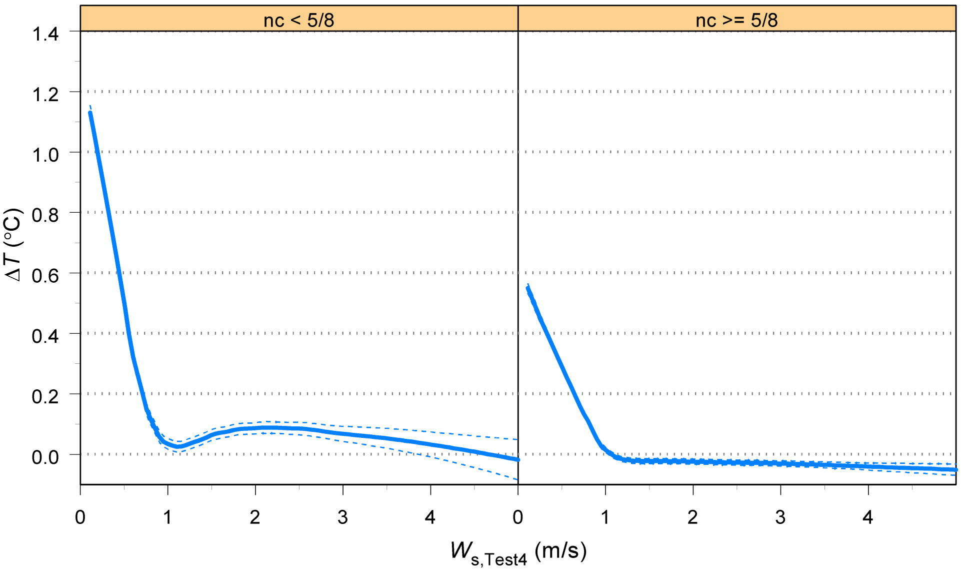

Figure 3.13: Relationship between the nighttime temperature differences between Test1 and Test4 and 1.5 m wind speed (W_s) at the Test4 site for two categories of cloud cover nc (fraction of cloud cover). Values refer to the May 2003 – June 2005 period.The solid lines are locally weighted running line smooth curves (Cleveland, 1979) with a span of 0.5. The dashed curves give the point-wise 2 times standard-error bands.

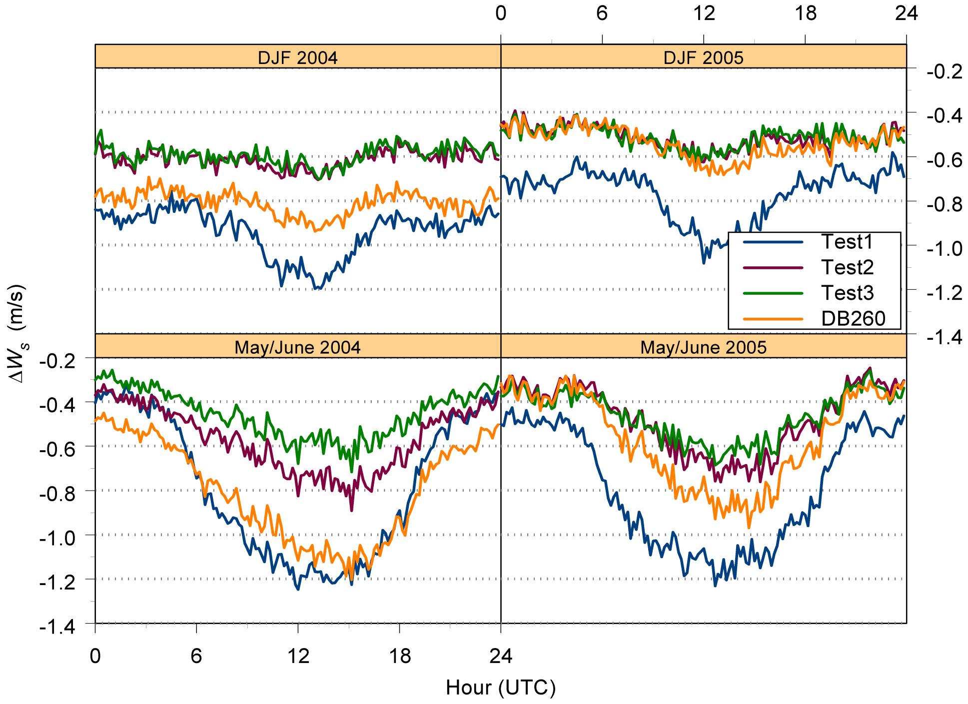

Figure 3.14: Diurnal wind speed cycle differences $\Delta W_s = W_s(\mathrm{site}X) - W_s(\mathrm{Test4})$ *for (a) winter (DJF) of 2004 and 2005 and (b) the May-June months of 2004 and 2005. The 2005 values represent the period after the renovation of the wasteland area.*

temperatures than DB260) and limit the development of a stable layer during the night (causing higher temperatures than DB260). Due to the renovation the wind speed at DB260 increases in both the winter and May/June periods relative to the wind speed at the reference site. In the May-June period also the wind speed at the Test2 site seems to increase. The increase in wind speeds may be an important cause of the observed changes in the temperature differences after the renovation of the wasteland area.

In the previous paragraph we showed the importance of small wind speeds during the night to explain inter-site temperature differences. Here we will look at the effect of the renovation of the wasteland area in September/October 2004 on small wind speeds at the DB260 site. Figure 3.15 shows the monthly mean wind speeds for DB260 relative to those at Test4 for situation where the 10-min wind speed at Test4 is small ($W_{s,Test4} \leq 1.0$ m/s). The figure indicates that after the renovation of the wasteland area, small wind speeds at DB260 became more equal to those at Test4. For the period October 2003-June 2004, the mean of the relative monthly values equals 0.70. For the corresponding period after the renovation (October 2004-June 2005) this equals 0.87. The difference between the two values is statistically significant (t-test, 5% significance level). Because cup anemometers have difficulties with measuring small wind speeds, a comparison as presented here should be taken with care.

