Parallel air temperature measurements at the KNMI-terrain in De Bilt (the Netherlands) May 2003 – April 2005

Interim report

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Foreword

From May 2003 through April 2005 a field experiment is being carried out at the terrain of KNMI in De Bilt. The objectives of the experiments are to study the representativeness of the current operational air temperature measurements site and 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 locations, including the operational location, temperature and wind speed are measured at a height of 1.5 m every minute, using identical instruments. The temperature differences between the sites are studied in connection with wind speed differences and operationally measured weather variables. The experiment is part of the KNMI-program 'Hisklim' (HIStorical CLIMate). The measurements can be followed real time at the KNMI-intranet site http://info.knmi.nl/ks/hisklim/Parallelmetingen/.

The present interim report presents the results of the first phase of the experiment (May 2003–April 2004). The report is meant to serve as a basis for deciding upon the optimal future location of the current operational temperature site. A Final report will be published at the end of the experiment.

Summary

Air temperature measurements at the KNMI-terrain in De Bilt are important mainly because De Bilt has a long and relatively homogeneous record and because its observations often serve as an indicator of changes in weather and climate for the Netherlands as a whole. Among others, relocations of the temperature measurements site and (gradual) changes in terrain may have influenced the measurements. To further improve the homogeneity of the long-term temperature record and to study the representativeness of the current measurements, a parallel experiment is being carried out at the terrain of KNMI in De Bilt from May 2003 through April 2005. The results of the first year of measurements (May 2003 – April 2004) are presented in this interim report.

Five locations at the KNMI-terrain, including the current operational location WMO 06 260 (further denoted as DB260), are equipped with identical (operational) instruments for measuring temperature and wind speed at a height of 1.5 m. The instruments are calibrated each half-year and the calibrations curves are used for correcting the data to minimize instrumental errors. With the measurements at DB260 as a reference, the temperature differences between the sites are studied in connection with the wind speed differences and the operationally measured weather variables at the KNMI-terrain.

The results show that a large tree barrier in the vicinity of the DB260 has a significant effect on the operationally observed temperatures. Compared to more open locations at the KNMI terrain, DB260 shows higher maximum temperatures and lower minimum temperatures. In the summer half year the daily maximum temperatures are on average 0.28°C higher than those for the most open site and the daily minimum temperatures are on average 0.48°C lower. Individual daily differences may, however, be much larger. Consequently, the representativeness of the measurements for the surrounding area of the KNMI-terrain may be seriously questioned. For operational temperature observations, it is therefore recommended to consider a move of the observations from DB260 to the most open location in the experiment, indicated as Test4. However, for climatological purposes a continuous record without artificial breaks is important. Therefore, the temperature observations at DB260 should be continued until a satisfactory transfer function is developed that can be used to reduce the temperature observations at Test4 to DB260.

The comparison also includes observations from a former historical site. In 1951 the temperature observations site was moved to the more open DB260 site. Together with a change in screen type, this resulted in a drop in summer maximum temperatures. The results for the historical site suggest, however, that the site is strongly affected by the growth of tall trees and placement of buildings since 1951. Compared to DB260 the difference in the mean of the daily maximum temperature does not differ significantly from 0°C while the difference in the mean daily minimum temperatures in the summer half year is 1.20°C. It is obvious that this result cannot explain the observed jump in the summer maximum temperatures around 1951.

Nevertheless, the results for this historical site are valuable for improving our understanding of observed temperature differences.

It is well known that wind speed influences the magnitude of the errors made in air temperature measurements, especially for daytime radiation errors. The results here stress the importance of high-accuracy wind speed measurements near the thermometer screen at screen height during both day and night. These wind measurements are an important measure for determining: differences in radiation errors between sites, local differences in atmospheric stability (resulting in differences in vertical temperature profiles near screens), and, eventually, for corrections. Consequently, this type of wind measurements may be important for objectively monitoring the homogeneity of temperature sites, and for developing improved weather dependent transfer functions in case of future inhomogeneities. Positioning of high-accuracy wind speed measurements (in particular at low wind speeds < 3.0 m/s) near the thermometer screen at screen height, in addition to the current operational wind measurements, is therefore strongly recommended. This refers especially to stations of climatological interest.

1 Introduction

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

1.1 Problem description

Temperature measurements techniques are often an object of debate. Questions arise whether the measurements are representative for the area that the stations are supposed to represent, 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. For instance, 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. Assessment of the representativeness and the homogeneity of the temperature series are thus important.

Concerning thermometer exposure and siting WMO (1996) 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 sunshine 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 particular exposure problems in De Bilt are illustrated in Figure1. The figure shows the location of the operational thermometer screen WMO 06 260 (DB260 in the figure and the remainder of the text) at the instruments field of KNMI. 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 meter. Because the thermometer

[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 & Pollak, 1962).

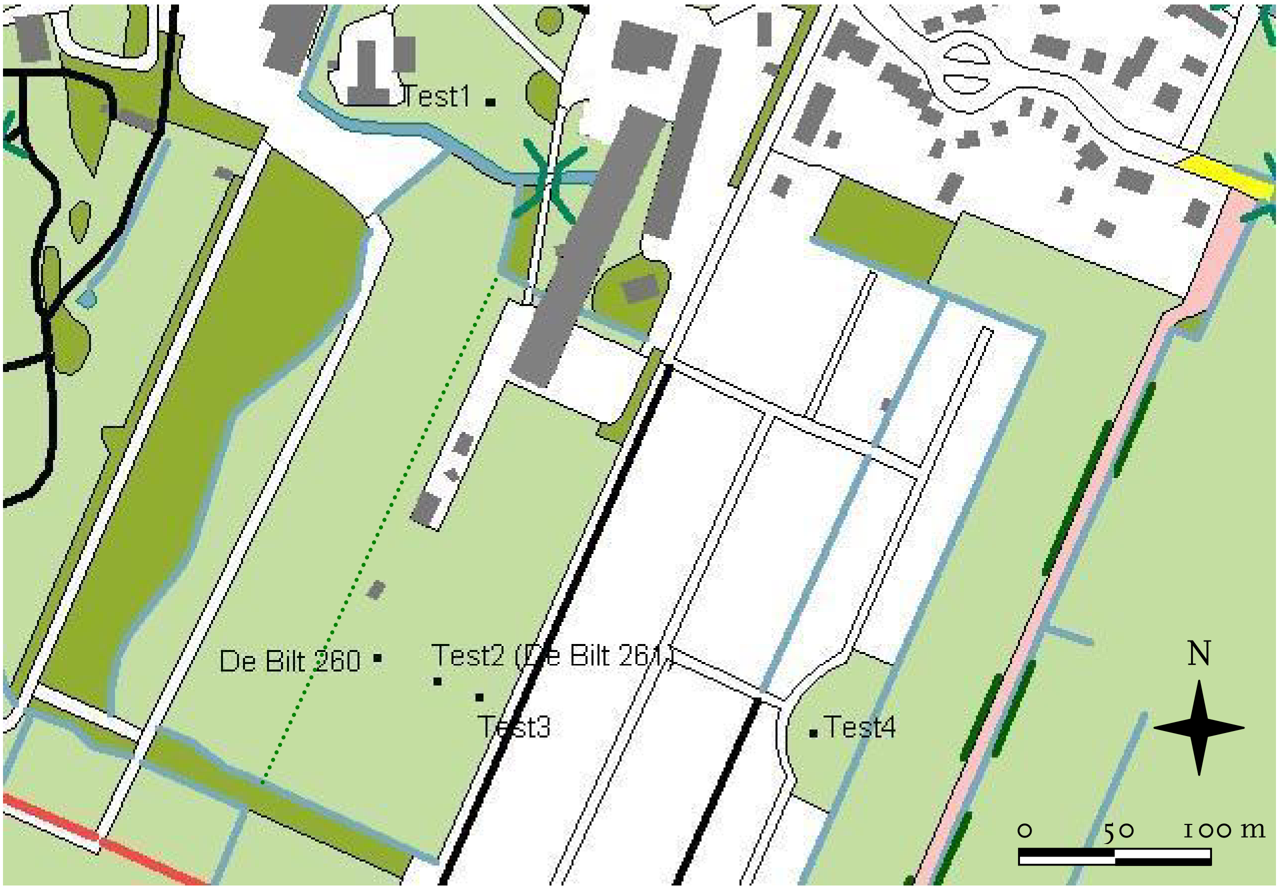


Figure 1: Location of the operational site (DB260) and the 4 parallel sites (Test1-Test4) at the KNMI terrain in De Bilt. Light green is grass cover and dark green trees. The white area that runs from mid bottom to top right consists mainly of vegetable gardens. The KNMI buildings are in gray (left from the vegetable gardens).

