Royal Netherlands
Meteorological Institute
*Ministry of Infrastructure
and Water Management*

Impact of a solar farm on temperature and radiation measurements at Groningen Airport Eelde in the Netherlands

Theo Brandsma

De Bilt, 2025| Technical report; TR 25-01

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Contents

Summary

In the summer of 2019 a 20 hectares solar farm was installed on Groningen Airport Eelde at a distance of about 30 m from the operational KNMI measurement site at the Groningen Airport. The solar farm has another surface roughness and a different energy balance than the surrounding areas and an impact of the farm on the measurements might therefore be expected. Especially temperature and global radiation could be affected. The present study analyses parallel measurements at the Groningen Airport to study the possible impact of the solar farm on temperature and radiation measurements. Due to uncertainty about the quality of the parallel measurements for temperature, the results for this variable are validated using the measurements of neighboring KNMI stations.

We found an increase in the annual mean maximum temperatures of about 0.1 °C and a decrease in the minimum temperatures of about 0.1 °C at the operational location compared to the back-up location. The back-up location is situated about 1.2 km from the solar farm and is not affected by the solar farm. The daily mean temperatures are hardly affected. As expected, the impact on maximum and minimum temperatures is especially visible for directions where the wind blows from the solar farm to the operational location. A comparison with the five nearest inland KNMI stations, confirms the increase in the maximum temperatures at the operational location but also suggest an annual average nighttime cooling of about 0.3 °C. The large nighttime cooling is further confirmed by a comparison with all KNMI land stations. This nighttime cooling is thus 0.2°C (annual mean) larger than suggested by the comparison with the parallel measurements at the airport. The reasons for this nighttime cooling are probably related to changes in surface roughness due to the solar farm.

After the installation of the solar farm, KNMI installed a possible new location close to the original location but 35 m further from the solar farm.

A comparison between this location and the operational location showed that using this new location would strongly reduce the impact of the solar farm.

A comparison of global radiation measurements at the operational location and the back-up location does not suggest a significant impact of the solar farm on these measurements.

It is recommended to relocate the current operational location to the suggested new location. The location is close to the current operational location but at a distance of 65 m from the solar farm. This reduces the impact of the solar farm on (a) the annual mean minimum temperature to a cooling of about 0.1°C and (b) the annual mean maximum to a zero change. It is recommended to monitor this new situation closely in the coming years.

CHAPTER 1

Introduction

Groningen Airport Eelde (06280)[1] is one of five main climate stations in the Netherlands with meteorological records longer than 100 years. The series consist of two parts. Until 1952 measurements were performed in the center of the nearby city of Groningen and from 1946 onward measurements were performed on Groningen Airport Eelde. Both series were connected using the data in the overlapping period [3, 10]. Series like these are indispensable for monitoring long-term climate trends. Any non-natural source of inhomogeneity in the series needs attention. The recent installation of solar panels on Groningen Airport Eelde close to the operational measurements, might be a cause for such an inhomogeneity. This report addresses this issue.

1.1 Background

In 2019, between Monday 29 July and Friday 27 September a solar farm was installed on Groningen Airport Eelde. The surface area of the solar farm equals 20 hectares. Figure 1.1 shows the position of the solar farm with respect to the operational KNMI automatic weather station (AWS) denoted TD23. The distance of the solar farm to the thermometer screen equals about 30 m. The airport also has a backup location (TD05) which is situated 1.6 km southwest of TD23.

The solar farm area replaces the former grassland. Although the albedoes of grassland and solar panels are of the same order of magnitude (0.25 for grassland and 0.15–0.25 for solar panels), the energy balances of grassland and solar panels may differ significantly. This results in differences in latent and sensible heat fluxes during both day and night. These differences may lead e.g. to the so called solar heat island effect, causing temperatures near

[1] This is the local identifier in the WMO Integrated Global Observing System (WIGOS) station identifier.

Figure 1.1: Map of Groningen Airport Eelde after installation of the solar farm. TD23 is the operational location, TD23_new is an alternative for TD23 that may replace TD23 in the future. TD05 is the backup location and TD05_new is situated just East of TD05 because of the shadow effect of the wind mast. The distance between TD23 and TD05 is about 1.6 km

a solar farm to be higher than those of the surrounding areas. Depending on the surroundings, a solar farm may cause nighttime cooling So far, most of the studies have been performed in arid or semi-arid areas [2, 7, 12], where the yield of solar farms is highest. Much is still unknown for situations like those on Groningen Airport Eelde, where a solar farm is surrounded by green grass.

KNMI anticipated that the solar farm might affect some of the operational measurements at the airport. Extra parallel measure measurements were therefore performed close to the operational location TD23 but 35 m further away from the solar farm at location TD23_new. TD23_new is regarded as a possible new operational location. In addition, about 40 m northeast of TD05 a new site TD05_new was installed because of a shading effect of the backup wind mast. Figures 1.2–1.5 show photos of all four locations in northerly direction. All photos were taken on 19 November 2024. Table 1.1 gives the positions of the four locations.

Figure 1.2: The operational TD23 location in northerly direction. The southern edge of the solar farm is visible in the back.

Figure 1.3: The TD23_new location in northerly direction southeast of TD23.

Figure 1.4: The backup TD05 location in northerly direction.

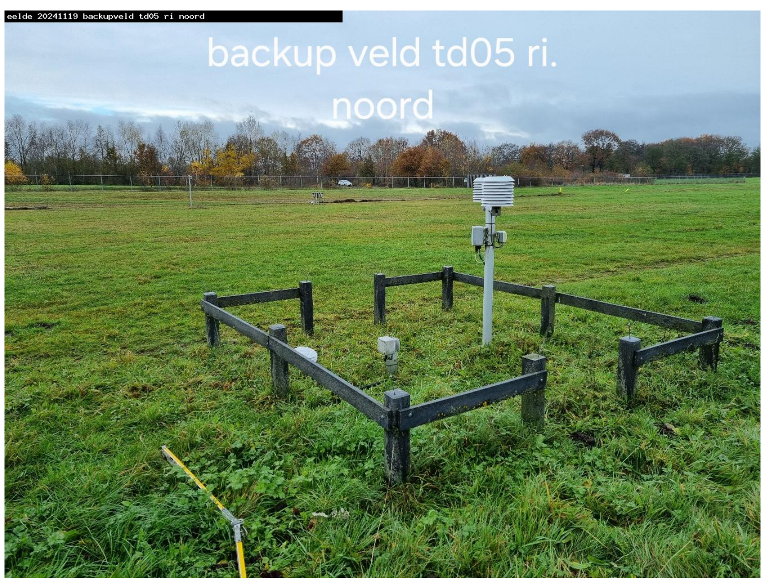

Figure 1.5: The TD05_new location northeast of TD05 in northerly direction.

Location	Lat (N)	Lon (E)	Elevation (m NAP)	Start
TD23	53.1238833	6.5847028	3.2	19510101
TD23_new	53.1235917	6.5847972	3.2	20210401
TD05	53.1143278	6.5652611	2.6	20120101
TD05_new	53.1140917	6.5648028	2.6	20210401

Table 1.1: Details of the four locations in Figure 1.1.

1.2 Objective and scope

The objectives of the study are:

1. To estimate the impact of the solar farm on the operational temperature measurements at TD23 and the impact on the proposed new operational temperature measurements at TD23_new.