3.6 Wind direction dependent differences

It is of interest to see how the inter-site temperature and wind speed differences are affected by the renovation. Figures 3.16 and 3.17 present wind direction dependent temperature differences between site*X* and Test4 for winter (DJF) and the May-June period before and after the renovation of the wasteland area for both day- and

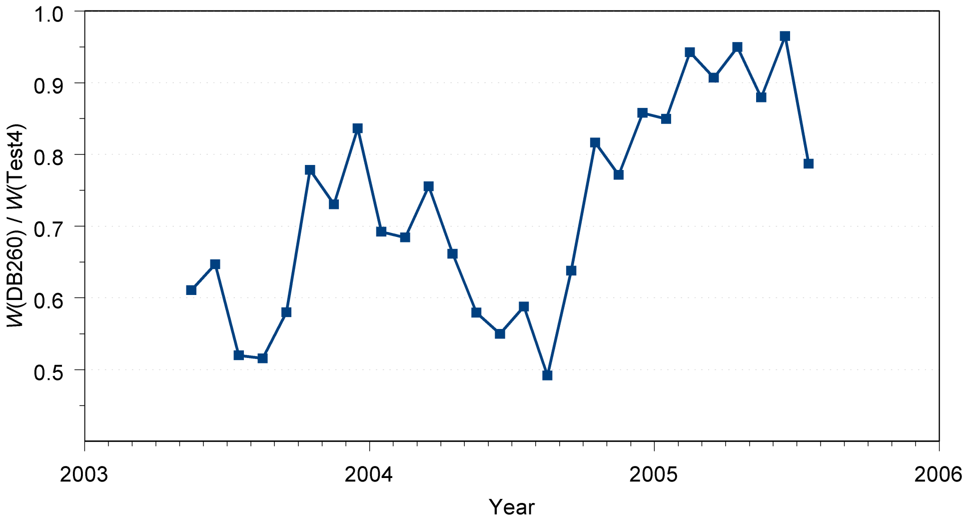

Figure 3.15: Monthly mean wind speed DB260, expressed as a fraction of the monthly mean wind speed at Test4 for small 10-min wind speeds ($W_{s,Test4} \leq 1.0$ m/s) for the period May 2003-June 2005.

nighttime hours. Day is defined here as the time with sun altitude $>$ 0 and night as the time with sun altitude $\leq$ 0. Sun altitudes were calculated from astronomical formulas. The results for DJF in Figure 3.16 show much similarity between the shapes of the plots of Test2, Test3 and DB260. During the day the ΔT values are small for all wind directions both before and after the renovation, also for Test1. During the night, ΔT for Test1 is large for directions between about 45-180° both before and after the renovation. For Test2, Test3 and DB260, ΔT is negative for directions between about 180-360°. After the renovation, these values become close to zero.

The ΔT values for the May/June period in Figure 3.17 are different from the DJF values in Figure 3.16, especially for nighttime conditions. For Test2, Test3 and DB260 ΔT is negative for all directions and after the renovation these values are much closer to zero than before the renovation. For some directions, they even become positive.

Figures 3.18 and 3.19 present the wind direction dependent wind speed differences between site*X* and Test4 for winter (DJF) and the May-June period before and after the renovation for both day- and nighttime hours. The results for DJF in Figure 3.18 show a clear similarity between the shapes of the plots of Test2, Test3 and DB260. These shapes are a reflection of the barrier of trees (see Figures 2.1–2.3) that runs from south of DB260 to north-northeast. The magnitude of ΔW_s reflects the distance to this barrier. Note the relatively small wind speeds at Test1, reflecting the enclosed character of that site. The daytime ΔW_s values are more negative than the nighttime values. The effect of the renovation seems that ΔW_s of Test2, Test3 and DB260 become more close to each other for westerly directions. Compared to the DJF values, the May/June ΔW_s values in Figure 3.19 are somewhat closer to zero.

The wind speed differences only partly explain the shape of the direction dependent temperature differences. Especially for the most enclosed site Test1, direction dependent cloudiness explains a part of the differences. The relatively large ΔT values for directions between about 45-180° correspond with relatively small cloud cover fraction for those directions. The large new KNMI building may also affect the temperatures for those direction.

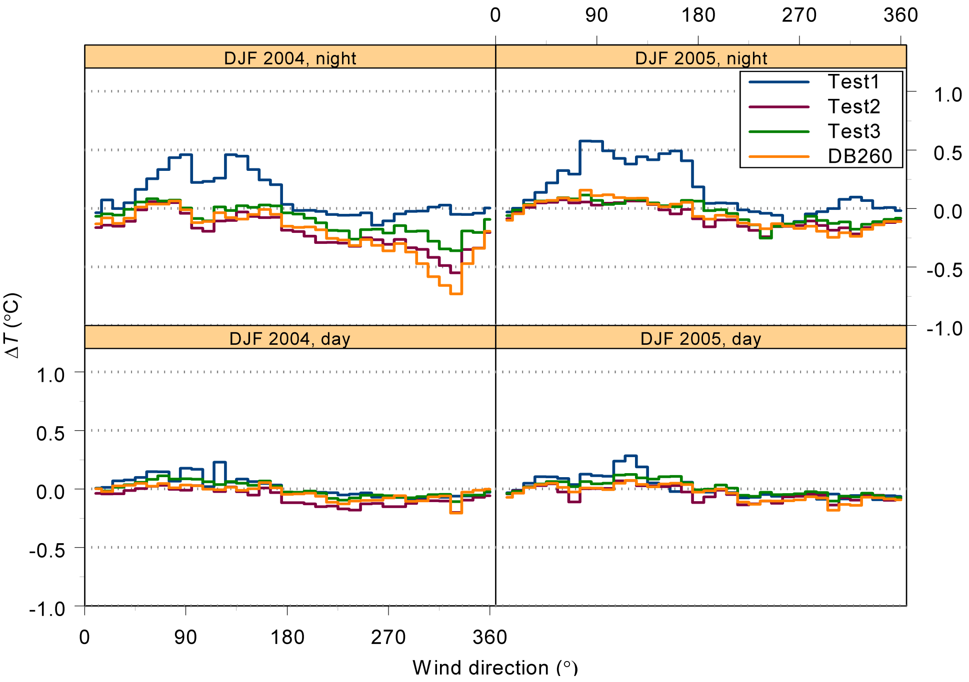

Figure 3.16: Daytime and nighttime temperature differences ΔT between SiteX and Test4 as a function of wind direction (10° bin width) for (a) winter (DJF) of 2004 (left panels), (b) winter (DJF) of 2005 (right panels. The second period represents the period after the renovation of the wasteland area.