screen at DB260 is amply within the range of 8-12 times the obstacle height, local effects may affect the temperature measurements. The predominant southwesterly flow further attributes to this problem. In addition, the past 3 years the area west of the dashed green line has been transformed into nature. During the period May 2003–April 2004 the bushes in the nature area reached heights up to 2 to 3 m at a distance of only 12 m from DB260, thus creating an extra shelter effect.

The second problem deals with long-term homogeneity. At 27 August 1951 the operational thermometer screen was moved from location Test1 to the current 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. The change in screen type was accompanied by parallel measurements. We digitized and analyzed these data and found that the screen transition partly explains the downward dump in summer 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 2 shows e.g. the situation in 1960. The height of the line of trees varied at that time between 5 and 25 m, indicating a gradual growth of the trees between that time and present.

1.2 Scope and objectives of the report

The experimental parallel measurements at the KNMI-terrain address the above-mentioned problems. This interim report presents the results of the

Figure 2: Plan of the KNMI terrain in 1960 indicating the tree height around the observations field. For comparison purposes the locations DB260, Test1 and Test4 are depicted on the map.

first year of the experiment (May 2003–April 2004). 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) within the KNMI-program Hisklim[2] (Brandsma *et al.*, 2000).

The report is meant to serve as a basis for deciding upon the future of the current operational temperature site. Furthermore, it should demonstrate the usefulness of the measurements for homogenizing the temperature series of De Bilt. The emphasis is on the temperature differences between 5 different locations at the KNMI-terrain. The subject of attribution of the observed temperature differences will also be dealt with. An exhaustive study of attribution is, however, beyond the scope of the present report, but will be dealt with more thoroughly in the Final report. The study only deals with local effects on the scale of the KNMI-terrain. 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 locations and Chapters 4 and 5 present a discussion and conclusions and recommendations.

[2] Hisklim stands for 'Historical Climate'. The Hisklim program aims at making historical land and sea data from Dutch sources physically accessible, with the highest possible time resolution and quality. The program started in 2000 and will run 5 to 10 years.

2 Data and methods

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

2.1 Station description and instrumentation

2.1.1 *Stations description*

The meteorological station at KNMI in De Bilt is situated at 52°06′N and 05°11′E. The KNMI-terrain 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 terrain 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 shows the position of the current operational site DB260 and the four selected experimental parallel locations indicated by TestN (N = 1,...,4). Test1 is located at the historical operational site; Test2 (the current back-up 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 vegetable gardens and the KNMI terrain (see Figure 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 vegetable gardens.

Figure 3 shows the obstacle altitude for each site. The figure clearly shows that Test1 is the most enclosed location and Test4 the most open location. This is also reflected in the annual cycle of the percentage of shade hours in Figure 4. 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 5 give an impression of the type of obstacles for each location.

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 location. In that same year, on 11 September 2003 the pasture west of the Test4 location was ploughed by the owner and

Figure 3: Obstacle altitude as a function of wind direction at the operational site DB260 and the 4 parallel locations.

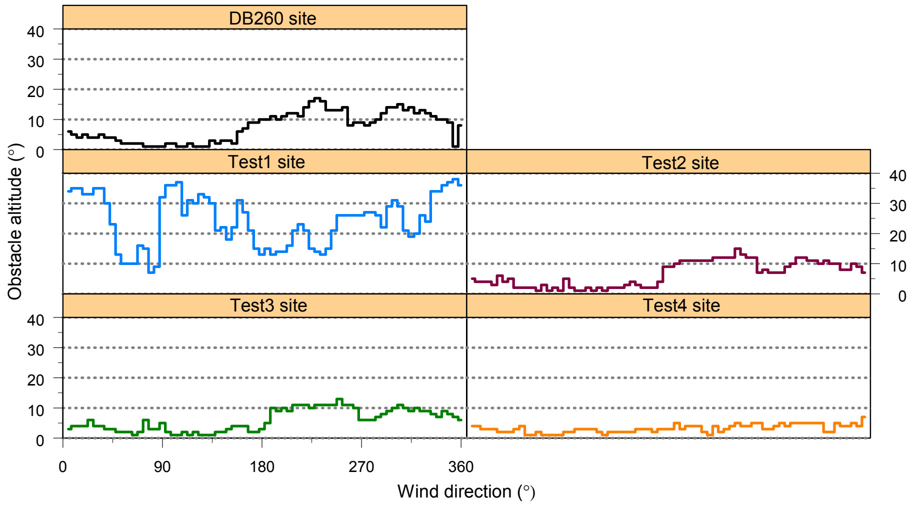
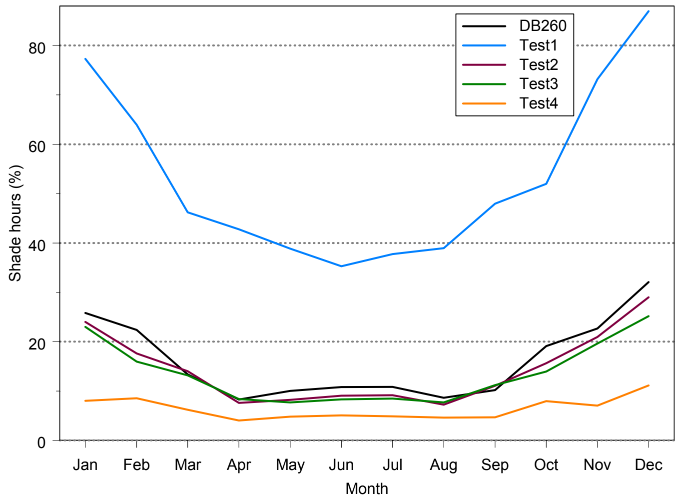


Figure 4: Annual cycle of the percentage of shade hours at the operational site DB260 and the 4 parallel locations.