2. To estimate the temperature differences between TD23 and TD23_new, and TD05 and TD05_new.

3. To estimate the impact of the solar panels on the global radiation measurements.

4. To present recommendations about the future position of the operational temperature and global radiation measurements at Groningen Airport Eelde.

The study is restricted to temperature and global radiation.

Chapter 2

Data and methods

In this chapter we describe how the data was obtained, processed, and analyzed. Extra attention is given to a problem with the temperature measurements at the TD05 location. TD05 is the intended reference location for studying the impact of the solar farm on the measurements at TD23.

2.1 Data collection

In this study 10-min sensor data was used as the basis for calculations. Table 1.1 gives the periods for which data was available for each of the four locations. Data for global radiation was available for locations TD23 and TD05_new.

The 10-min data of TD23 was available from the KNMI climatological data base (RobuKIS). Data from TD05 was also in RobuKIS but only from 7 April 2019 onward. TD05_new and TD23_new were not in RobuKIS. The 10-min data that were not in RobuKIS, were extracted from the so-called MUF (Maximum Usable Frequency) dataset, containing 12 sec strings of all data from a location.

2.2 Data Preparation and Cleaning

For temperature each 10-min value (TAm) is the mean of the five 12-sec temperature samples in the last minute of a 10-min interval. The 10-min minimum (TAn) and maximum (TAx) temperatures in a 10-min interval are the minimum and maximum of all running 1-min values in a 10-min interval. The daily mean, minium and maximum temperatures (Tmean, Tn, Tx) were calculated as the mean, minimum and maximum of all 144 TAm, TAn and TAx, respectively, in a day. A day runs from 0:00–0:00 UTC. In case of missing 10-min data, daily values were specified as not available (NA).

For global radiation, we used the mean radiation in a 10-min interval (QGa). Both the operational sensor at TD23 and the parallel sensor at TD05_new have been calibrated in the KNMI calibration lab[1]. We calculated daytime values from the 10-min values of QGa, where daytime was defined as solar zenith angle (sza) $\leq 85°$ (to prevent the impact of low bushes around the sites).

In recent years, KNMI shifted from using CM-11 to SMP-11 pyranometers. Appendix A summarizes the information about the pyranometers that have been used at Groningen Airport Eelde in the period of the comparison. The impact of this shift is described in [9].

In addition to temperature and global radiation data, we used 10-min averaged data of wind direction (DD), wind speed (FF) and cloudiness (N) of the TD23 location.

All 10-min data were visually inspected for outliers. These outliers were sporadic and were set to NA.

The temperature sensors were calibrated in the KNMI calibration lab. Appendix B describes how the resulting calibration values were used to correct the sensor values[2]. Theoretically, this reduces the measurement uncertainty from about 0.1°C to 0.01°C. In practice, the reduction is smaller because on the hightest time resolution of 12 seconds (in the SIAM[3]) values are rounded to 1 decimal.

2.3 Methods

Statistical methods

We compared the temperature differences (Site X - Site Y) for Tmean, Tn and Tx (ΔTmean, ΔTn, ΔTx). The differences were compared at a monthly and annual time scale. In addition, diurnal cycle differences were considered and the dependence of temperature differences on wind speed. Except when stated otherwise, the corrected 10-minute temperature values were the basis for the derived daily or monthly values.

[1] Calibrations of all pyranometers of the network of pyranometers are performed in the KNMI calibration lab and are traceable to the World Radiometric Reference (WRR). The calibration consists of a sensitivity (in $\mu V/W/m^2$) and an offset (in μV). The latter corrects for heat dissipation of the AD converter and has been determined by the manufacturer of the pyranometers (Kipp & Zn). Uncertainties in KNMI pyranometer measurements are further described in [9].

[2] This is not standard practice for operational sensors at KNMI, but sometimes used for research purposes.

[3] Sensor Intelligent Adaption Modules (SIAM). These are independently functioning units that serve as an intelligent interface between meteorological sensors and data processing automatic systems.

For the calculation of the statistical significance of monthly mean values calculated from daily values it is often necessary to take into account the serial correlation of the daily values. The method used here[4, 8] is described below.

For n independent observations $x_1, x_2, ..., x_n$ the standard error of the mean $se_{\overline{x}}$ is defined as:

$$se_{\overline{x}} = \frac{s}{\sqrt{n}} \tag{2.1}$$

where s is the sample standard deviation.

As daily meteorological observations are usually not independent $se_{\overline{x}}$ has to be multiplied by a factor resulting in a corrected standard error $se^*_{\overline{x}}$:

$$se^*_{\overline{x}} = f\, se_{\overline{x}} \tag{2.2}$$

where the factor f is defined as:

$$f = \sqrt{\left(\frac{1+\rho}{1-\rho}\right)} \tag{2.3}$$

where ρ is the lag 1 auto-correlation.

Reference temperature TD05

The backup location TD05 is not affected by the solar farm and has measurements in the years before and after the installation of the panels. Therefore, it was considered as the ideal reference. However, a first analysis suggested problems with the temperature measurements at TD05.

Figure 2.1 shows the temperature differences between TD23 and TD05. The figure shows a rather odd behavior of TD23 versus TD05. For instance, till the end of 2014 the differences in Tmean (TD23 – TD05) is about –0.3°C, thereafter it fluctuates around 0.0°C till about the middle of 2017. Thereafter, the difference in Tmean increase to a maximum level of about 0.5°C and after the middle/end of 2020 it again fluctuates around 0.0°C.

In summary, the differences in Tmean (TD23 – TD05) range between −0.3 °C and 0.4 °C. This is large. It seems that the inhomogeneites coincided with sensor replacements, occurring on average once every three years. The calibration certificates of the sensors did not show any peculiarities. At TD05 there was a change of temperature SIAM on 3 April 2021. This was before planned calibration interval expired (the previous SIAM was installed on 6 May 2016). There was no clear error message, it was only specified that the SIAM had to be sent for repair. It has been suggested that there might have been a problem with a connector.

To study the above temperature differences further, we compared TD23 and TD05 for weather conditions where, naturally, both locations should have

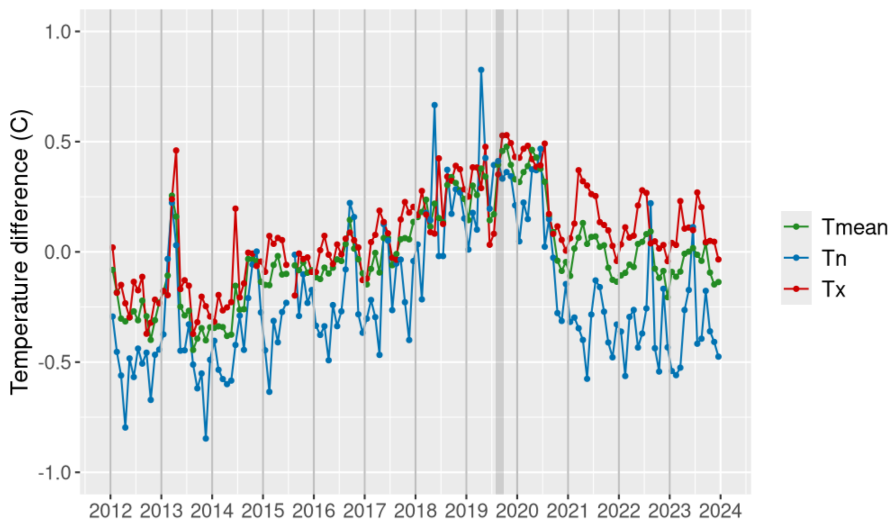

Figure 2.1: Monthly mean temperature differences (TD23 – TD05). The grey band represent the period where the solar panels were installed.

the same temperature (also with the solar farm installed). Here we specified these conditions as:

1. nighttime (UTC >= 20 and UTC <= 4)
2. overcast weather (N = 8)
3. large wind speeds (FF > 8 m/s).