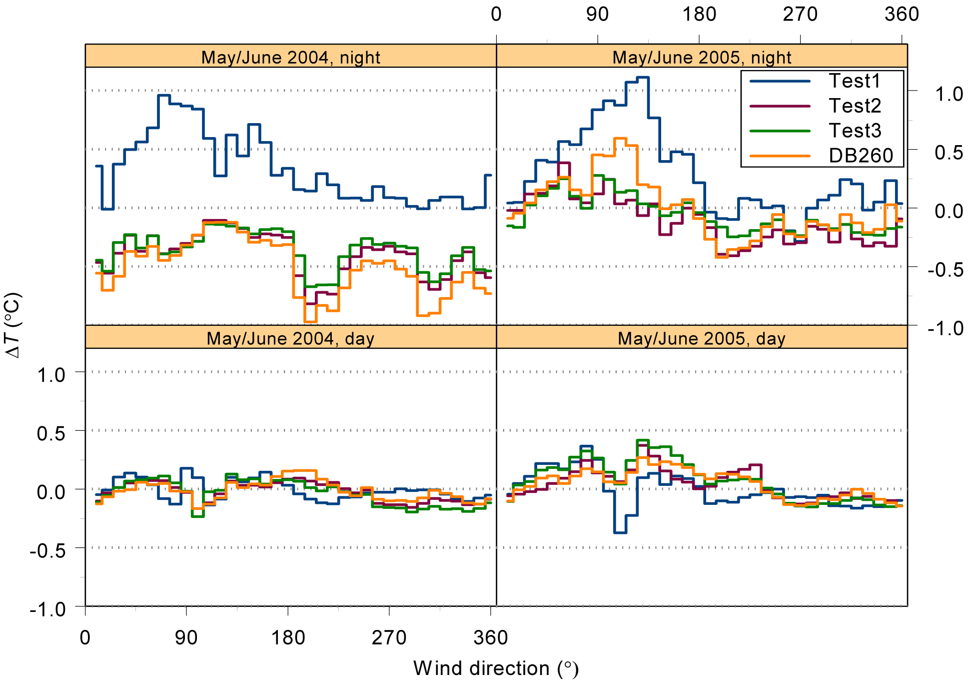

Figure 3.17: Daytime and nighttime temperature differences ΔT between SiteX and Test4 as a function of wind direction (10° bin width) for (a) May/June 2004 (left panels), (b) May/June of 2005 (right panels. The second period represents the period after the renovation of the wasteland area.

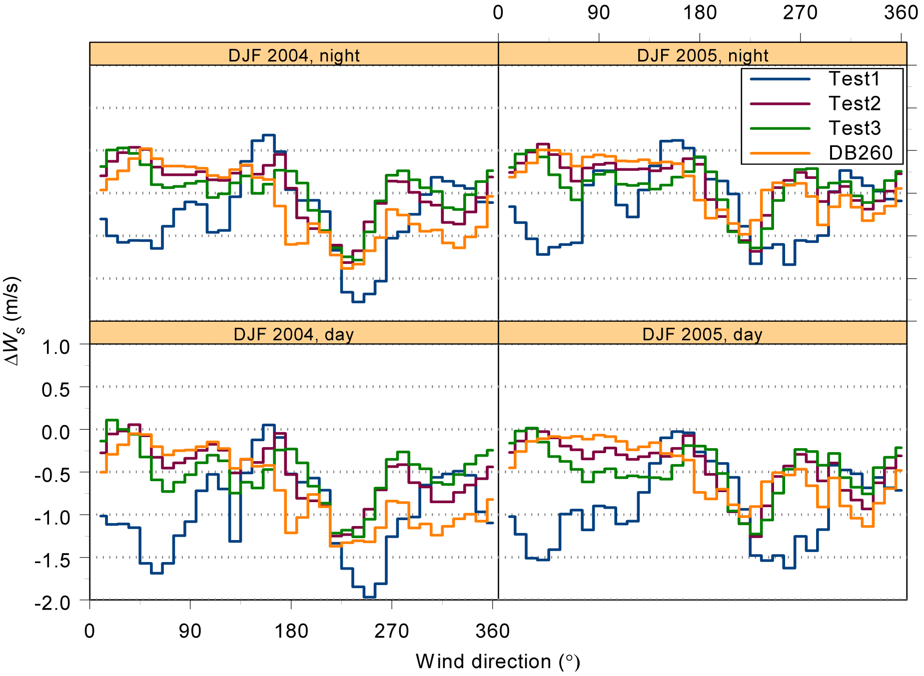

Figure 3.18: Same as Figure 3.16 but for wind speed differences ΔW_s.

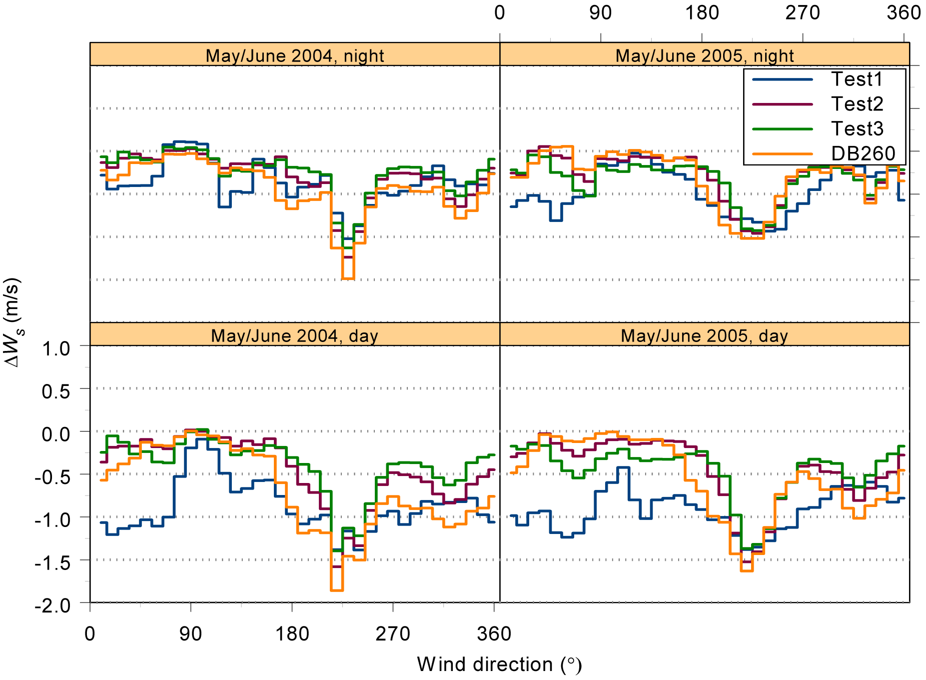

Figure 3.19: Same as Figure 3.17 but for wind speed differences ΔW_s.