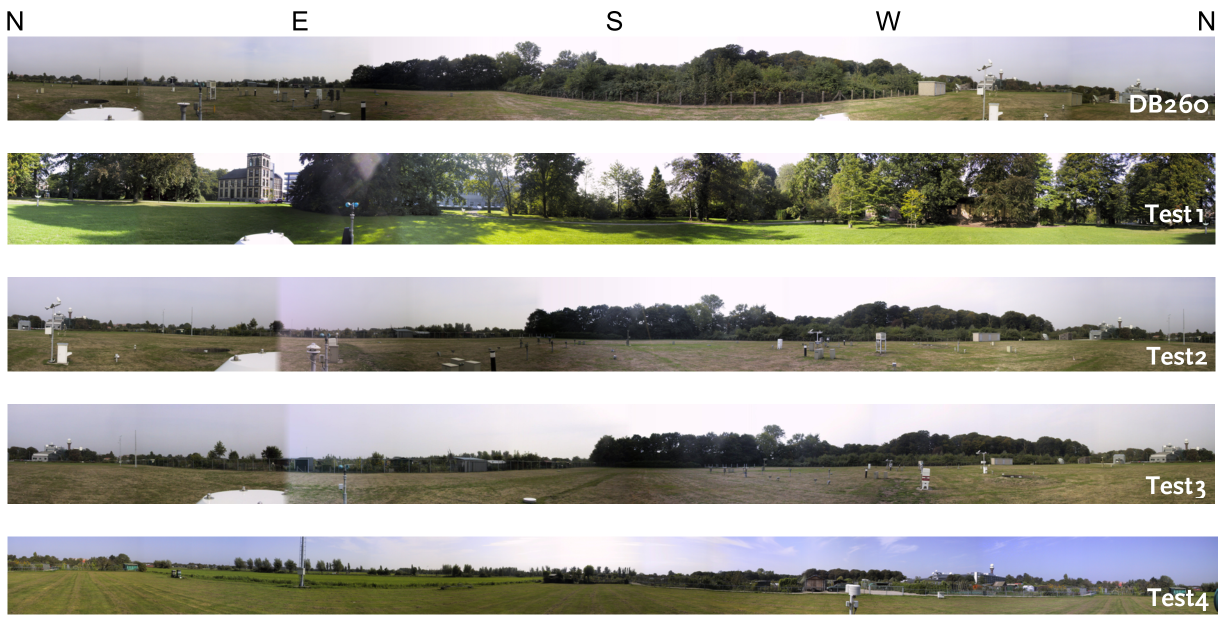


Figure 5: Panorama photos at the operational site DB260 and the 4 parallel locations.

re-sown with grass. We have no indication that this affected the measurements.

2.1.2 *Instrumentation*

All 5 locations are equipped with identical instruments and sensors. Figure 6 shows the instruments at DB260. Air temperature is 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) using PT500 temperature sensors. The standard measurement uncertainty (uncertainty always refer 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 higher 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. For more details on the calibration see Appendix A. Figure 6 shows two radiation shields on the pole, directed west-east. For DB260, Test2 and Test4, the westerly radiation shield contains a humidity sensor, for Test1 and Test3 the corresponding shield is empty. Humidity measurements are not used in the present report.

Wind speed is measured at each site with anemometers on top of a pole (see Figure 1) at the same height as the air temperature measurements (1.5 m). The anemometers are situated at a distance of 4 m northeast of the thermometerscreens. 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.

Besides the experimental temperature and wind speed measurements also the following operational 10-minute measurements at the KNMI terrain are stored and used: wind direction, actual total cloud cover and total cloud cover in the last 30 minutes (both with ceilometer), 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 Handboek Waarnemingen (KNMI, 2000).

Figure 6: Instruments at the operational site DB260. To the left the KNMI multi-plate radiation shield for measuring temperature and to the right the cup anemometer. Both instruments operate at 1.5 m above ground level. The 4 parallel locations are equipped with the same instruments.

2.2 Methodology

The differences between the 5 locations are studied by comparing the air temperature differences T(TestN – DB260), where N = 1,...,4. DB260 thus acts as a reference. The main causes of observed temperature differences are hypothesized to be:

1. advection of warm/cold air
2. local stability differences
3. screen ventilation differences (radiation error)
4. sky-view factor/horizon differences
5. radiation by surrounding objects
6. local soil type/groundwater level differences
7. instrumental errors.

Advection of warm or cold air may be important because of the non-uniformity of the KNMI-terrain. For instance, the vegetable gardens may have energy balances different from those of the surrounding grassland, resulting in different Bowen ratios (sensible heat flux/latent heat flux). Local stability differences are probably most important during nighttime stable conditions (clear sky, small wind speeds) when inversions develop, causing low temperatures near the ground. Differences in wind speed between the locations may then cause different strengths of the inversion, resulting in higher temperatures at the location with the larger wind speed. Screen ventilation differences are especially important during the day when radiation errors increase with decreasing wind speed. Small sky-view factors restrict radiation. Mainly at the Test1 location this may be important. Also a restricted horizon is most important at this location (see Figure 4). Local differences in soil type and groundwater levels between the locations 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 results 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 climatological temperature differences between the 5 locations from May 2003 – April 2004. The differences are discussed in connection with wind direction and with speed differences, because these are strongly related to most of the aforementioned causes of temperature differences.

3 Results

In the Chapter, we first present the temperature and wind speed differences between the five sites. In Section 3.2 we attempt to increase our understanding of the observed differences by studying the differences as a function of wind direction. In Section 3.3 we study the role of atmospheric stability and its relation to local wind speed. We are not studying individual days but rather integrate the results across months or seasons.

3.1 Temperature and wind speed differences

Maximum, minimum and mean temperature differences

Figure 7 presents the differences between the mean monthly daily maximum T_{max} and minimum T_{min} temperatures between the TestN sites and DB260. T_{max} and T_{min} were calculated for each day as the maximum and minimum of the 144 10-minute average temperatures[3], respectively. The results for T_{max} in Figure 7 (a) show that the current operational site DDB260 is relatively warm during the day compared to all the other sites, especially in summer. The most open location, Test4, shows the largest reduction in the mean T_{max} of up to 0.43°C in July 2003. The results for T_{min} in Figure 7 (b) again show a distinct behavior of DB260, but now its nighttime coolness stands out. In contrast, Test1 is exceptionally warm during the nights compared to all other locations. This location is the most insulated one and nighttime cooling there is probably strongly reduced by the small sky-view factor and by radiation from the surrounding objects.

Compared to the monthly mean differences of T_{max} and T_{min} in Figure 7, the daily differences of T_{max} and T_{min} show much larger variation (not shown). For T_{max} these differences range between −1.18°C for Test4 (on 22 July 2003) and 0.81°C for Test1 (3 August 2003). The standard deviation of the daily differences (365 values) ranges between 0.13°C (Test2) and 0.28°C (Test1). For T_{min} the daily differences range between −0.69°C for Test3 (on 10 June 2003) and 2.58°C for Test1 (20 June 2003). Here the standard deviation of the daily differences ranges between 0.15°C (Test2)