Figure 2.2 shows the monthly medians of the 10-min temperature differences. The figure shows an odd behavior before the first sensor replacement and between second and third sensor replacement. As the temperatures of TD23 are routinely validated at KNMI and those at TD05 are not, it might be expected that the temperatures at TD05 cause the problems. To check if this correct, we compared the temperatures at TD23 and TD05 with the grass minimum temperatures at both locations and with the mean of the surrouding KNMI stations Nieuw Beerta (06286), Hoogeveen (06279), Leeuwarden (06270), Lauwersoog (06277) and Marknesse (06273). This comparison showed that the TD05 location is indeed the cause of the odd behavior of TD23 – TD05 in Figs 2.1 and 2.2.

From Figure 2.2 we deduced that the years 2015–2016 (period I) and 2021–2023 (period II) were probably not affected by instrumental problems. Therefore, period I was used as representative for the situation before the installa-

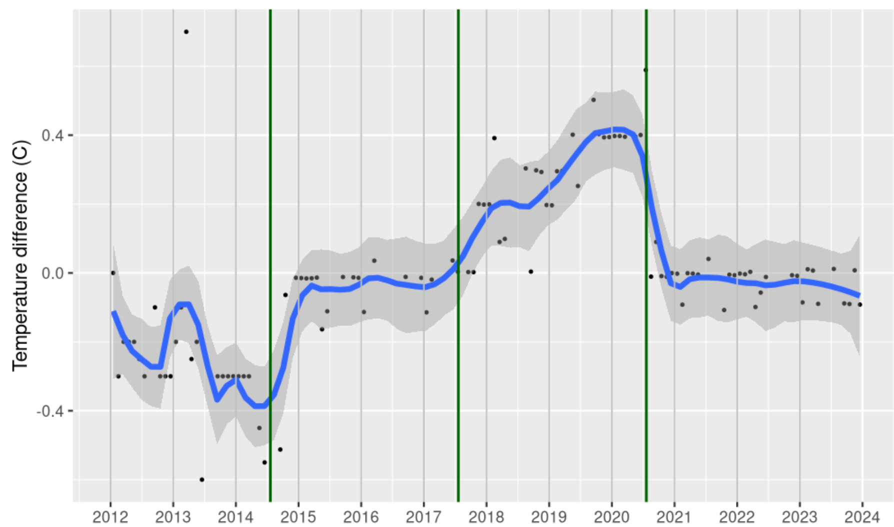

Figure 2.2: Monthly medians of the nighttime individual 10-min temperatures differences (TD23 – TD05) for overcast and windy weather. The blue line is a loess smoother[6] (span = 0.15) with a 95% confidence interval (dark grey). The green vertical lines represent months where temperature sensors were replaced.

tion of the solar farm and period II for the situation thereafter. A comparison with surrounding KNMI stations was used to validate the results.

CHAPTER 3

Results

In this chapter we present the results of the impact of the solar farm on the temperature and radiations measurments at Groningen Airport Eelde. The main focus is on (a) the temperature differences between the operational location TD23 and the backup location TD05, and (b) its validation using neighbouring KNMI stations. Thereafter, we look at TD23_new as a possible alternative for TD23 and TD05_new as a possible alternative for TD05. The last section is devoted to the impact of the solar farm on global radiation.

3.1 Temperature (TD23 – TD05)

Monthly mean temperatures

Figure 3.1 shows the temperature differences between TD23 and TD05 for period I (2015–2016) and period II (2021–2023). Where the first period refers to the undisturbed situation and the second to the situation with the solar farm installed. Note that these monthly values in the correspinding period in Figure 2.1.

Before the installation of the solar panels (period I), the figure shows lower Tn at TD23 than at TD05 (0.26°C annual mean). The temperature differences for Tx and Tmean are close to zero. After the installation of the solar panels (period II), Tx at TD23 is higher than at TD05, especially in the summer half year, and Tn at TD23 decreased somewhat further compared to TD05 (0.24°C annual mean). The differences for Tmean are still close to zero but more variable, reflecting the seasonal change in Tx.

Figure 3.2 shows the temperature differences between period II and period I. So for each variable this equals the temperature difference in period II minus the temperature difference in period I. This reflects the impact of the solar farm on the measured Tn, Tx and Tmean at the operational location

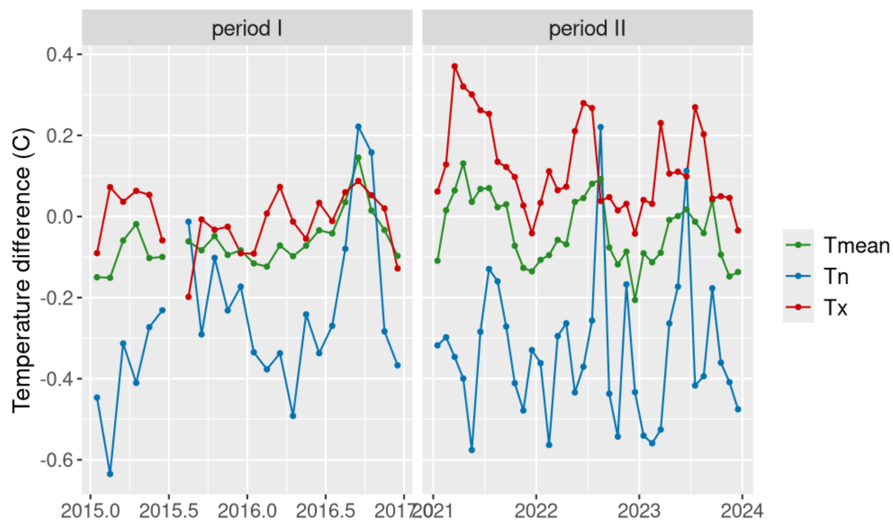

Figure 3.1: Monthly mean temperature differences (TD23 – TD05) for period I (2015–2016) and period II (2021–2023).

Period	ΔTmean	ΔTn	ΔTx
I	–0.06	–0.25	–0.01
II	–0.04	–0.33	0.12
(II – I)	0.03	–0.07	0.13

Table 3.1: Annual mean temperature differences in (TD23 – TD05) for periods I and II and their difference (II – I).

TD23. The figure suggest an increase in Tx, especially in the summer months up to about 0.3 °C in July. The impact on Tn is less clear and seem more or less random with September and October being outliers. The impact on Tmean is small. The annual mean changes are also small and are 0.03, –0.07 and 0.13°C for Tmean, Tn and Tx, respectively.

Table 3.1 summarizes the annual mean differences as discussed above.