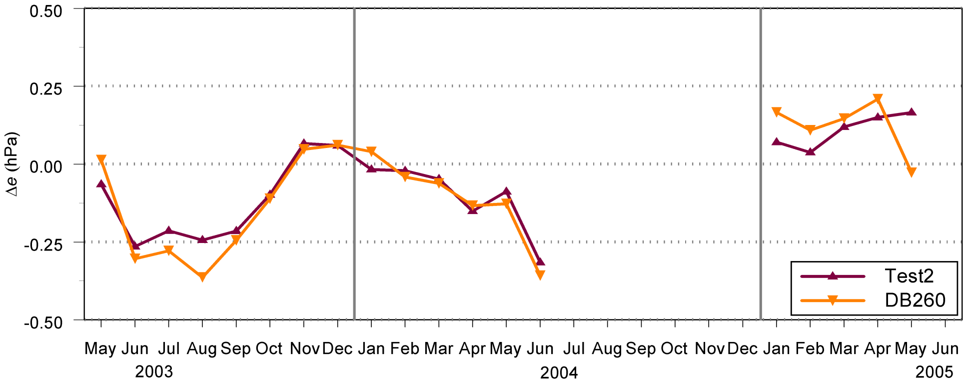

Figure 3.20: Monthly means of the daily vapor pressure differences $\Delta e = e(\mathrm{site}X) - e(\mathrm{Test4})$ *for the period May 2003-June 2005. Missing month are due to malfunctioning of some of the relative humidity sensors.*

3.7 Vapor pressure differences

In Section 2.2 local groundwater level differences were mentioned as one of the possible causes of temperature differences. The depth of the groundwater, in combination with soil type, determines to a great extent whether or not a soil dries out. In the Netherlands, that normally only occurs in dry summers. Drying out of the soil causes an decrease of the latent heat flux and an increase of the sensible heat flux, thus increasing the local temperature. Local vapor pressure differences may be an indication of differences in soil dryness. Here we compare the vapor pressures of the field containing DB260, Test2 and Test3 with that of the field containing Test4.

For the calculation of vapor pressure e we first calculated the saturation vapor pressure e^* (in hPa) as (WMO, 2008):

$$e^*(T) = 6.112 \exp\left(\frac{17.62T}{T + 243.12}\right) \tag{3.1}$$

where T is temperature (°C). Vapor pressure e is then calculated as:

$$e = e^*(T)rh/100 \tag{3.2}$$

where rh is relative humidity in % and e is in hPa.

Figure 3.20 presents the time series of the monthly mean vapor pressure differences Δe for DB260 and Test2 with respect to the reference site Test4. Vapor pressure could not be calculated for the Test1 and Test3 site because relative humidity was not measured there. Also, due to malfunctioning of the (non-operational) sensors, results cannot be given for the July-December period in 2004 and for the June-July period in 2005.

Figure 3.20 shows that the vapor pressures at the DB260 and Test2 are similar. This could be expected because they are situated in the same field. In the summer half year DB260 and Test2 are somewhat dryer than Test4 which may be due to the differences in groundwater levels between the two sites. The relative dryness of the DB260 and Test2 sites was also visually observed in the dry summer of 2003, when the grass at the Test4 site remained greener than the grass at the operational measuring field. The vapor pressure differences in the summer half year may contribute to the observed temperature differences.

3.8 Comparison of DB260 with neighboring stations

The results in this chapter suggest that the temperature measurements at the operational site DB260 have been affected by (a) the gradual growth of the bushes in the wasteland area since about the year 1999, and (2) the renovation of the wasteland area in September/October 2004. Consequently, the temperature differences between DB260 and Test1 are not representative of the temperature differences of the situation till 1951, before the relocation to the DB260 site. In addition, the Test1 site is probably also not representative of the conditions around 1951. For instance, the wind direction dependent temperature differences show that the Test1 temperatures are probably affected by the new KNMI building.

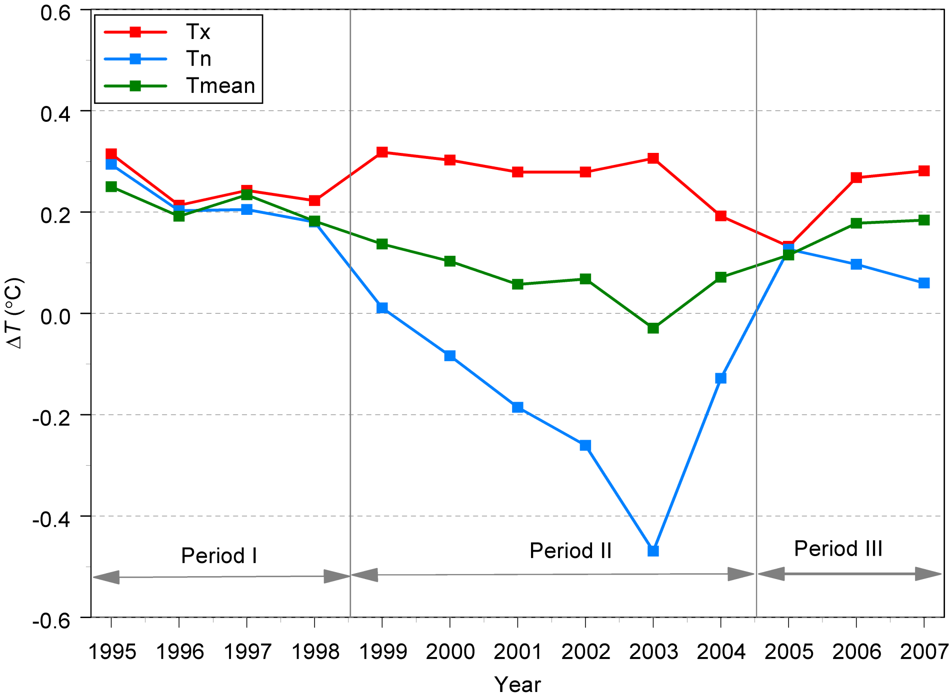

Figure 3.21: Annual mean temperature differences ΔT for T_x, T_n and T_{mean} between DB260 and the mean of the four neighboring stations: Schiphol, Deelen, Cabauw and Herwijnen in the 1995-2007 period. Period I represents the undisturbed situation in De Bilt, period II represents the period with the growth of the bushes in the wasteland area, and period III represents the new situation after the renovation of the wasteland area.

Comparison of the operational temperatures of DB260 with those of neighboring stations may give an indication of the magnitude of the effect of the growth the bushes in the wasteland area and the subsequent renovation of the wasteland area. Figure 3.21 shows the comparison of annual mean temperatures of DB260 with the mean of the four neighboring stations: Schiphol (36 km northwest of DB260), Deelen (48 km east), Cabauw (25 km southwest) and Herwijnen (30 km south) in the period 1995–2007. The four four surrounding stations have no known inhomogeneities is this period. The figure shows that from 1999 onwards the changes in land use directly west of DB260 start to affect the operational temperature measurements. There is a strong decrease of the annual mean T_n, a slight increase in the annual mean T_x. The net result is a slight decrease in T_{mean}. After the renovation (period III), the temperature differences seem to resemble those in the undisturbed situation of period I, especially for T_x and T_{mean}.