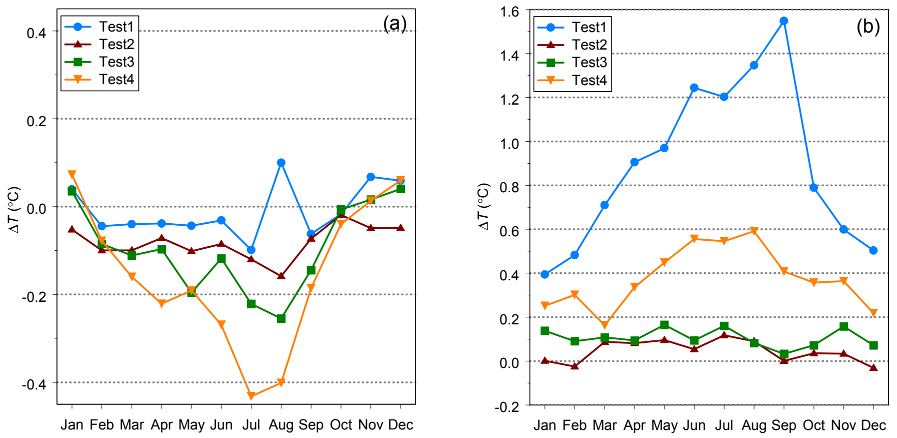
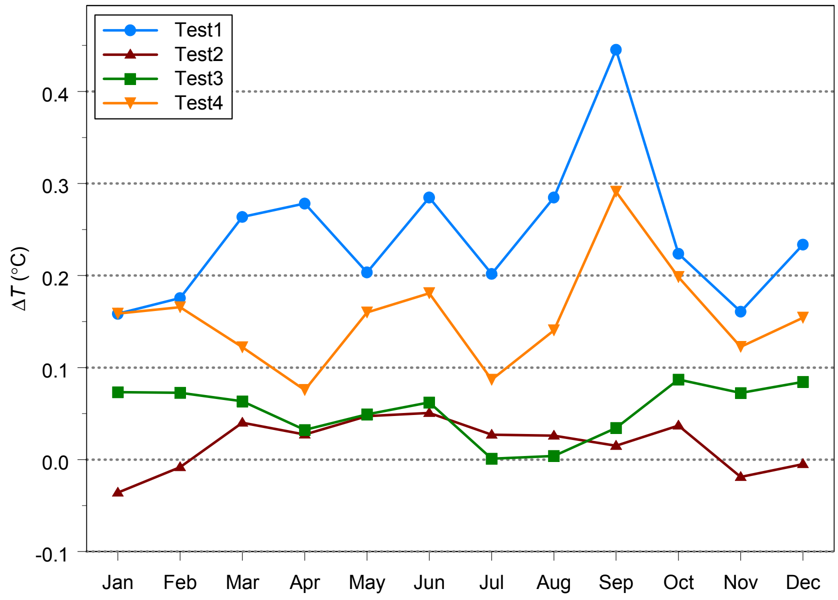


Figure 7: Mean monthly temperature difference ΔT between TestN and DB260 for (a) the daily maximum temperature, and (b) the daily minimum temperature. Measurements refer to the May 2003–April 2004 period. Note the different vertical scales

[3] Operationally T_{max} and T_{min} are determined from 1-minute averages; the 10-minute averages used here produce a less noisy estimate.

Figure 8: Mean monthly temperature difference ΔT between TestN and DB260 for the daily mean temperature. Measurements refer to the May 2003–April 2004 period.



and 0.67°C (Test1). T_{min} is thus more sensitive to location changes than T_{max}.

Figure 8 presents the differences between the monthly mean temperatures T_{mean} of the Test sites and DB260. The figure shows that Test1 is clearly the warmest site, which can mainly be attributed to its relative nighttime warmth. Test4 is on average 0.15°C warmer than DB260. Here the relatively high nighttime temperatures, compared to DB260, dominate the relatively low daytime temperatures.

Table 1 summarizes the temperature differences for the winter half year, the summer half year and the whole year. Like Figures 7 and 8, the table shows that the Test1 site is distinct from all the other sites. Its annual T_{mean} is 0.24°C higher than that of DB260, which is mainly the result of the relatively high nighttime temperatures. The relatively high T_{min} at Test1 (0.89°C annually) combined with a slightly lower T_{max} (−0.01°C) would suggest a much larger increase in annual T_{mean}. Below we will show that relatively low temperatures during sunrise and sunset temper the increase.

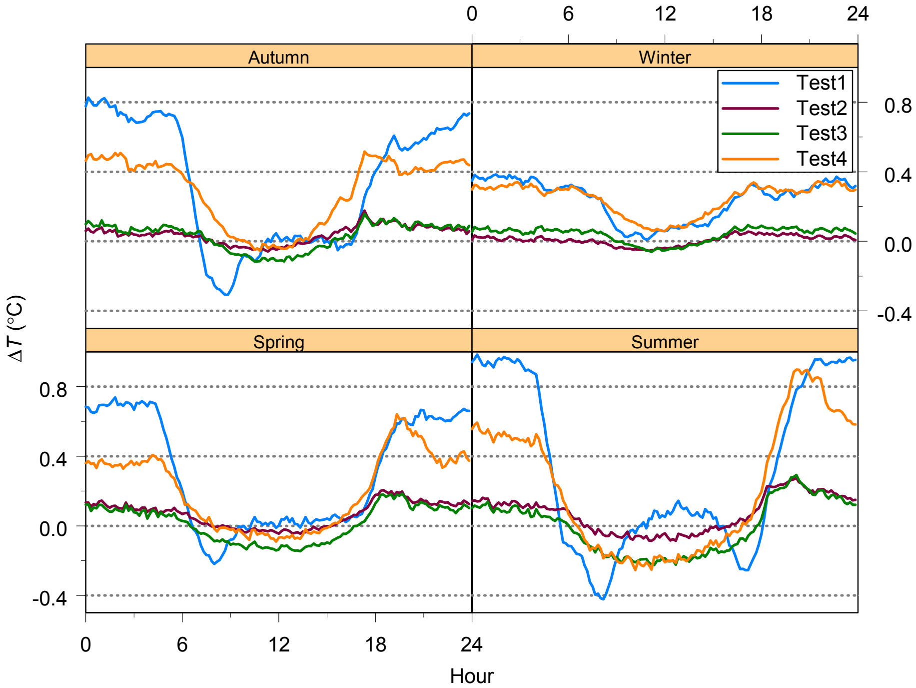
Table 1: Mean differences between the TestN sites and DB260 for the daily maximum (T_{max}), minimum (T_{min}), and mean temperatures (T_{mean}) in the winter half year (win), summer half year (sum) and the year. Underlined values differ less than 2 times the standard error from zero.

	ΔT_{max} (°C)			ΔT_{min} (°C)			ΔT_{mean} (°C)		
	win	sum	year	win	sum	year	win	sum	Year
Test1	0.011	-0.029	-0.009	0.581	1.202	0.892	0.203	0.282	0.243
Test2	-0.061	-0.102	-0.082	0.017	0.074	0.046	0.002	0.032	0.017
Test3	-0.017	-0.173	-0.095	0.106	0.105	0.106	0.076	0.030	0.053
Test4	-0.022	-0.284	-0.153	0.275	0.481	0.378	0.153	0.155	0.154

Diurnal temperature cycle differences

Figure 9 presents the mean diurnal temperature cycle differences between TestN and DB260 for each of the four seasons. Note the behavior of Test1, especially in the summer, 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. Note also the correspondence between Test1 and Test4. This is interesting because Test1 is the most enclosed site and Test4 is the most open site. As suggested in Section 2.2, different mechanisms may be responsible for the observed temperature differences at the sites.

Figure 9: Mean diurnal temperature cycle differences between TestN and DB260 for spring, summer, autumn and winter (figure is read from left to right and from bottom to top). Measurements refer to the May 2003–April 2004 period.