Diurnal temperature cycle

Figure 3.3 shows the difference in the diurnal temperature cycles between TD23 and TD05 for each season before and after installing the solar farm. The figure reflects the results in Figure 3.1, but gives some additional details. For instance, before the installation of the solar farm, TD23 is cooler than TD05

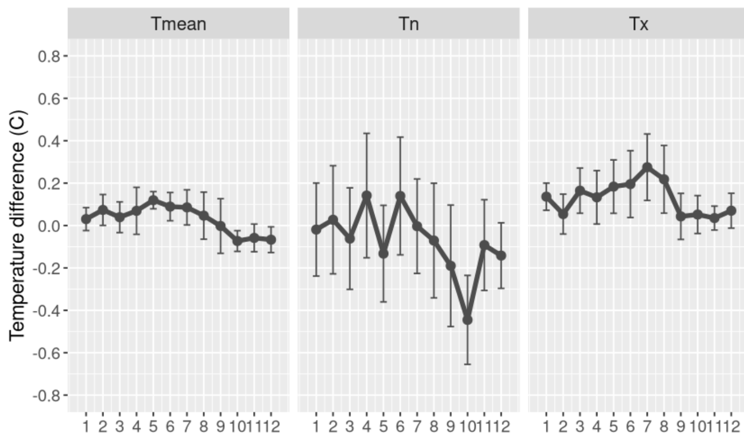

Figure 3.2: Change in the annual cycle of the monthly mean temperature differences (TD23 – TD05) between period II (2021–2023) and period I (2015–2016). The error bars give the 2 times standard errors.

during nighttime mainly in winter and spring. After the installation of the solar farm, TD23 being cooler during nighttime seems extended to autumn too. For daytime temperatures, all seasons show a warmer TD23 with the largest change in spring and summer.

Figure 3.4 shows the diurnal cycle differences between period II and period I for each season. The daytime warming is visible in each season whereas only autumn shows a nighttime cooling. This is related to the outliers in September and October in Figure 3.2

Wind direction dependent temperature differences

In this section we present results for two wind direction categories, one for wind flowing from the solar farm to TD23 and one for the other directions. The line separating the solar farm from the measurement area runs from 230° to 50°. We left out 10 degrees space on either side. The categories are thus specified as follows:

1. 240–40° (wind from solar farm)

2. 60–220° (other directions)

Figures 3.5 and 3.6 show the diurnal cycles of hourly mean temperature differences (TD23 – TD05) for the two categories for the period I and II. For the category ’other directions’ the changes are small from from period I to

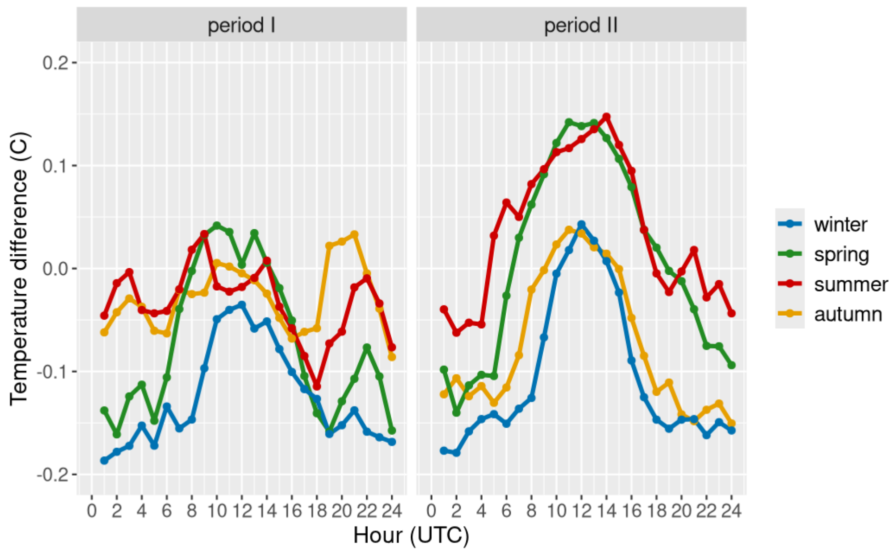

Figure 3.3: Diurnal cycle of hourly mean temperature differences (TD23 – TD05) for period II (2021–2023) and period I (2015–2016).

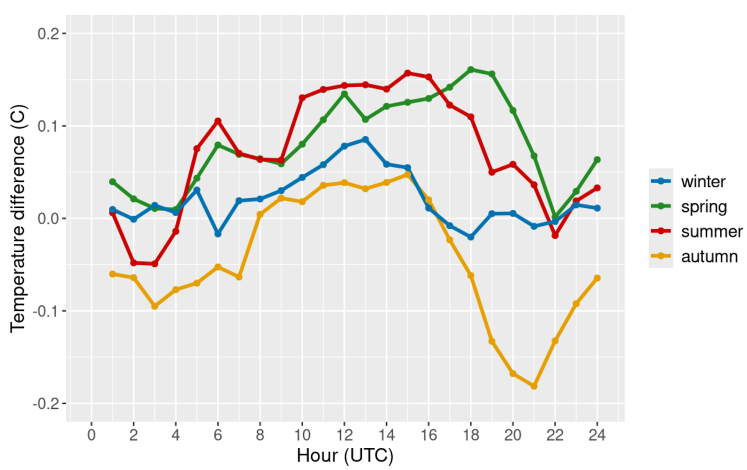

Figure 3.4: Change in the diurnal cycle of hourly mean temperature differences (TD23 – TD05) between period II (2021–2023) and period I (2015–2016).

period II, respectively. In contrast, for category 'wind from solar farm' there are large changes the changes from period I to period II, especially for spring, summer and autumn. A peculiarity of autumn, compared to the other seasons, is the nighttime cooling for wind coming from the solar farm (compare also Figure 3.4). The reason for this is unclear.

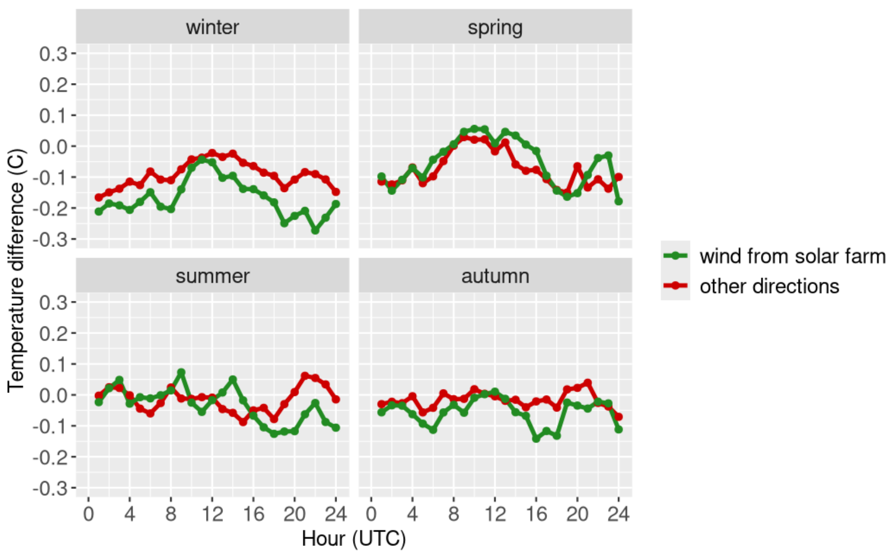

Figure 3.5: Diurnal cycle of hourly mean temperature differences (TD23 – TD05) for wind flowing from the solar farm and for the other directions, for each season in period I (2015–2016).

Independent comparison with the five nearest AWS stations

In this section we compare the temperatures at TD23 with the mean of the five nearest inland AWSs in the Northeast of the Netherlands. The following stations have been selected: Leeuwarden (06270), Nieuw Beerta (06286), Hoogeveen (06279), Marknesse (06273) and Heino (06278), from now on referred to as NL5. The distances of these stations to Groningen Airport Eelde range between 35 and 80 km.