Table 3.2 compares the annual mean temperature differences in 2003 and 2007 with

Table 3.2: Comparison of the annual mean ΔT values of 2003 and 2007 in Figure 3.21 for T_x, T_n and T_mean with those in the undisturbed situation in 1995–1998 (period I). Values in brackets give the standard error, calculated from the comparisons for the individual stations.

	ΔT (°C) (2003) – (1995–1998)	ΔT (°C) (2007) – (1995–1998)
T_x	0.06* (0.10)	0.03* (0.05)
T_n	$-$0.69(0.06)	$-$0.16* (0.08)
T_mean	$-$0.24(0.06)	$-$0.03* (0.05)

* values differ less than 2 times the standard error from zero

those of the undisturbed situation of period III. The year 2003 is the year with largest deviation from the undisturbed situation and 2007 can be considered as representative for the new situation. The table shows for T_n a relative temperature decrease of 0.69°C compared to the undisturbed situation of period I. The relative increase in T_x is small and not significant. T_mean decreases with 0.24°C. The annual mean temperature differences between DB260 and Test4 around 2003 are of the same order of magnitude as those found here, thought somewhat smaller.

The comparison of the year 2007 in Table 3.2 with the undisturbed situation shows only small (not significant) temperature differences. T_n shows the largest difference with undisturbed situation, a cooling of 0.16°C. This temperature differences may be a result of the land use west of DB260, which is different in period III (nature area with ponds) from that in period I (grass land).

4 Discussion

The first objective of this work was to study the representativeness of the operational site DB260. We demonstrated that the growth of the bushes in the wasteland area, since about the year 1999, directly west of DB260, seriously affected the temperature measurements at that site. The renovation of the wasteland area in September/October 2004 restored to some extent the temperatures of the old situation of before the year 1999. However, the land use west of the DB260 has permanently been changed (no longer grassland as in the period 1951-1999, but landscaped park with ponds). Therefore, operational measurements at DB260 became problematic and KNMI decided to move the operational site to the Test4 site in September 2008. The Test4 site is much more open than the DB260 location and has no ponds in its vicinity and is therefore more representative of the surrounding area than DB260. Comparison with neighboring stations, shows that the temperatures of DB260 after the renovation of the wasteland areas are comparable to those of the undisturbed situation of before 1999.

The results suggest that it was mainly the vertical growth of the bushes in the wasteland area and its effect on low wind speeds that caused the growing temperature differences between DB260 and Test4 and between DB260 and the surrounding stations. The kind of surface, grassland or nature with some ponds, seems a second order effect compared to the sheltering effect of the growing bushes close to the thermometer screen.

The second objective was to explore the possibilities of using present-day parallel measurements to correct for inhomogeneities caused by changes in the surroundings since 1951 and a relocation of the thermometer screen in that year. The results show that it is not realistic to use the present-day parallel measurements for that purpose. First, parallel measurements took place in a disturbed situation. As explained above, the disturbance caused DB260 to be no longer representative. Second, the old location Test1 is probably not representative of the conditions of before 1951. The site is more enclosed by trees than in 1951 and the nearby large new KNMI building probably also affects the temperature measurements as could be seen from the wind direction dependent temperature differences for Test1.

Although not all objectives could be met, the measurements do increase our understanding of the causes of inter-site temperatures differences. They also give a feeling of the order of magnitude of the temperature differences that can be expected when moving a thermometer screen from one location to the other. In general, the results indicate that the magnitude of the inter-site temperature differences strongly depends on wind speed and cloud cover.

Differences in sheltering seem the most important cause of inter-site temperature differences. Compared to open sites, sheltering (a) stimulates the build up of a stable layer near the ground as a result of lower wind speeds, causing lower night-time temperatures at screen height, (b) decreases the outward long-wave radiation due to the small sky-view-factor causing higher night-time temperatures, (c) causes shading of the screen after sunrise and before sunset, resulting in lower temperatures at those times, and (d) increases the radiation error of screens due to decreased natural ventilation, causing higher day-time temperatures. Depending on the degree and nature of the sheltering, the net effect of sheltering on temperatures may be a temperature increase or decrease.

The Test1 site is an example of a strongly sheltered site where the net effect is a temperature increase compared to the open Test4 site. Especially the minimum temperature is affected and is on average 0.5°C higher than that at Test4. Apparently the effect of the small sky-view factor on night-time temperature more than counteracts the effect of the build-up of a strong stable boundary layer. The maximum temperatures are on average only 0.1°C higher than those of Test4, probably as a result of the reduced ventilation of the screen. The temperature decrease due to the shading effect is clearly visible in the diurnal temperature cycle differences in the hours after sunrise and before sunset. The temperature differences are related to the weather condition, they increase with decreasing wind speed and cloudiness. Overcast skies and large wind speeds nullify the temperature differences. The temperature differences between Test1 and Test4 may serve as an example of the differences that may occur when an old and enclosed station (like Test1) is relocated to a more open location (like Test4). This is, however, only valid when both the new and old site are equally affected by urban warming.

The DB260 site (before the renovation of the wasteland area) is an example of a sheltered site where the net effect is a temperature decrease compared to the open Test4 site. The effect of sheltering due to the lines of trees that runs from south of DB260 to north-northeast, seems not of major importance for the temperature measurements at DB260. Apparently the trees are at such a distance from the DB260 screen that they (1) do not significantly restrict the outward long-wave radiation at night, and (2) do not decrease the wind speed to such an extent that it significantly affects the natural ventilation of the screens during the day. In contrast, the growth of the bushes in the wasteland area at a distance of only 12 m west of DB260 had noticeable impact on the temperature measurements, mainly by a decreased wind speed. The decreased wind speed resulted in (a) a stronger stable layer at night, lowering the minimum temperature, and (b) larger radiation errors during the day, increasing the maximum temperature. The effect on minimum temperature was larger than the effect on maximum temperature. On average DB260 was 0.2°C too cold during the period of the experiment and compared to the undisturbed situation of before the year 1999.

The relative dry conditions at the DB260 site compared to the Test4 site, may partly explain the extreme temperature differences in the dry summer of 2003. This is supported by the vapour pressure differences between these two sites. To study this further, it might be interesting to compare the soil moisture conditions and groundwater levels at the two sites in future dry summer conditions.