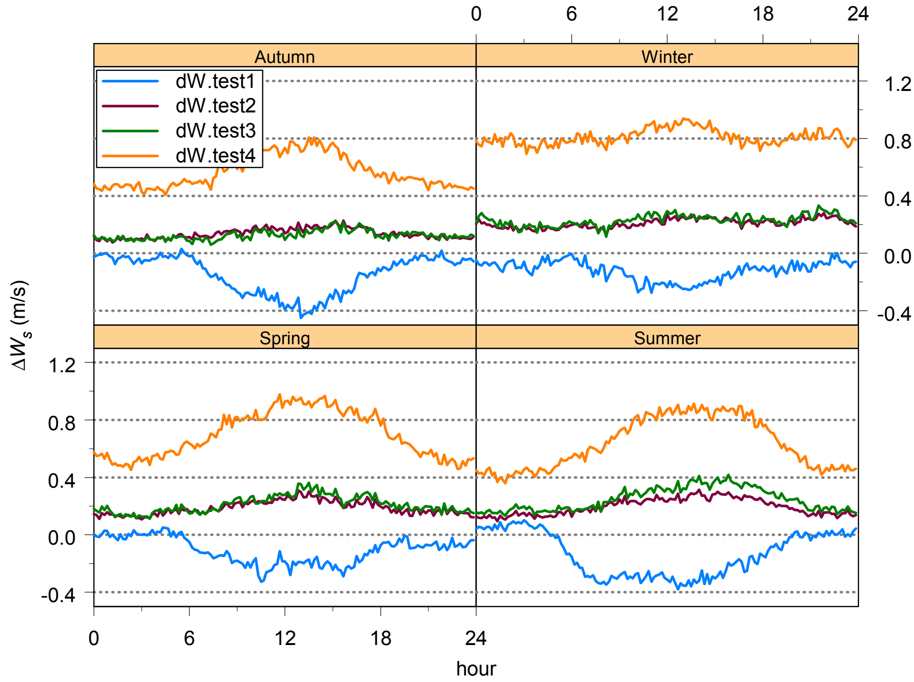
Diurnal wind speed cycle differences

Figure 10 presents the mean diurnal cycle differences between TestN and DB260 for the 1.5 m wind speed W_s for all seasons. The figure shows obvious differences between the most enclosed site Test1 and the most open site Test4. The results for Test1 in the figure suggest that the high nighttime temperature differences between Test1 and DB260 (see Figure 9) are not a result of wind speed differences, because these are close to zero. It is plausible that the temperature differences are caused by the small sky-view factor and the radiation of surrounding objects at the Test1 location. The results for Test4, on the other hand, suggest that wind speed differences in that case may be an important cause of the observed temperature differences. The relatively large wind speeds at Test4 reduce the radiation error during the day (causing lower temperatures than DB260) and limit the development of a stable layer during the night (causing higher temperatures than DB260). Test2 and Test3 show the same behavior as Test4 but the magnitude of the differences with DB260 is smaller.

Radiation errors

To study the radiation errors somewhat further, we re-analyzed data from an earlier instruments comparison experiment at the KNMI terrain (Meijer, 2000). From that experiment, we compared the daytime temperatures of the KNMI muli-plate screen with the dry-bulb temperatures of two artificially ventilated psychrometers. Assuming that the daytime radiation error of the psychrometers is negligible, we defined the radiation error as T (KNMI multi-plate screen – psychrometer). We studied the relationship between this radiation error on the one hand, and wind speed at 1.5 m and incoming short-wave radiation on the other. On clear-sky hours in summer (incoming short-wave radiation > 600 W/m^2), the radiation error drops almost linearly from about 0.5–0.6°C to about 0.0–0.1 °C when the 1.5 m wind speed increases from 1.0–3.0 m/s. For wind speeds > 3.0 m/s radiation errors are negligible. For the conditions considered, we thus infer that the differences in daytime radiation errors between the locations in the present experiment amount to about 0.25°C per 1.0 m/s wind speed difference (1.0 m/s ≤ wind speed ≤ 3.0 m/s). From wind tunnel experiments, it is

Figure 10: Mean diurnal wind speed cycle differences between TestN and DB260 for spring, summer, autumn and winter (figure is read from left to right and from bottom to top). Measurements refer to the May 2003–April 2004 period.



know that for wind speeds < 1.0 m/s radiation errors may be much larger (e.g. Gill, 1983).

3.2 Wind direction dependent differences

Figures 11 and 12 present the wind direction dependent wind speed and temperature differences between the TestN sites and DB260 for summer (JJA) and winter (DJF) for both day- and nighttime hours. Day is defined here as the time with positive sun altitude and night with smaller or equal than zero solar altitude. Sun altitudes were calculated from astronomical formulas. Figure 11 shows a clear similarity between the shapes of the plots of Test2, Test3 and Test4. These shapes are a reflection of the barrier of trees (see Figure 1) that runs from south of DB260 to north-northeast. The vertical location of the lines reflects the distance to this barrier. Note the relatively small wind speeds at Test1, reflecting the enclosed character of that site.

The results in Figure 12 for the direction dependent temperatures differences show also much similarity between the shapes of the plots of Test2, Test3 and Test4. In general these plots, combined with the corresponding plots in Figure 11, suggest that high wind speeds during the day result in small radiation errors (relatively low temperatures) and that high wind speeds during the night prevent the development of a stable layer (relatively high temperatures). It is of interest to note that the daytime summer temperatures of Test4 are higher than those of DB260 for 250° < wind direction < 360°, despite the higher wind speed of Test4. This may be caused by advection of relatively warm air from the vegetable gardens to Test4.

In Figure 13 we explore the advection problem in some more detail. The figure presents the summertime temperature differences (TestN – DB260) as a function of average local wind speeds for westerly and easterly winds at nighttime and daytime. Consider first the nighttime situation on the left of

Figure 11: Daytime and nighttime wind speed difference (ΔW_s) between TestN and DB260 as a function of wind direction (10° categories) for summer (JJA) and winter (DJF). Wind direction is measured at a height of 20 m 20 m east of Test4. The Measurements refer to the May 2003–April 2004 period.

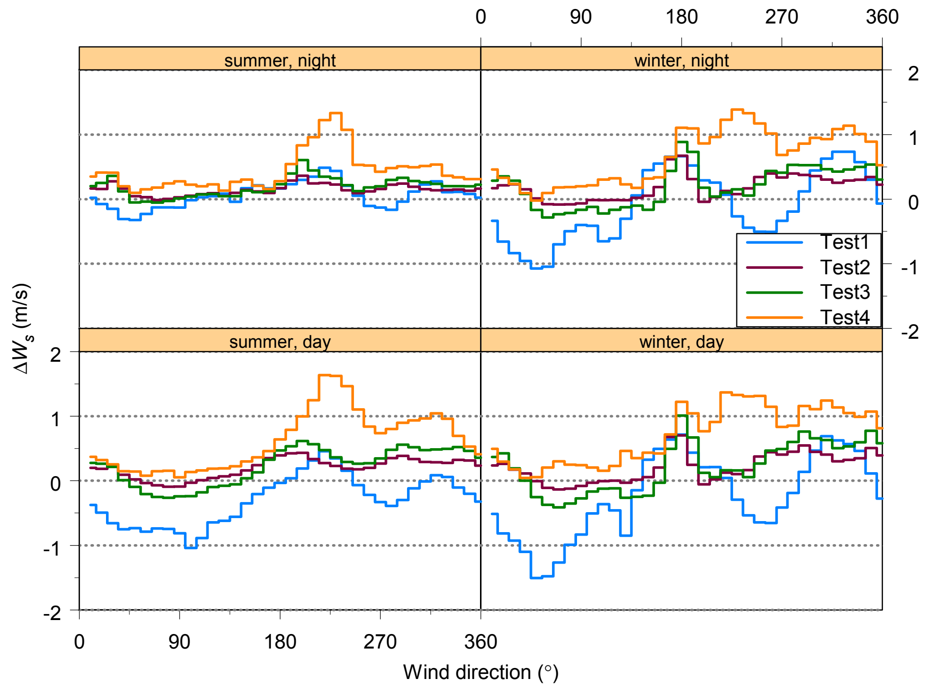
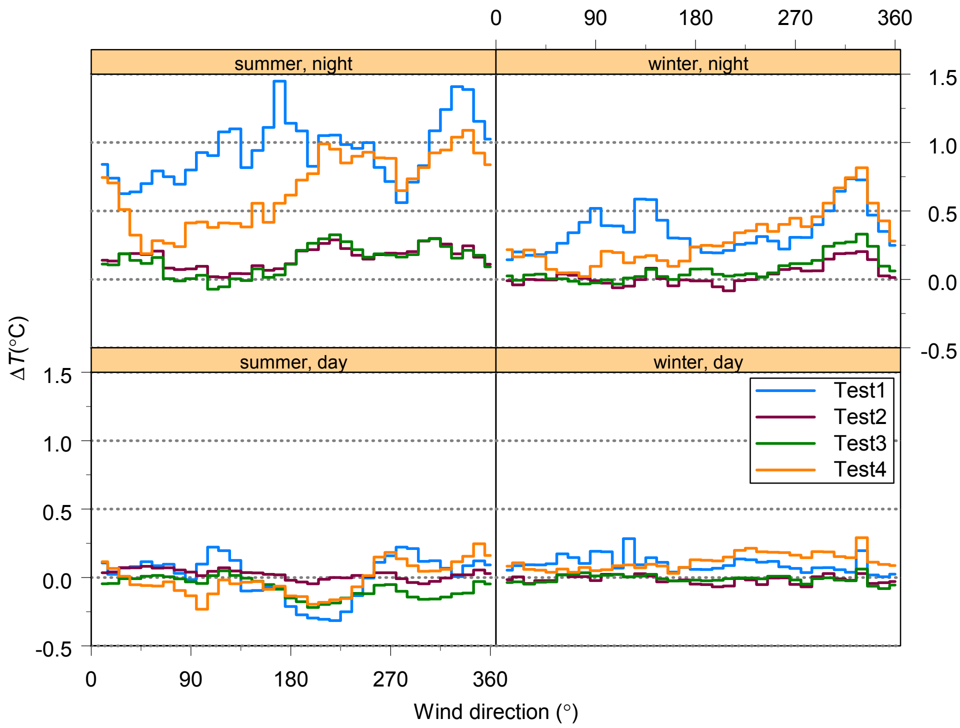