Figure 3.7 shows the results of the comparison. The figure suggest no change for Tmean due to installation of solar farm. This corresponds well to the results in Figure 3.2. For Tn the figure suggest a cooling of about 0.5°C from May to October. The cooling is larger and extends over more months than in Figure 3.2. For Tx the results are quite similar to those in Figure 3.2.

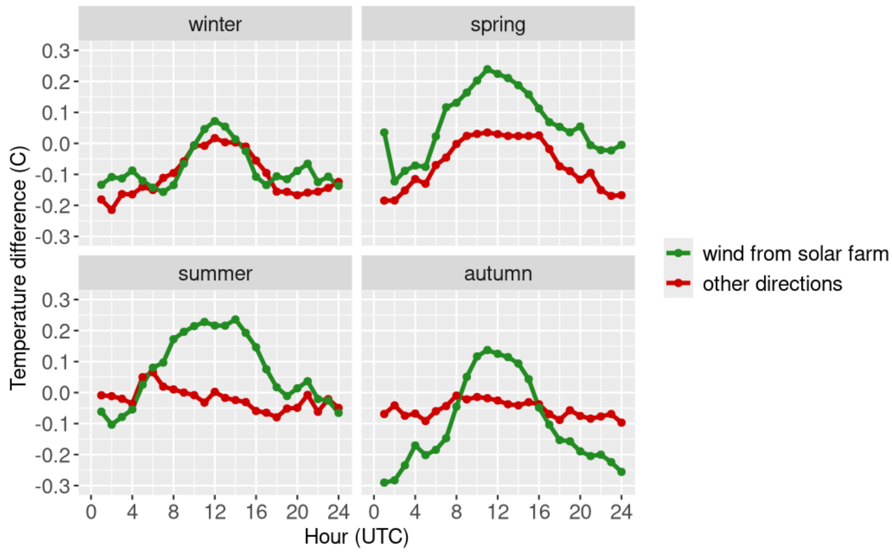

Figure 3.6: Diurnal cycle of hourly mean temperature differences (TD23 – TD05) for wind flowing from the solar farm and for the other directions, for each season in period II (2021–2023).

The annual mean changes are –0.07, –0.32 and 0.10°C for Tmean, Tn and Tx, respectively.

In contrast to the results for TD23 – TD05, these results suggest a large nighttime cooling of Groningen Airport Eelde. To study this further, we compare Eelde with the mean of all land stations in the Netherlands.

Independent comparison with all land AWSs

In this section, we further explore the possibility of a large decrease of the nighttime temperatures at Groningen Airport Eelde. We restrict ourselves to stations with complete data in the 2001–2024 period. Together these are 29 AWSs (excluding Eelde but including NL5), further denoted as NL29.

Figure 3.8 compares the annual mean temperatures of Eelde in the period 2001–2024 with NL29. For Tmean there is a slight downward trend but this is not statistically significant. For Tn there is a downward trend. Homogeneity tests (SNHT[1], Buishand range test[5]) show a statistically significant break ($p=0.000$) in the year 2015 of 0.34°C. Tx shows a break in 2009 and thereafter a small upward trend. In this case, however, the homogeneity tests show no significant inhomogeneities.

The homogeneity test suggest that the minimum temperatures at Gronin-

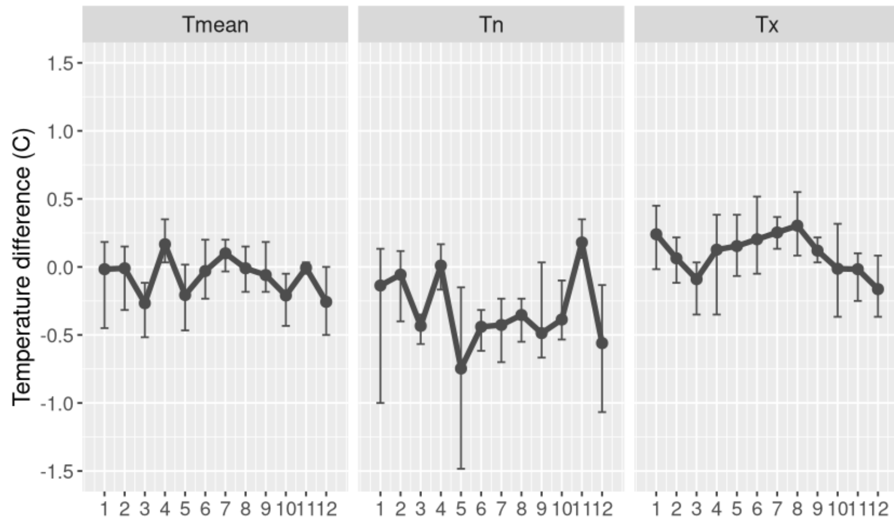

Figure 3.7: Change in the annual cycle of the monthly mean temperature differences (TD23 – NL5) between period II (2021–2023) and period I (2015–2016) using NL5 as a reference. The error bars spans the range of the results for the five individual AWS.

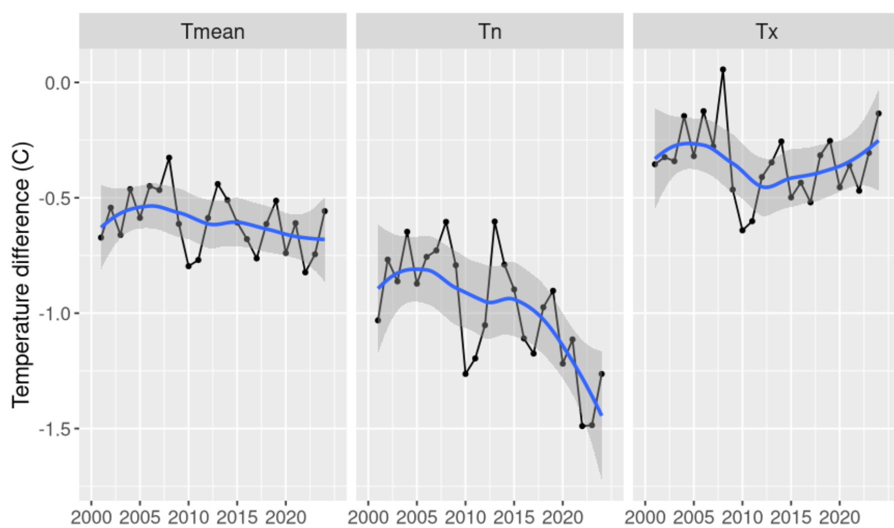

Figure 3.8: Annual mean temperature differences (Eelde – NL29) in the 2001–2024 period. The blue line is a loess smoother (span = 0.75) with a 95% confidence interval (dark grey).

gen Airport Eelde decreased since about 2015. However, inspection of the Tn time series in Figure 3.8 shows that the decrease might just as well have started from 2019 onward (the year where the solar farm was installed). This decrease is larger than can be explained from the comparisons with TD05. It is possible to make the comparison completely independent of the comparsion with NL5 by omitting these five stations from NL29, yielding NL24. Using NL24 shows the same results (not further presented here).

Figure 3.8 also shows some odd behavior of Tmean, Tn and Tx around 2010. From the KNMI metadata archive, we found that there has been a relocation of the operational location on the airport around May 2009. This may explain the deviant behavior around this date.

