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# Analysis of parallel measurements of the automatic weather stations Valkenburg and Voorschoten in the Netherlands

Theo Brandsma

De Bilt, 2022 | Technical report; TR-394

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# Contents

# Summary

This document describes the analysis of the parallel measurements between the two coastal automatic weather stations (AWS) Valkenburg (06210) and Voorschoten (06215) in the Netherlands. The airport station Valkenburg was relocated to Voorschoten on 16 July 2014 because the airport was given another destination. The airport is located at a distance of 4.2 km from the coast while AWS Voorschoten is located 2.2 km further inland. Besides differences in distance to the coast, their situation with respect surrounding urban areas differs. Both stations operated in parallel until 2 May 2016, when the measurements at AWS Valkenburg had to be terminated due to construction activities. The measurements of the period August 2014–April 2016 have been used for studying the climatological differences between the two sites. Despite the relatively small distance between the two stations, the results show statistically significant differences for most weather variables. For climatological applications, AWS Voorschoten can, therefore, not be considered as a continuation of AWS Valkenburg. Depending on the application, corrections can be made using the parallel measurements to obtain homogeneous time series.

# 1 Introduction

## 1.1 Background

Changes in the measurement infrastructure are sometimes unavoidable. This often involves a forced relocation (e.g. due to cancellation of land leases) or relocations due to changes in the direct surroundings of the measurement site. In the latter case, the measurements are often no longer representative of the area surrounding the station. Changes in infrastructure may also result from the desire to be more cost efficient or to improve the quality of measurements by, for example, better sensors and/or screens.

Both changes in the measurement infrastructure or conditions often lead to inhomogeneities in measurement series. For climate research and applications these artificial (not caused by the climate) jumps or trends are undesirable and should thus be limited as much as possible. It is essential to recognize and quantify such jumps or trends so that it is possible to correct for them. Otherwise such an artificial inhomogeneity could be wrongly interpreted as a change of climate.

The KNMI Protocol Measurement Infrastructure Changes (PVM) [2] ensures that (a) inhomogeneities are minimized, and (b) where changes are inevitable, that timely and accurate assessment of the magnitude of any inhomogeneity is made and communicated in the right way. Parallel measurements in the 'old' and 'new' situation may be part of this. This makes correction possible, and is thus part of the quality assurance of all climatological observations carried out under the responsibility of the KNMI. In this way, PVM contributes to our computation of reliable trends and variability in climate variables on well homogenized series.

PVM also helps to implement the GCOS (Global Climate Observing System) principles of climate monitoring [6] at KNMI. GCOS has prepared a list of Essential Climate Variables, this is a list of variables to be observed, which are essential for climate monitoring and research. A number of these variables are relevant for KNMI. For these PVM is applicable. It concerns both land and maritime observations.

For a relocation of a weather station or relocation of one or more instruments PVM prescribes:

1. In case of an essential relocation of a complete weather station or of one or more instruments outside the measurement site, parallel measurements will always be performed to examine the effects for KNMI's relevant ECVs. One speaks of an essential relocation if the movement is more than 100 m, or the movement is to a location, which is different in terms of surrounding of the previous one. It is only allowed to deviate from this rule in case of compelling reasons (force majeure) and after assessment by the Observations Advisory Group.

2. Parallel measurements are implemented for a standard period of 2 years. This period is equal to the WMO directive.

3. The results of the parallel measurements are documented in a public report. The metadata published on the internet noting the change references this report.

4. In case of significant differences between the old and new location, the report indicates whether and how the measurements of the two locations can be combined with one another.

5. The old location will only be terminated after completion of the report mentioned under (4), which makes clear whether the new measurement is considered a continuation of the old station or a new station.

6. When the need arises only the KNMI Observations Advisory Group can decide to deviate from the above points.

## 1.2 The relocation of AWS Valkenburg to Voorschoten

The relocation of AWS Valkenburg to Voorschoten is an essential relocation, since the relocation is more than 100 m from the previous one and to an area with different surroundings (2.2 km further inland). PVM prescribes 2 years of parallel measurements between the two sites.

The PVM prescriptions of 2 years of parallel measurements (2) and termination of the station after completion of the report about the parallel measurements (5) could not be met. First, the exact closure time of AWS Valkenburg was unknown, depending on the progress of construction activities at the airport. Second, KNMI was hesitant establishing a new site, probably related to reorganization and savings at that time. In the end, fortunately 21 months of parallel measurements could be performed before the closure of AWS Valkenburg.