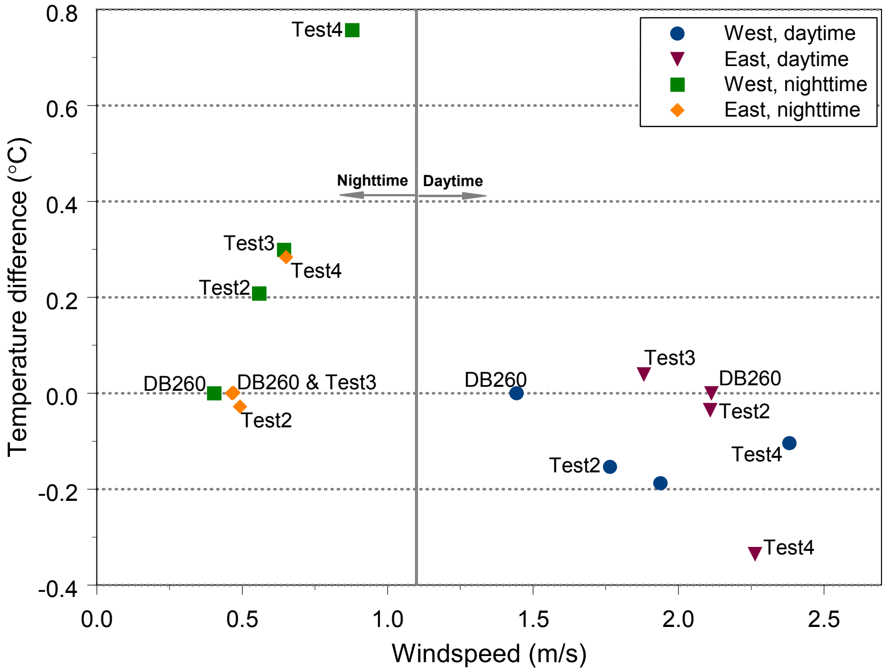
Figure 12: Daytime and nighttime temperature difference (ΔT) between TestN and DB260 as a function of wind direction (10° categories) for summer (JJA) and winter (DJF). Wind direction is measured at a height of 20 m east of Test4. Measurements refer to the May 2003–April 2004 period.



the figure. For westerly flow, the average wind speed increases with distance from the tree-barrier in the west. The temperature differences increase about linearly with the average wind speeds. For nighttime easterly winds, the average wind speeds of DB260, Test2 and Test3 are close to each other and the temperatures at these sites are almost equal. The average wind speed at Test4 is then about 0.2 m/s higher than at DB260, Test2 and Test3 and the corresponding temperature differences is in line with that for the nighttime westerly flows. The results suggest that advection from the vegetable gardens (see Figure 1) is not important during the night.

Considering now the daytime situation on the right of Figure 13, it follows for westerly flow that the cooling at Test4 with respect to DB260, is less

Figure 13: Temperature difference between TestN and DB260 as a function of average local wind speeds for westerly (220–310°) and easterly (70–160°) winds in the summer (JJA) of 2003 at nighttime (left of vertical gray line) and daytime (right). Wind direction is measured at a height of 20 m 20 m east of Test4.



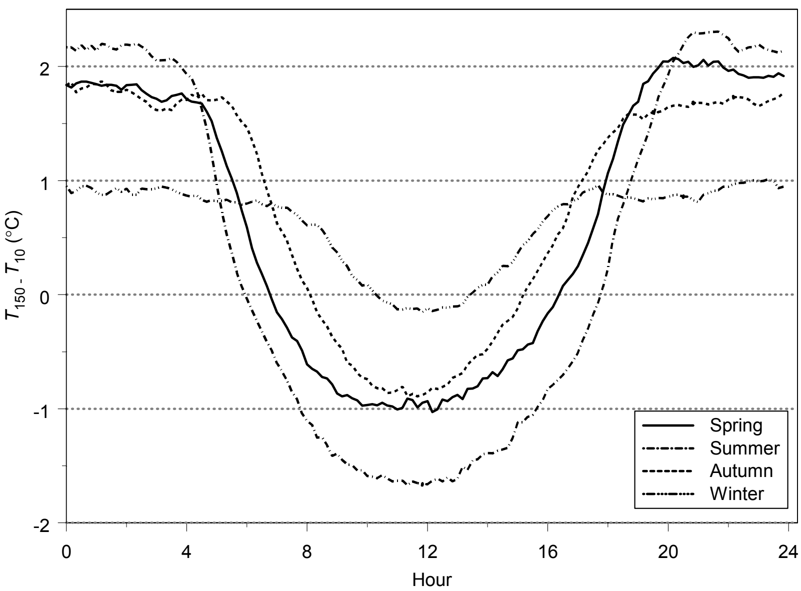
than expected given the observed wind speed difference. On the other hand, for easterly flow the cooling is more than expected given the observed wind speed difference. We tentatively conclude that on summer days there is indeed advection of relatively warm air from the vegetable gardens to Test4 (westerly flow) or to DB260, Test2 and Test3 (easterly flow). We estimate that on summer days this effect may amount to about 0.15°C for the considered wind directions.

3.3 The role of atmospheric stability

The stability of the atmosphere determines to a large extend the shape of the vertical temperature profiles near the thermometer screens. Local differences in atmospheric stability may thus be a cause of temperature differences between the sites studied here. Stability is mainly a function of incoming global radiation/cloudiness and wind speed. As local global radiation or cloudiness differences cannot be considered important on the scale of the experiment, only wind speed differences may cause local differences in atmospheric stability. The results in Sections 3.1 and 3.2 already showed that the wind speed differences between the locations are significant.