The results illustrate that the introduction of an inhomogeneity, like the renovation of the wasteland area, causes not only a shift of the location of the pdf of the daily temperature differences but also a change in the shape. This means that for the homogenization of a daily temperature series it is not sufficient to correct only the mean.

We showed that in homogeneity studies (slow) changes in sheltering due to e.g. site changes or growth of nearby trees of bushes are important. It is important to realize that some effects, like the built up and (partly) breaking down of the stable layer, are highly non-linear processes and therefore difficult to model. The fact that these processes are mostly active at low wind speeds (< 1.0 m/s) further complicates the modeling. Regular cup anemometers are not really suited to measure low wind speeds. Operationally, these anemometers have a threshold wind speed of about 0.5 m/s after maintenance and calibration and this threshold wind speed often increases with time whence the anemometer is in the field. In addition, anemometers are mostly situated at a height of 10 m. During night-time stable conditions the correlation between wind speed at 10 m and wind speed at screen height is weak.

This a complicating factor for the homogenization of daily temperature series.

Another complicating factor for homogenization of daily time series is the homogeneity of the time series of the explanatory variables, notably wind speed and cloudiness.

5 Conclusions and recommendations

In the present report we presented the results of a comparison of five sites for measuring air temperature at 1.5 m at the KNMI terrain in De Bilt in the period May 2003-June 2005. Wind speed at screen height was measured at all sites using cup anemometers. To study the temperature differences, the most open site, Test4, was used as the reference site.

The results indicate that changes in surroundings complicate or impede the use of present-day parallel measurements for correcting for sites changes in the past. In a few years time, the growth of bushes close to the thermometer screen may seriously disturb the temperature measurements.

We quantified the possible effects of sheltering on temperature measurements at five sites. It appeared that, especially in summer, these effect on the the monthly mean temperatures may have the same order of magnitude as the long-term temperature trend (about 1.0°C/100yr in De Bilt). However, for most sites the inter-site temperature differences for maximum and minimum temperature have opposite signs. The net effect on the daily mean temperatures is, therefore, small (< 0.1 K). In practice, the largest inhomogeneities in mean temperature series may be anticipated in case of relocations from very enclosed sites (like Test1) to more open sites (the other sites). The renovation of the wasteland area, close to the operational site DB260, had a significant effect on the temperature of DB260. Both the location and shape of the distribution of daily temperatures differences are affected.

The results indicate that the magnitude of the inter-site temperature differences strongly depends on wind speed and cloud cover. In the case of homogenization of daily temperature series, it is important to take this into account. A complication is that for wind speed the largest effects on inter-site night-time temperature differences occur in the range 0.0–1.0 m/s at screen level, thus strongly affecting the minimum temperature. In practice (a) wind speed is mostly not measured at screen level but at heights of 10–20 m (during stable nights, wind speeds at these heights are largely uncoupled from those at screen height), and (b) the measurement uncertainty for small wind speeds is large and often increases with the time during which the anemometer is in the field. The first problem may be solved by installing additional anemometers at screen height at locations important for climate monitoring. The second problem may largely be met by the introduction of sonic anemometers.

Another complication for the modeling of daily temperature series, is the homogeneity of the time series of the explanatory variables wind speed and cloudiness. More research is needed in this area.

Improvement of our understanding of inter-site temperature differences may enable the modeling of them. In the case of De Bilt there are certain aspects that are likely important and should be studied further. First, the non-uniformity of the KNMI-terrain may affect downstream sites by daytime advection and may cause temperature differences to be dependent on wind direction. It is recommended to study this further by measuring the sensible and latent heat fluxes at several locations at the same time. Second, during night-time conditions, there are two main mechanisms that affect temperature differences between sites: (a) local stability differences, and (b) differences in sky-view-factor. Both mechanisms have an opposite effect on night-time temperature differences between sites and the net result may be a cooling (like the DB260 site before the renovation) or a warming (like the Test1 site). The interaction of those two mechanisms is not fully understood and needs to be investigated further to enable the modeling of them. Finally, local differences in soil type and groundwater levels between the sites may affect (apart from advection) the energy balance and may cause differences in observed temperatures. This may be investigated further by flux measurements and measurements of the groundwater levels.

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A Experimental details and calibration

A.1 Sites and data collection details

Table A.1 presents details about the so-called field codes for each instrument as used internally at KNMI. Table A.2 gives information about the instrument numbers and the replacements dates. Anemometers were replaced when the 6-monthly calibration in the KNMI wind tunnel indicated that the threshold speed became > 0.3 m/s. The table shows that this was often the case.

Tables A3 - A5 give information on the variables that were stored by the author in the database for the parallel experiments. The data were obtained from the so-called KMDS data storage system that acts as a temporary database at KNMI. Each day a file with all the data of the previous 24-hour period was automatically sent to the author by e-mail.

The 1′ TAm data are stored to obtain an estimate of the 10′ average TAa with two decimals. The variable ffs is already in two decimals but it is not always exactly a 10′ average, therefore we also calculated 10′ average values from the 1′ WSm values.

A.2 Instrument calibration

For this field experiment, the PT-500 sensors and the anemometers were calibrated about every 6 months. In the operational practice of KNMI, calibration values are only used to decide whether or not to reject a sensor or instrument. PT-500 sensors were replaced when the(rounded) deviation from the calibration standard was $>$ 0.1°C. Anemometers were replaced when the threshold speed was > 0.3 m/s. For a better adjustment, we used the calibration curves of the PT-500 sensors and calibration values of the anemometers to correct the observed values afterwards. A typical uncertainty of 0.05°C is acquired. This minimizes the instrumental errors in the mutual comparisons of the 5 sites. Comparisons of the calibration curves of successive calibrations within the calibration interval of 36 shows that the decay of the PT-500 sensors is negligible.

Temperature sensors

Figure A.1 shows the calibration curves of the PT-500 sensors. We determined the linear least-squares fits through the values determined in the calibration lab of KNMI. Subsequently, these fits were used to obtain corrections for each sensor for

Table A.1: Descriptions and field codes of the instruments at the 5 sites in Figure 1.1.

Site (re port code)	**Description**	**Instrument**	**Field code-sensor code**
DB260	Site of operational temperature measurements	Thermometer Anemometer	1-S2 1-S5
Test1	Site of historical temperature measurements (sep 1950-aug 1951)	Thermometer Anemometer	11-S1 11-S2
Test2	Site of backup measurements (30 m from DB at 118°)	Thermometer Anemometer	5-S2 5-S5
Test3	Site (50 m from DB at 118°)	Thermometer Anemometer	9-S3 9-S4
Test4	Site 20 m west of the 20 m mast	Thermometer Anemometer	10-S2 10-S3

Table A.2: Sensor numbers and replacement dates.