The comparison of TD23 with NL5 and NL29 suggest that the quality of the parallel measurements at TD05 is, at least, questionable.

3.2 Temperature (TD23 - TD23_new)

In this section we study the feasibility of TD23_new location as a new location for the operational temperature measurements. TD23_new is situated southeast of TD23, about 35 m further removed from the solar farm.

Figure 3.9 shows a summary of the daily temperature differences for Tmean, Tn and Tx. With respect to Tmean, TD23 and TD23_new show only slight differences. For Tmean and Tn, TD23 is cooler than TD23_new (0.04 and 0.18°C annual average) and for Tx warmer than TD23_new (0.07°C annual mean). Comparison with the impact of the solar farm on the annual means in TD23 in Figure 3.7, suggest that a relocation of TD23 to TD23_new partly compensates for the decrease in Tmean and Tn and the increase in Tx by the solar farm (there remains a cooling in Tmean and Tn of 0.03 and 0.14°C, respectively, and a warming in Tx of 0.03°C).

To study the differences further, Figure 3.10 presents the diurnal cycle differences for each season and wind direction category. Note that TD23 is always colder than TD23_new during nighttime and that it is colder for wind from coming from 'other directions' and not for wind coming from the solar farm. During daytime TD23 is mostly warmer than TD23_new and here the impact is stronger for 'wind from solar farm'.

In conclusion, with respect to Tmean, Tn and Tx TD23_new seems less affected by the solar farm than TD23. It compensates to some extent for the impact of the solar farm on Tmean, Tn and Tx. A complicating effect might be TD23_new being closer to the runway than TD23.

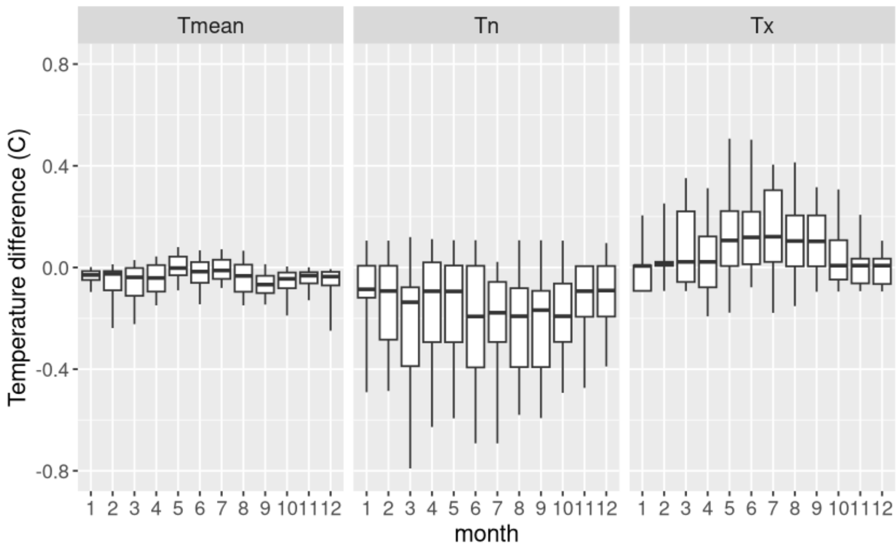

Figure 3.9: Boxplots of the annual cycle of the daily temperature differences (TD23 – TD23_new) from May 2021 through December 2023. The lower and upper boundaries of the box correspond with the 25 and 75th percentile, respectively, the whiskers correspond with the 5 and 95th percentiles and the horizontal line is the median.

3.3 Temperature (TD05 - TD05_new)

In this section we study the feasibility of TD05_new location as a replacement for the measurements at the backup location TD05. TD05_new is situated about 40 m east of TD05 because of a shading effect of the back-up wind mast at that location.

Figure 3.11 shows a summary of the daily temperature differences for Tmean, Tn and Tx. For all variables the figure does not show any significant change in the monthly mean values between the two locations. For Tn and Tx there may be small day-to-day differences, but these may be attributed to natural variations between two locations exposed to the same weather but separated 40 m from each other.

The diurnal cycles differences between TD05 and TD05_new (not shown) are insensitive to wind direction as compared to (TD23 – TD23_new) in Figure 3.10.

In conclusion, with respect to temperature, TD05_new can safely replace TD05.

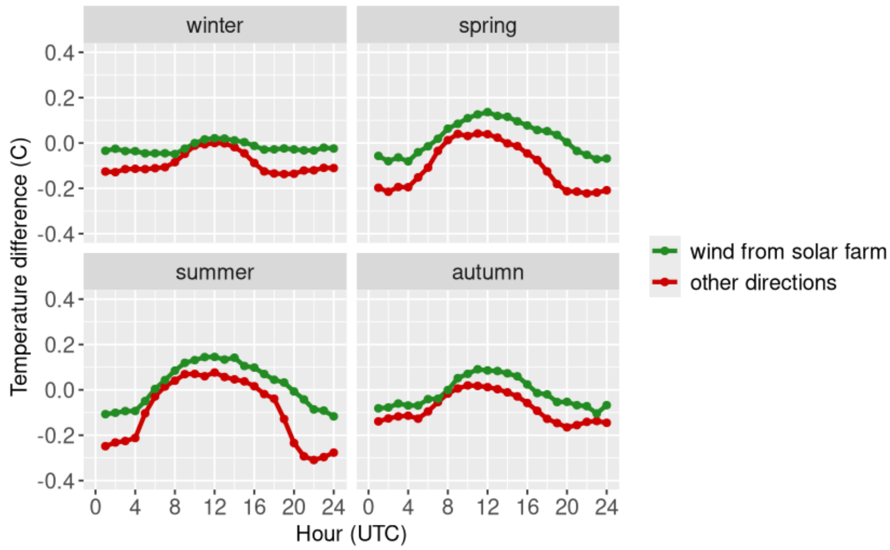

Figure 3.10: Diurnal cycle of hourly mean temperature differences (TD23 – TD23_new) for wind flowing from the solar farm and for the other directions, for each season in the period May 2021 through December 2023.

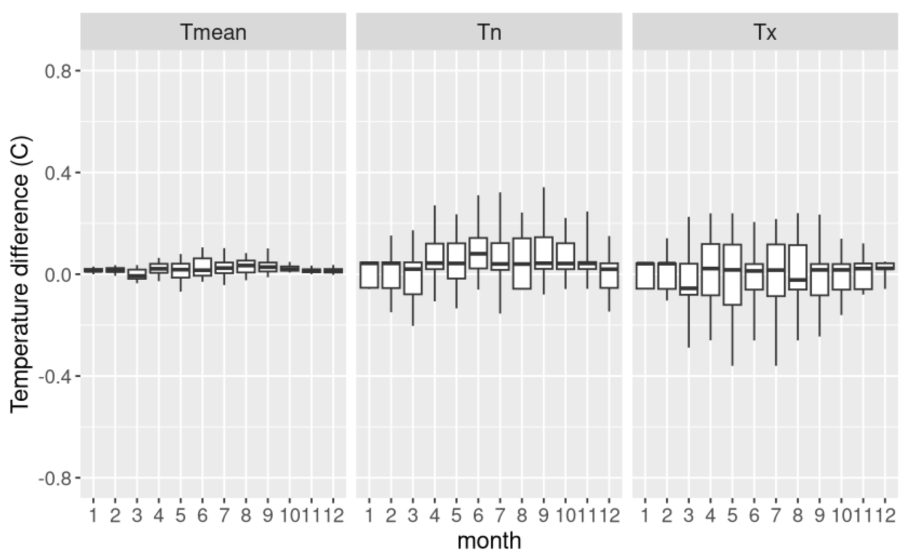

Figure 3.11: Boxplots of the annual cycle of the daily temperature differences (TD05 – TD05_new) from May 2021 through December 2023.See Figure 3.9 for an explanation of a box.