## 1.3 Scope and Objectives

The objective of this report is to document the results of the parallel measurements between AWS Valkenburg and AWS Voorschoten. For the ECVs the report indicates whether and how the measurements of the two locations can be combined with one another. The comparison is restricted to the 21 month period August 2014 until April 2016. The variables being studied are: air temperature, humidity, wind speed and direction, global radiation, precipitation, cloudiness and visibility. The latter two variables were not mandatory for the comparison and have only been measured in a 7 month period. Air pressure is not considered as the differences on a spatial scale of 3.2 km (inter-station distance) can be considered negligible.

# 2 Data and methods

## 2.1 Data and instruments

Figure 2.1 shows a map of the two stations in the coastal area of the Netherlands. The figure shows the location of the stations with respect to the North Sea (upper left corner) and with respect to surrounding urban areas. The distance of AWS Valkenburg to the coast equals 4.2 km while Voorschoten is situated 2.2 km further inland at a distance of 6.4 km from the coast. The mutual distance between the stations equals 3.2 km.

Both stations are situated in a flat area. Valkenburg is surrounded by urban areas in all directions except for directions between southwest and northwest. Voorschoten is almost completely surrounded by urban areas. The main difference between the two stations is Valkenburg being closer to the dune area and sea than Valkenburg.

Figures 2.2 and 2.3 show photographs (in westerly direction) of AWS Valkenburg and AWS Voorschoten, respectively. Both stations are situated in open


Figure 2.1: Map of the area surrounding AWS Valkenburg and AWS Voorschoten.


Figure 2.2: AWS Valkenburg (in westerly direction).

| Name | WMO no. | Height (m) | Lat (N) | Lon (E) |
|---|---|---|---|---|
| Voorschoten | 06215 | -1.15 | 52.14 | 4.436 |
| Valkenburg | 06210 | -0.20 | 52.17 | 4.429 |

Table 2.1: Metadata of AWS Valkenburg and AWS Voorschoten.

grassland areas. The stations are equipped with standard KNMI sensors. The following variables are measured: temperature, relative humidity, wind speed and -direction, global radiation, precipitation, air pressure, cloudiness and horizontal visibility. Stations are operated following WMO guidelines as formulated in the CIMO-guide [5]. Further details can be found in the KNMI Handboek Waarnemingen [1] (This document is being updated).

Details of the two stations are presented in Table 2.1. Table 2.2 presents the so-called CIMO station classification for the relevant variables (see [5] for explanation of the classes). The table shows that Valkenburg and Voorschoten have identical CIMO classifications.

Table 2.3 shows the instrument measurement uncertainty for all relevant


Figure 2.3: AWS Voorschoten (in westerly direction).

| Name | No. | T/RH | Prec. | Wind | Env. | Q | Inspection date |
|---|---|---|---|---|---|---|---|
| Valkenburg | 06210 | 1 | 1 | 4-5 | 2 | 1 | 20140630 |
| Voorschoten | 06215 | 1 | 1 | 4-5 | 2 | 1 | 20160818 |

Table 2.2: CIMO station classification of AWS Valkenburg and AWS Voorschoten.

variables as prescribed by WMO [5] and realised by KNMI. For the comparison in this report, it is important to know these uncertainties. For instance, when – for a specific variable – the uncertainty is larger that the inter-station differences, the results should be handled with care. The instrument measurement uncertainty is determined in laboratory conditions. In the field the measurement uncertainty is also affected by other factors like maintenance, environmental effects and instrument coupling. These factors are considered the same for Valkenburg and Voorschoten and are assumed to have no effect on the comparison.

The stations Valkenburg and Voorschoten operated in parallel from 16 July 2014 until 2 May 2016. From May 2 onwards the measurements at the airport

| Variable | WMO | KNMI |
|---|---|---|
| Temperature | 0.1 K | 0.1 K |
| Relative humidity | 1% | 1% |
| Cloud amount | 1/8 | 1/8 |
| Wind speed | 0.5 m/s for ≤ 5 m/s<br>10% for > 5 m/s | 0.1 m/s for ≤ 5 m/s<br>2% for > 5 m/s |
| Wind direction | 5° | 3° |
| Precipitation int. | n/a for 0.02–0.2 mm/h<br>0.1 mm/h for 0.2–2 mm/h<br>5% for > 2 mm/h | 3% |
| Global radiation | 2% | 1% |
| Visibility (MOR) | 50 m for ≤ 600 m<br>10% for > 600 m– ≤ 1500 m<br>20% for > 1500 m | 10% for 10 m–10 km<br>20% for 10-50 km |

Table 2.3: Instrument measurement uncertainty, guideline of WMO and obtained by KNMI. MOR stands for Meteorological Optical Range; cloud amount ranges between 0/8–8/8.

of Valkenburg were terminated. Here we consider only the months with complete data August 2014 until April 2016 (21 months).