Site	Instrument	Field code-sensor code	Sensor no.
DB260	Thermometer Anemometer	1-S2 1-S5	01.02.203.005 01.00.029.054 (replaced 12/01/2005) 01.00.029.012
Test1	Thermometer Anemometer	11-S1 11-S2	01.02.203.113 01.00.029.025 (replaced 23/01/04) 01.00.029.088 (replaced 17/03/05) 01.00.029.001
Test2	Thermometer Anemometer	5-S2 5-S5	01.02.203.078 01.00.029.080 (replaced 23/01/04) 01.00.029.112 (replaced 13/07/04) 01.00.029.033
Test3	Thermometer Anemometer	9-S3 9-S4	01.02.203.052 01.00.029.074 (replaced 13/07/04) 01.00.029.083
Test4	Thermometer Anemometer	10-S2 10-S3	01.02.203.155 01.00.029.066 (replaced 13/07/04) 01.00.029.026

Table A.3: Description of the variables (Var) at the 5 sites at the KNMI-terrain stored in the database of the parallel experiment.

Resolution	Var	Data Type	Variable Description
1 min	TAm	Temperature	Ambient temperature 1′ average
1 min	TAa*	Temperature	Ambient temperature 10′ average
1 min	WSm	Windspeed	Wind speed 1′ average
10 min	ffs	Windspeed	Wind speed sensor 10′ characteristic average
10 min	rh	Humidity	Relative humidity 1.5 m 1′ average

*Running 10-minute average sampled once per minute

Table A.4: Positions of the variables in Table A.3 in the KMDS storage system.

Site	Tam,TAa	WSm	ffs	rh,rhb
De Bilt 260	A260a/1Min	A261g/1Min	A261g/10Min	A260a/10Min
Test1	A261f/1Min	A261f/1Min	A261f/10Min	–
Test2	A261a/1Min	A261c/1Min	A261c/10Min	A261a/10Min
Test3	A261d/1Min	A261d/1Min	A261d/10Min	–
Test4	A261e/1Min	A261e/1Min	A261e/10Min	A261e/10Min

Table A.5: Additional operational 10-minute observations at the KNMI-terrain (A260a) stored in the database of the parallel experiment dataset.

Var	Data Type	Variable Description
dd	WindDirection	Wind direction 10′ vector characteristic average
ffs	WindSpeed	Wind speed sensor 10′ characteristic average
nc	CloudAmount	Total cloud cover ceilometer in last 30′
pp	Pressure	Air pressure at MSL 10′ average
pr	Time	Precipitation duration in last 10′ (Pres.Wea.Sensor)
qd	Radiation	Direct radiation 10′ average
qf	Radiation	Diffuse radiation 10′ average
qg	Radiation	Global radiation 10′ average
rg	PrecipitationIntensity	Precipitation intensity 10′ average (Rain gauge R)
tgn	Temperature	Grass minimum temperature at 10 cm in last 10′
vv*	Visibility	Horizontal visibility 10′ average
zm	Visibility	Meteorological optical range 10′ average

* vv observations were terminated on 28 November 2003

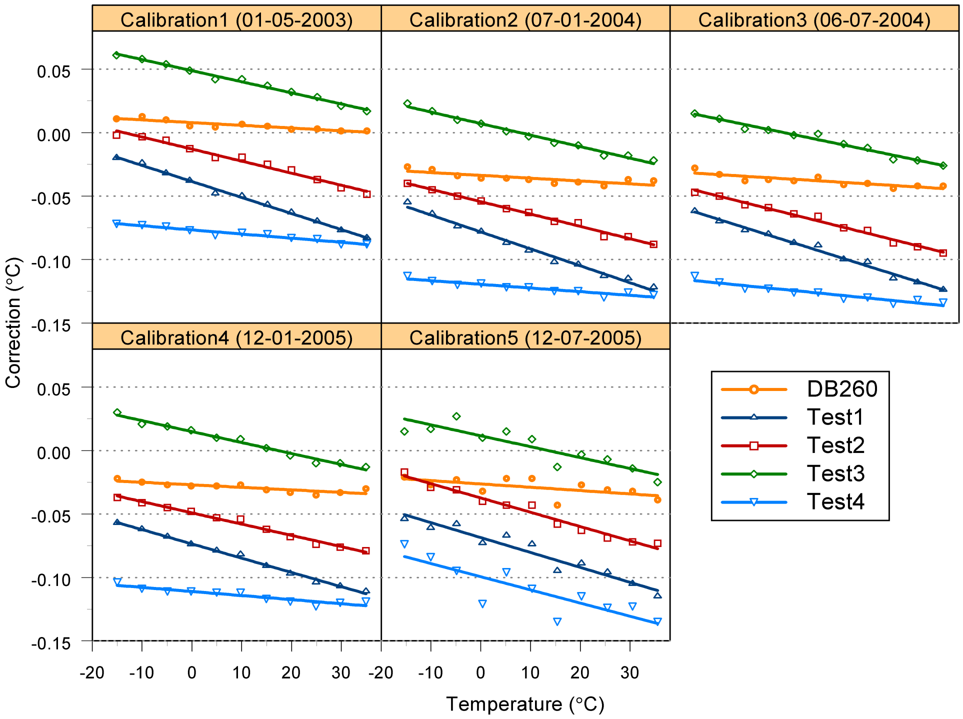

Figure A.1: Calibration curves of the PT-500 temperature sensors for the operational site DB260 and the 4 parallel sites, giving for each sensor the temperature correction as a function of temperature. Each panel represents a calibration: one at the beginning and end of the experiment and at three intermediate times. The symbols give the values as determined in the KNMI calibration lab, the lines present linear least-squares fits.

temperature. For instance, the calibration values of Calibration1 were used to correct the temperature values for the period of 1 May 2003 - 7 January 2004.

The real temperature is obtained as:

$$T = T_{\text{sensor}} + \text{correction} \tag{A.1}$$

where correction is obtained from the linear least-squares lines in Figure A.1.

For the first calibration, Calibration1, the sensors of Test1, Test3 and Test4 were calibrated at the indicated time but those of DB260 and Test2 were calibrated earlier. DB260 on 2 December 2002 and Test2 on 4 April 2002. Because the shapes and the mutual locations of the calibration curves hardly change from one calibration to the other (PT-500 senors are known as stable sensors), we were able to estimate the calibration curves of DB260 and Test2 at the beginning of the experiment 1 May 2003 (a vertical translation of -0.04°C for each of the two sensors was applied). On 3 June 2005 the sensor of Test2 was accidentally replaced by another sensor. The panel for Calibration5 in Figure A.1 shows only the calibration curve of the old sensor. However, the calibration curve of the new sensor has been used for correcting the temperature values of Test2 for the period 3-30 June 2005.