3.4 Global radiation (TD23 - TD05_new)

In this section we study the impact of the solar panels on the global radiation measurements at TD23. For this, we compare the global radiation measurements at TD23 with those at TD05_new. The pyranometer at TD05_new was installed in the end of April 2021 and operates since then in parallel to the operational pyranometer at TD23.

Figure 3.12 shows the monthly absolute and percentage differences in global radiation between TD23 and TD05_new. In general the differences vary between about −5 and 0 W/m^2 and −2 and 0%, which is well within the 5% measurement uncertainty of good quality pyranometers, defined for network operations by the WMO Guide to Meteorological Instruments and Methods of Observation (Table 7.4)[11]. Over the whole period TD23 receives 0.66% less radiation than TD05.

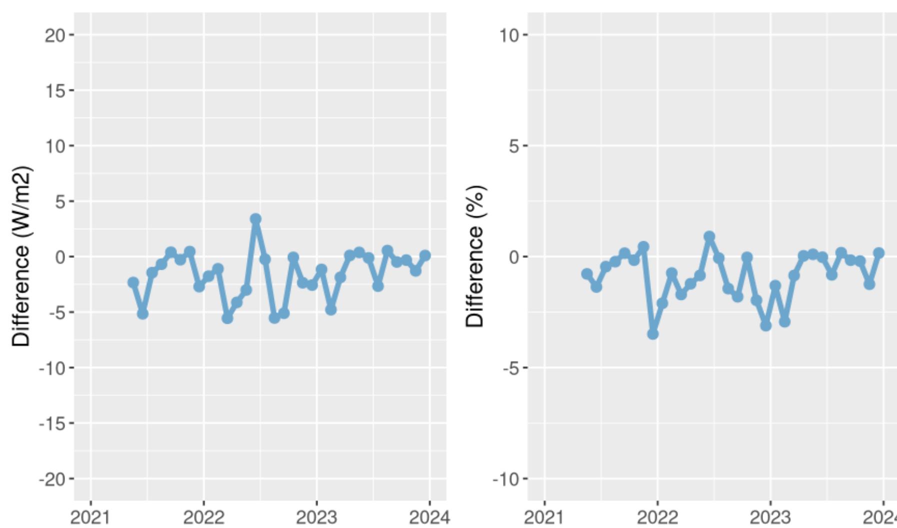

Figure 3.12: Absolute and percentage differences of the monthly mean daytime (sza ≤ 85°) global radiation between TD23 and TD05_new from May 2021 through December 2023.

Figures 3.13 shows boxplots of daily values for each month of the year, both for the absolute daily differences and the percentage differences. The boxplots confirm that the global radiation for the two locations does not differ significantly, although there seems to be a tendency for a small difference for low sun (wintertime). However, for low sun, pyranometer measurements are uncertain for different reasons, such as deviation from the ideal cosine response. The fact that there is convergence for high sun, suggests that both locations are comparable in terms of the bulk amount of solar energy that reaches the surface of the pyranometers. In view of the aforementioned WMO uncertainty of 5% for network operations, we conclude that there is no significant difference in global radiation at the two locations.

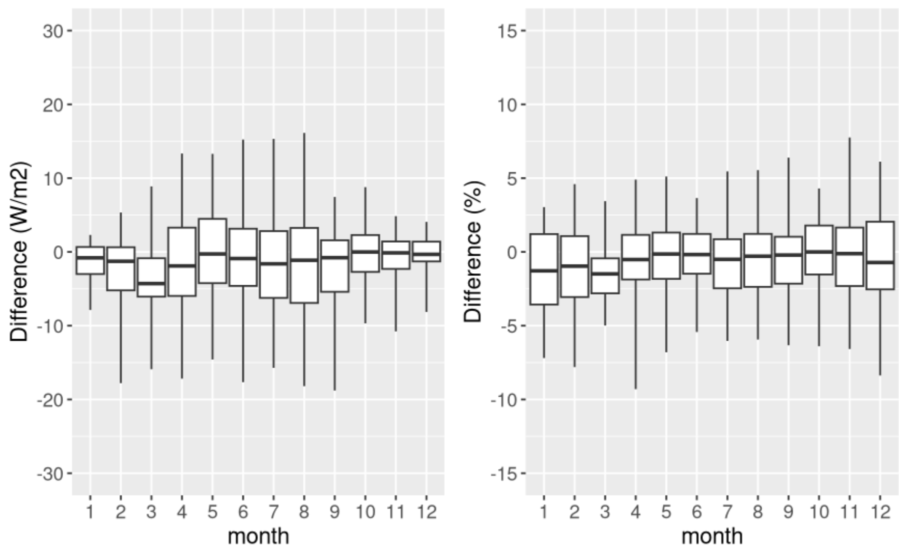

Figure 3.13: Boxplots of daily daytime (sza $\leq 85°$) global radiation differences between TD23 and TD-5_new from May 2021 through December 2023. On the left absolute differences, on the right percentage differences. See Figure 3.9 for an explanation of a box.

Chapter 4

Discussion and conclusions

Estimating the impact of the solar farm on Groningen Airport Eelde on the operational temperature measurements at the TD23 location could have been relatively easy, if all measurements at the airport could be trusted. Unfortunately, there were major problems with the temperatures at the backup location TD05. These backup temperatures are not routinely validated by KNMI. Assuming equal temperatures for cloudy and windy nighttime conditions, we selected a homogeneous period before (period I) and after (period II) the installation of the solar farm.

For period I, the results suggested TD23 being 0.26°C cooler for Tn than TD05. For Tmean an Tx both sites look the same in period I. Mainly because of Tn, TD05 and TD23 cannot be considered as climatologically equal locations. We can, however, use TD05 to estimate the impact of the installation of the solar farm by comparing the temperature differences in period II with those in period I. For Tmean this resulted in an increase of the annual mean Tmean of 0.03°C at TD23, an annual mean decrease of Tn of 0.07°C, and an annual mean increase in Tx of 0.13°C. Although these values are small, they differ for each season with the impact for Tx largest in spring and summer and the impact for Tn largest in autumn. Especially for wind flowing from the direction of the solar farm, there are large changes in the diurnal cycle of temperature.

An independent comparison between periods I and II, where the five closest inland AWSs were used as the reference, showed comparable results for Tmean and Tx. However, for Tn this comparison suggested an annual mean cooling –after the installation of the solar farm – of TD23 of about 0.32°C. This is much larger than the cooling resulting from the comparison with TD05.

The contradictory results for Tn are summarized in Table 4.1. This table also includes a comparison with NL24 containing all land AWS stations except Eelde and NL5. The independent comparisons of TD23 with NL5 and NL24

Reference	ΔTn_I	ΔTn_II	ΔTn_II-I
TD05	–0.26	–0.34	–0.07
NL5	–0.50	–0.82	–0.32
NL24	–1.11	–1.48	–0.37
TD23_new	-	–0.18*	-

Table 4.1: Annual mean differences in Tn (TD23 – reference) for periods I and II and their difference (II – I). *Calculated for the period May 2021–December 2023.

suggest both a large decrease of 0.32–0.37°C in Tn after the installation of the solar farm. This would be partly compensated for (about 0.2°C) when moving TD23 to TD23_new. The results imply that the use of TD05 as a reference in this study is, to some extent, questionable.