In this report we use the temperature difference between screen level at 1.5 m and at 0.1 m as a measure of atmospheric stability, further denoted as $T_{150} - T_{10}$. Air temperature at 0.1 m is measured operationally at the DB260 site. Figure 14 presents for DB260 the daily cycle of $T_{150} - T_{10}$ for all seasons. Positive values of $T_{150} - T_{10}$ indicate stable conditions while negative values indicate unstable condition. Values close to zero indicate neutral conditions. As expected, the diurnal range of $T_{150} - T_{10}$ is greatest in summer and smallest in winter. In contrast to the other seasons, in winter conditions rarely become unstable during the day. The moment that $T_{150} - T_{10}$ changes sign depends mainly on the altitude of the sun (not shown). On clear days in the summer half year, $T_{150} - T_{10}$ changes sign at a sun altitude of 20° in the morning and 16° in the evening. In the winter half year the

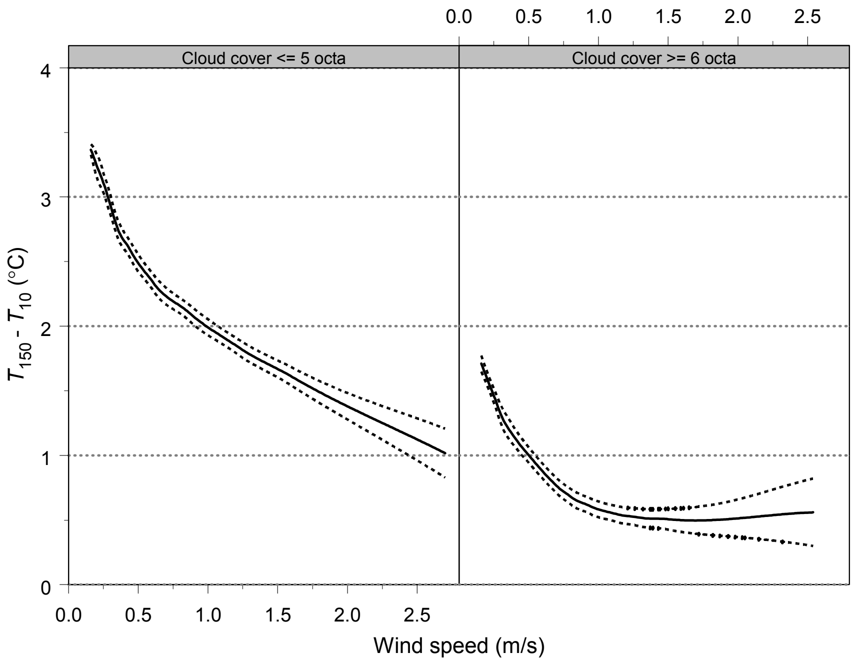
Figure 14: Mean diurnal cycle of the temperature difference between screen level (1.5 m) and grass level (0.1 m), $T_{150} - T_{10}$ at the DB260 site for spring, summer, autumn and winter. Measurements refer to the May 2003–April 2004 period.



corresponding values are slightly smaller: 14° in the morning and 13° in the evening.

Figure 15 presents $T_{150} - T_{10}$ as a function of wind speed W_s for summer nights for two cloud cover categories. The figure shows strongly non-linear relationships between $T_{150} - T_{10}$ and W_s and a clear dependence on cloudiness. It is important to note that especially at low wind speeds (< 1.0 m/s), relatively small changes in wind speed cause large differences in $T_{150} - T_{10}$. Situations with low wind speeds occur often during the night. An increase in wind speed then causes increases in both T_{150} and T_{10}, with the largest increase near the ground surface. Local differences in atmospheric stability are therefore an important cause of nighttime temperature differences between the sites studied here. During the day (not shown) atmospheric stability is mainly a function of incoming radiation. The effect of local wind speed differences on vertical temperature profiles is insignificant then.

Figure 15: Temperature difference between screen level (1.5 m) and grass level (0.1 m), $T_{150} - T_{10}$, at the DB260 as a function of local wind speed (at 1.5 m) for summer nights (June 2003–August 2003). The solid lines are locally weighted running-line smooth curves (Cleveland, 1979) with a span of 0.5. The dashed curves give the pointwise 2 times standard-error bands.



4 Discussion

The results for the former historical site Test1 show that, in comparison with the other sites, the behavior of this site is completely different. Trees and buildings enclose the site to a large extent (see Figure 5). Consequently, a significant part of the day the thermometer screen is in the shade and wind speeds are relatively small. Moreover, the surrounding objects, resulting in a small sky-view factor, hinder long-wave nighttime radiation from Test1. At the same time, the objects emit long-wave radiation to the test site. It is probable that these two aspects cause the relatively high nighttime temperatures at Test1. It is also likely that due to the growth of trees and the placement of new buildings since 1951, the present conditions at Test1 are not really comparable to the situation in 1951. Consequently, using the results of Test1 to correct for the replacement in 1951 is questionable. Nevertheless, the results for Test1 provide useful information about the effect of nearby trees and buildings on temperature measurements.

The results for the current operational site DB260 show that the representativeness of the site is seriously hampered by the barrier of trees that runs from the south of DB260 to the north-northeast. Comparison with Test2, Test3 and Test4, shows that wind speeds at DB260 are relatively low causing relatively high maximum temperatures and relatively low minimum temperatures. The most open location, Test4, shows the largest differences with DB260 (see Table 1). For instance, in the summer half year the mean maximum temperature at Test4 is 0.28°C lower than at DB260 and the mean minimum temperature is 0.48°C higher. The annual mean temperature of Test4 is 0.15°C higher than at DB260. From the operational point of view, the Test4 site clearly is a better location than DB260, mainly because it is hardly influenced by the local wind barrier (see Figure 1). However, from the climatological point of view, transition to an alternative location like Test4, would result in significant jumps in maximum, minimum and mean temperatures.

The height of the tree barrier near the operational DB260 site, increased gradually since 1951, especially the southerly part of the barrier. It should therefore be kept in mind that, in addition to the step change in 1951, there is also a gradual change in air temperature contributing to the above-mentioned current observed temperature differences. The results of the present experiment can probably be used to derive a time dependent correction.

The observed temperature differences between the sites may be attributed to several factors. Especially for DB260, Test2, Test3 and Test4, the results suggest that the indirect effect of wind speed on the vertical temperature profile during the night is the most important factor for explaining the observed temperature differences. The effect of wind speed on the radiation error and the effect of advection of heat from the vegetable gardens towards the thermometer screens are mainly important during the day. In the remainder of the study, these effects will be studied more thoroughly and an attempt will be made to parameterize them.

In September 2004 a renovation started of the nature area between the dotted green line and the tree barrier in Figure 1. The bushes in the nature area (up to 3 m height) were cut down resulting in a more open DB260 site. It is not expected that this activity affect the conclusions to a large extent because the impact of the large tree barrier on wind speed is much larger than that of the former bushes in the nature area. This can be verified by extrapolating the results of Test3 and Test2 to DB260 (taking into account their mutual distance). The two test sites are outside the sphere of influence of the bushes. We estimate that the error introduced by the bushes is about 0.05°C at maximum. An important aspect of the renovation of the nature areas is the construction of a large pond west of DB260. It is probable that this affects the temperature measurements at DB260. Because of these current renovations, it is recommendable to continue the measurements at least a year after finishing the renovation.

The results in the present report may affect the estimate of urban heat advection for the KNMI-terrain made by Brandsma *et al.* (2003). This effect is mainly important during nighttime. Brandsma *et al.* (2003) used the current DB260 site for their estimation. However, the results here show that the DB260 temperatures are too low during the night. Consequently, the effect of urban heat advection is probably underestimated. We estimate that the underestimation amounts to about 0.15°C. To obtain a more precise estimate, we will repeat the calculations in Brandsma *et al.* (2003) with the DB260 temperatures transferred to the Test4 site.

Although the results in this report concern the KNMI-terrain and instruments in De Bilt only, they may be useful for other stations in the Netherlands and abroad as well. They provide insight in the order of magnitude of errors, stemming from different sources, in air temperature measurements due differences in siting and exposure.