Figure A.1 shows that the slope of the curves and their mutual positions are about the same in all calibrations. There is a vertical translation of all curves from calibration to calibration. This is probably caused by changes in the liquid bath used in calibration lab. Note that in Calibration5 the calibration values of most sensors deviate from their linear approximations. An explanation for this is not known.

Anemometers

At the start of the experiment there were no wind speed measurements at 1.5 m height at the KNMI-terrain, therefore 5 newly calibrated anemometers were placed. Before placement in the field all anemometers are calibrated in the wind tunnel of KNMI. An important calibration value is the detection limit of threshold speed. At the moment the anemometer is placed in the field, this value should be < 0.5 m/s. This is the standard practice at KNMI. Because small wind speeds are important in the present experiment, we lowered the value to 0.3 m/s. When recalibration shows larger values, the anemometer is replaced. Table A.2 already showed that this was often the case.

For each anemometer also a calibration factor C and correction are determined from the wind tunnel test. These values were used here to obtain improved wind speed values. Operationally, wind speed W_s is determined as:

$$W_{s,\mathrm{operational}} = C_{\mathrm{operational}} f \tag{A.2}$$

where f is the frequency of the anemometer and the calibration factor $C_{operational}$ = 0.061875 m for all anemometers. The corrected wind speed in this study is determined as

$$W_s = Cf + \mathrm{offset} \tag{A.3}$$

where C and correction are obtained from the wind tunnel calibration for each anemometer separately and f is calculated from Equation A.2 using the observed W_s, $\mathrm{operational}$ and $C_{\mathrm{operational}}$ = 0.061875 m. Combination of Equation A.2 and A.3 gives:

$$W_s = \frac{C}{C_{\mathrm{operational}}} W_{s,\mathrm{operational}} + \mathrm{offset} \tag{A.4}$$

Typical values of the offset are in the range +0.10 to +0.15 m/s and $C/C_{\mathrm{operational}}$ varies between 0.99 and 1.01.

B Effect of tent placement

In May 2004 KNMI celebrated its 150 years anniversary. As part of the festivities large tents were placed in the blue area in Figure B.1 during the period 6–17 May. It was anticipated that the tents would affect the operational measurements at the operational DB260 site. Therefore, the temperature and humidity measurements of the Test4 site were temporarily used as operational measurements and archived in the climate database system. This was done in the period 29 April 2004 7:40 UTC until 19 May 2004 6:30 UTC. In this appendix we study the effect of the tents on the operational temperature measurements. We will focus on the differences between DB260 and Test4.

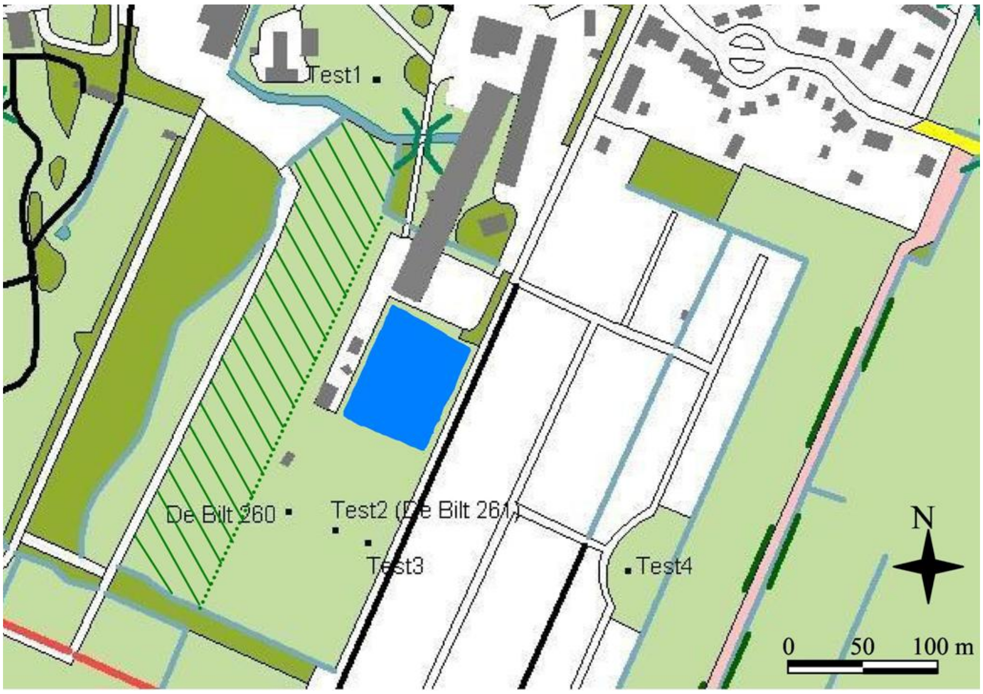

Figure B.1: Location of the tents (blue area) during the feast week in May 2004.

Table B.1 shows ΔT for the combined days in May 2003 and 2004 with and without the presence of the tents (2005 is not representative because of the renovation). There are only small differences between the ΔT values with and without tents. A two-sample t-Test shows no significant differences between the situation with and without the tents[4]..

A further look at the weather conditions reveals that the mean wind speed (at 20 m) was 2.5 m/s during the period of the presence of the tents and 2.8 m/s in the remainder of the 2003/4 May days. The mean cloudiness was 5.4 octa when there were tents and 4.8 octa when there were no tents. These are only small differences. There was, however, a significant difference in wind direction. During the presence of the tents, the wind direction was in the northwesterly quadrant for 83% days while without the presence of the tents this was only 26%. Comparison of ΔT, restricted to

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[4] The average autocorrelation of the daily ΔT values in the May months of 2003–2005 is not larger than 0.3 for all variables, which may be considered small enough to apply the t-Test

Table B.1: Means of the daily temperature differences ΔT (°C) between DB260 and Test4 for for days in May 2003 and 2004 with the presence of the tents (12 days) and without (50 days).

	tents	**no tents**
ΔT_{x}	0.087 (−0.006,0.180)	0.219 (0.150,0.287)
ΔT_{n}	−0.540 (−0.814, −0.266)	−0.502 (−0.598,−0.406)
ΔT_{mean}	−0.264 (−0.383,−0.146)	−0.180 (−0.218,−0.142)

values between brackets give the 95% confidence interval of the values above

days with wind direction in the northwesterly quadrant, shows no significant differences between the situation with and without tents.

In conclusion, there is no evidence that the presence of the tents affected the operational temperature measurements at DB260.