Assuming that the results for TD05 are indeed questionable, it is likely that they are only questionable in period I. This is because the independent comparison of TD05 with TD05_new in period II, showed no differences between the two locations. Consequently, the results (TD23 – TD05) in period II in Table 3.1 may give a good indication of the impact of the solar farm on temperature. The annual mean differences correspond well with those found from the comparison with the neighboring KNMI stations.

The mechanism responsible for the large change in Tn due to the solar farm is not clear and needs more research. There may, at least, be two possibilities. First, the solar farm increases the roughness of the area. This may cause smaller windspeeds close to the farm, resulting in increased nighttime stability near the ground and, thus, lower temperatures. Second, the solar park has probably a larger outward nighttime radiation than the surrounding area. This may cause stable air above the solar farm which may partly block the horizontal wind close to the solar farm. This may have a similar impact on temperatures as the increased roughness.

Based on the findings so far, a relocation of the temperature measurements at TD23 to TD23_new seems a logical step. This reduces the the jump in annual mean Tn from about 0.3° (NL5 comparison) to about 0.1°. In addition, it partly compensates for the higher Tx at TD23. This transition should be further monitored in the coming years.

As expected a relocation of TD05 to TD05_new has no noticeable impact on the temperature measurements.

The comparison of solar radiation measurements at TD23 and TD05_new gives no indication of an impact of the solar farm on these measurement.

Chapter 5

Recommendations

1. Make TD23_new the new operational location for temperature and global radiation measurements at Groningen Airport Eelde and monitor over the coming years the temperature differences with the surrounding stations.

2. Keep the temperatures measurements at TD23 operational till at least the end of 2026.

3. Make back-up locations – which are common practice at airports – part of the routine validation practice at KNMI.

4. Use the standard control procedures at regular AWS for all measurements at airports (e.g. operational validation and use of dummy sensors).

5. TD05_new can be used as the backup location for temperature.

6. Study the impact of the solar farm in more detail, for instance by (1) installing an array of low-cost stations between the edge of the solar farm and the runway, and (2) by making infrared photographs of the solar farm and its surroundings on clear and calm summer days and nights.

Acknowledgements

The author is grateful to his colleagues from the Observation Operations department for providing metadata of the measurements at Groningen Airport Eelde. He further thanks his colleagues Cees de Valk, Wiel Wauben and Wouter Knap for constructive comments on the manuscript. Wiel Wauben extracted the 10-min data from the MUF strings.

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Appendix A

Pyranometer metadata

Table A.1 gives details about the pyranometers that have been used at Groningen Airport Eelde in the study period. The pyranometers are described in [9].

Location	placed	removed	instrument	no.
TD05	29-01-2024	–	SMP-11	01.23.013-030
	28-03-2023	29-01-2024	SMP-11	01.23.013-026
	29-04-2021	28-03-2023	SMP-11	01.23.013-001
TD23	29-03-2024	–	SMP-11	01.23.013-033
	02-12-2022	29-03-2024	SMP-11	01.23.013-014
	20-05-2022	02-12-2022	CM-11	01.23.010-066
	02-07-2020	20-05-2022	CM-11	01.23.010-054

Table A.1: Details about the pyranometers used at Groningen Airport Eelde in the study period.

Appendix B

Temperature calibration results

Figure B.1 shows the temperature calibration curves for the four locations at Groningen Airport Eelde. The calibration curves have been determined in the KNMI calibration lab. The figure shows different calibration curves for the individual locations and periods. Once a sensor it taken out of the field it brought to KNMI for a new calibration. If the sensor still meets the specifications, it becomes part of the sensor pool and may be installed at any location. This is standard practice at KNMI. The corrected temperature equals the measured temperature plus the correction. Corrections for intermediate temperatures were obtained by linear interpolation.

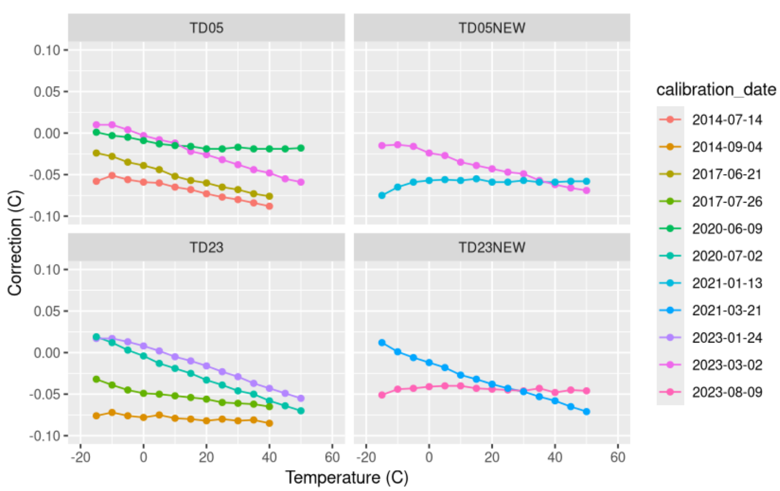

Figure B.1: Calibration curves of the sensors used at Groningen Airport Eelde. Calibration dates (yyyy-mm-dd) refer to the moment the sensors were placed in the field.

Appendix C

AWS station metadata

no.	station	lat (N)	lon (E)	alt (m)
06235	De Kooy Airport	52.93	4.78	1.20
06240	Schiphol Airport	52.32	4.79	-3.30
06249	Berkhout	52.64	4.98	-2.40
06251	Hoorn Terschelling	53.39	5.35	0.70
06260	De Bilt	52.10	5.18	1.90
06267	Stavoren	52.90	5.38	-1.30
06269	Lelystad Airport	52.46	5.52	-3.70
06270	Leeuwarden Airport	53.22	5.75	1.20
06273	Marknesse	52.70	5.89	-3.30
06275	Deelen Airport	52.05	5.87	48.20
06277	Lauwersoog	53.41	6.20	2.90
06278	Heino	52.43	6.26	3.60
06279	Hoogeveen	52.75	6.57	15.80
06283	Hupsel	52.07	6.66	29.10
06286	Nieuw Beerta	53.19	7.15	-0.20
06290	Twenthe Airport	52.27	6.89	34.80
06310	Vlissingen	51.44	3.60	8.00
06319	Westdorpe	51.22	3.86	1.70
06330	Hoek van Holland	51.99	4.12	11.90
06340	Woensdrecht Airport	51.45	4.34	19.20
06344	Rotterdam Airport	51.96	4.45	-4.30
06348	Cabauw	51.97	4.93	-0.70
06350	Gilze-Rijen Airport	51.56	4.94	14.90
06356	Herwijnen	51.86	5.15	0.70
06370	Eindhoven Airport	51.45	5.38	22.60
06375	Volkel	51.66	5.71	22.00
06377	Ell	51.20	5.76	30.00
06380	Maastricht Airport	50.91	5.76	114.30
06391	Arcen	51.50	6.20	19.50

Royal Netherlands Meteorological Institute

PO Box 201 | NL-3730 AE De Bilt
Netherlands | www.knmi.nl