## 2.2 Methods

Depending on the variable of interest we compare the monthly values and/or daily values. Hourly values are used to compare diurnal cycles or frequency distributions, wherever applicable. In all cases validated hourly values are the basis for derived daily or monthly values.

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 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 $\rho$ is the autocorrelation coefficient.

# 3 Results

In this section we compare Voorschoten and Valkenburg for respectively temperature, humidity, windspeed, global radiation, rainfall,cloudiness and visibility. The monthly results are summarized in appendix A.

## 3.1 Monthly time series

Figure 3.1 shows the monthly time series of a selected set of variables of Valkenburg. The figure gives an impression of the variability of the weather conditions during the measuring period as compared tot the 30-year mean values. For instance, the figure shows an unusual warm December month in 2015. Note also the large month-to-month variability of rainfall amounts in the second half of the measurement period. Such variability is common in the climate of the Netherlands.

## 3.2 Temperature

Figure 3.2 shows the mean diurnal temperature cycle of Valkenburg and the difference Voorschoten–Valkenburg in winter (DJF), spring (MAM), summer (JJA) and autumn (SON). The diurnal cycle is affected by the vicinity of the sea causing autumn to be warmer and spring cooler than inland stations. The temperature differences between the diurnal cycles of Voorschoten and Valkenburg illustrate the effect distance to the coast. Although Voorschoten is situated only 6.4 km from the coast its temperatures show a more continental character than Valkenburg situated 4.2 km from the coast.

Figure 3.3 shows the monthly mean temperature differences and their $2se^{*}$ values. The figures shows the largest variations for the minimum temperature Tn and the smallest for the mean temperature Tmean. With respect to Tn Voorschoten is mostly cooler than Valkenburg. For the maximum temperature Tx Voorschoten is warmer than Valkenburg in winter and spring and cooler in the beginning of the summer. For Tmean the differences are close to zero but Voorschoten has a tendency to be cooler from July onward. Note the

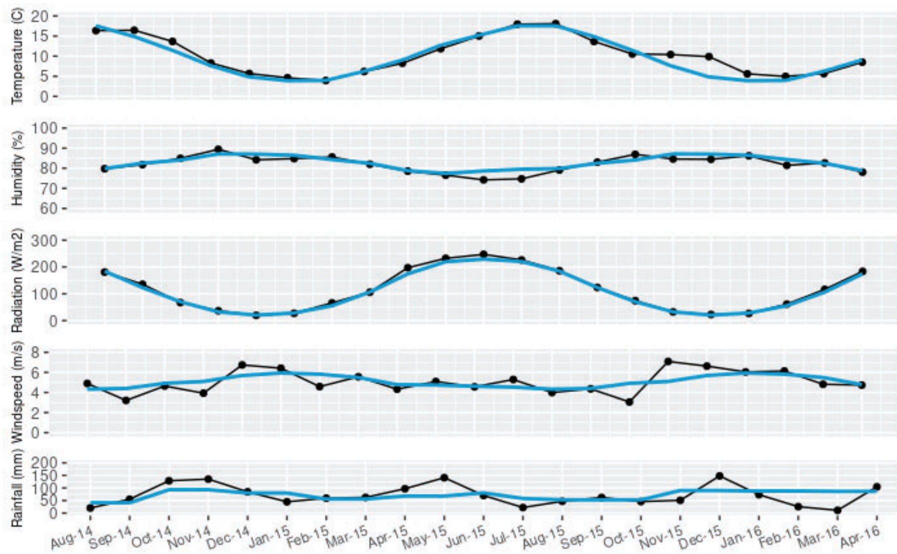


Figure 3.1: Monthly time series of selected meteorological variables for Valkenburg in the August 2014–April 2016 period. The blue lines give the 30-year mean values (1986-2015).