5 Conclusions and recommendations

In the present report we presented the interim results of the first year of a two-year parallel comparison of five temperature sites for measuring air temperature at the KNMI-terrain in De Bilt at 1.5 m. The results show that there are significant climatological differences between the sites for both temperature and wind speed. The results for the former historical site Test1 can probably not be used for correcting the jump in summer maximum temperature around 1951. The temperature observations at this site are too much affected by the growth of trees and placement of buildings since 1951. This results mainly in relatively high nighttime temperatures and can thus not explain the observed downward jump in the summer maximum temperatures around 1951, which was partly caused by a screen change in 1950 and partly by a major site change in 1951.

The local wind barrier close to the current operational location DB260, seriously affects the temperatures at that site. The resulting reduced wind speeds at DB260 cause higher maximum temperatures and lower minimum temperatures than at the more open sites. The magnitude of the effects is important with respect to long-term temperature trends, also for the mean temperatures. For the current operational temperature observations, movement of the observations from DB260 to the much more open location at Test4 is recommended. In contrast to the DB260 site, the Test4 site is in agreement with the WMO demands for air temperature measurements. However, for climatological purposes, temperature observations at DB260 should continue until a satisfactory transfer function is developed that reduces the temperature observations at Test4 to DB260.

So far, the results of the parallel measurements stress the importance of wind speed measurements near the thermometer screen at screen height. Especially high accuracy wind speeds in the range 0.0–3.0 m/s seem important. These wind speeds allow for (a) objectively monitoring the homogeneity of temperature sites, and (b) the development of improved weather dependent transfer functions in case of future inhomogeneities. For (at least) temperatures stations of climatological interest, it is therefore recommended to equip them with anemometers for high-accuracy (especially in the range 0–3 m/s) wind speed measurements, placed near the thermometers screen at screen level. These measurements should be performed in addition to the current operational wind speed measurements (in the Netherlands mostly at 10 m height).

The present report dealt only briefly with the different causes of the temperature differences between the sites. For the remainder of the study, it is recommended to put more emphasis on quantifying the magnitude of the individual causes. A clear separation between instrumental and siting causes is then important.

Acknowledgements

Many persons are involved in carrying out an experiment like the one reported here. Willem Hovius (KS/AO) assisted in setting up the experiment in its initial phase. Ronald van de Vate (WM/OD) assisted in the selection and the mapping of the sites. The instrumental department (MI/INSA) equipped the sites with instruments and takes care of the maintenance and (re)calibration of the instruments. Frank Duin (MI/AUT) takes care of the data collection and sending. Lex Snijders (MI/AUT) built and maintains the intranet-site with the real-time observations. Valuable discussion took place with the feedback group of the project 'Homogenization De Bilt 20th century', and with Wim Kohsiek, Fred Bosveld, Jitze van der Meulen, and Wiel Wauben.

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Appendix A: Experimental details and calibration

A 1 Locations and data collection details

Table A1 presents details about the field codes for each instrument as used internally at KNMI. Table A2 presents details about the instrument numbers and the replacements dates (touched up till July 2004). Anemometers are replaced when their detection limit of threshold speed becomes > 0.3 m/s. The table shows that this is often the case.

Table A1: Descriptions and field codes of the instruments at the 5 sites in Figure 1.

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

Table A2: Instrument numbers and replacement dates.

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

Tables A3–A5 give the information on the variables that are stored by the author in the database for the parallel experiments. The data are 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 is automatically send 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.

Table A3: Description of the variables at the 5 locations at the KNMI-terrain stored in the dataset of the parallel experiment.

Res	Var	DataType	VariableDescription
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
10 min	rhb	CodeWord	Relative humidity Boolean

*Running 10-minute average sampled only ones per 10-minutes

Table A4: Positions of the variables in Table A3 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 A5: Additional operational 10-minute observations at the KNMI-terrain (A260a) stored in the dataset of the parallel experiment dataset.

Var	DataType	VariableDescription
dd	WindDirection	Wind direction 10′ vector characteristic average
ffs	WindSpeed	Wind speed sensor 10′ characteristic average
n	CloudAmount	Total cloud cover
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 at 28 November 2003

A 2 Instrument calibration

For this field experiment, the PT-500 sensors and the anemometers are 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. For a better adjustment, we used the calibration curves and values 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 locations. It is assumed that the decay between two successive calibrations within the calibration interval of 36 months is << 0.05 °C.

Temperature sensors

The first two sets of calibrations curves of the PT-500 sensors are shown in Figure A1. 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 temperature.

In contrast with Figure A1 (b), the sensors in Figure A1 (a) were not all calibrated at the same time. The sensors of Test1, Test3 and Test4 were calibrated at the beginning of the experiment using the same liquid bath in the calibration lab. The sensor of DB260 was calibrated on 2 December 2002 and the sensor of Test2 on 4 April 2002. Comparison of the curves for Test1, Test3 and Test4 in Figure A1 (a) and (b) showed that the curves were almost identical, except from a vertical translation of –0.04°C for each sensor. As PT-500 are considered as very stable sensors, it is reasonable to assumes that the differences between the calibration for Test1, Test3 and Test4 in Figure A1 (a) and (b) are mainly caused by the liquid bath in the calibration lab. We used this assumption to transform the original calibration curves of DB260 and Test2 (not shown) to curves comparable to those of Test1, Test3 and Test4 at the beginning of the experiments in Figure A1 (a). The figure shows the transformed curves.

The real temperature is obtained as:

$$T = T_{\text{sensor}} + \text{correction} \qquad (1)$$

where correction is obtained from the linear least-squares lines in Figure A1 (a) and (b).

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 of the detection limit of threshold speed, the anemometer is replaced. Table A2 already showed that this is often the case.

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

$$W_{s,\text{operational}} = C_{\text{operational}} \times f \qquad (2)$$

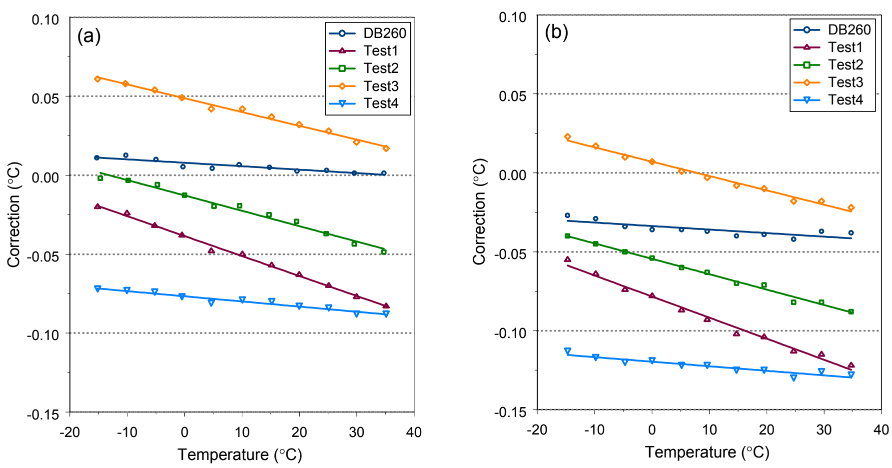

Figure A1: Calibration curves of the PT-500 sensors for the operational site DB260 and the 4 parallel locations, giving for each sensor the temperature correction as a function of temperature: (a) at the beginning of the experiment on 1 May 2004, (b) from 7 January 2004 onwards. The symbols give the values as determined in the KNMI calibration lab, the lines present linear least-squares fits.

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

$$W_s = C \times f + \text{correction} \tag{3}$$

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

$$W_s = \frac{C}{C_{\text{operational}}} W_{\text{s,operational}} + \text{correction} \tag{4}$$

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