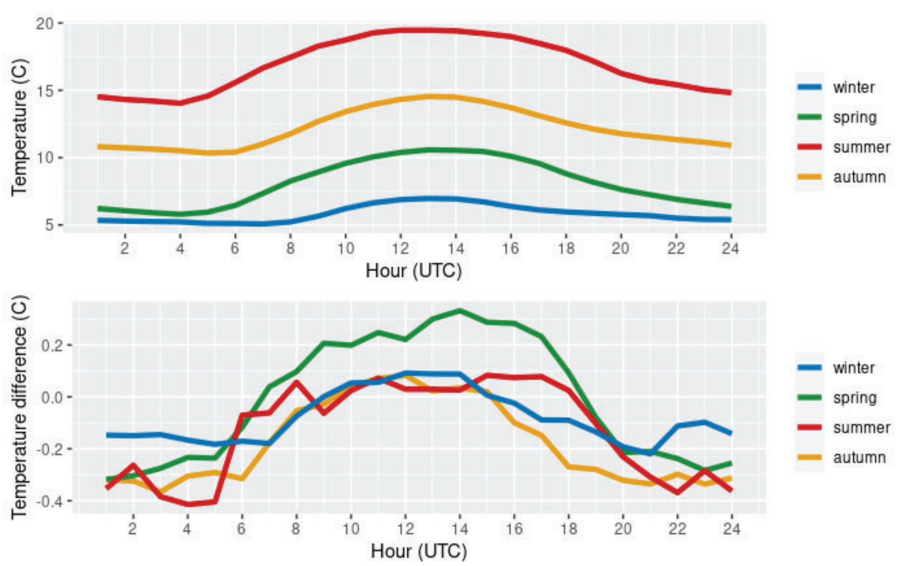


Figure 3.2: Seasonal mean daily temperature cycle of Valkenburg (top) and the differences Voorschoten – Valkenburg (bottom) in the August 2014–April 2016 period.

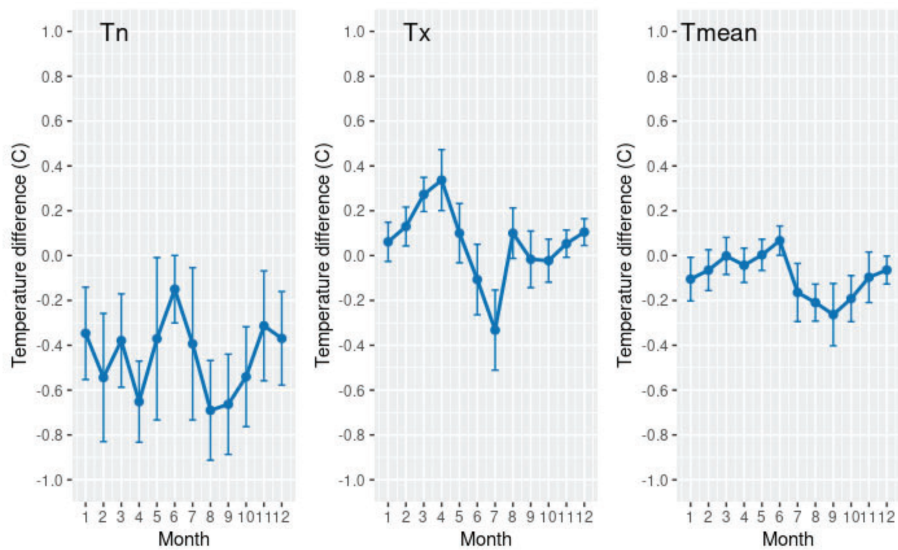


Figure 3.3: Monthly mean temperature differences (Voorschoten – Valkenburg) for minimum (Tn), maximimum (Tx) and mean (Tmean) temperatures in the August 2014–April 2016 period. The error bars present the 2xse* values.

seasonal variation in the temperature differences, which is probably related to the difference in distances to the nearby North Sea.

From the figure we can conclude that with respect to temperature Voorschoten is climatologically different from Valkenburg. Tn temperature differences vary between –0.15°C in June and –0.69°C in August and are all significantly different from zero. Tx differences vary between 0.34°C in April and –0.33°C in July and are significant except for the autumn months. Tmean differences vary between 0.07°C in June and –0.26°C in September and are significant from about July to January.

Although the stations are almost equal with respect to CIMO classification, there are differences in the positioning of the stations with respect to the coast and the surrounding areas (urban, sea, dune). It is therefore of interest to have a further look at the temperature differences as a function of wind direction. We used the hourly temperatures and wind directions and distinguished between nighttime and daytime temperatures. Nighttime temperatures are defined here as temperatures in the interval 20–4 UTC and daytime temperatures in the interval 10–16 UTC. Wind direction has 36 classes and ranges from 10° to 360°, where 90° corresponds to Easterly, 180° to Southerly, 270° to Westerly and 360° to Northerly directions. Here wind direction of

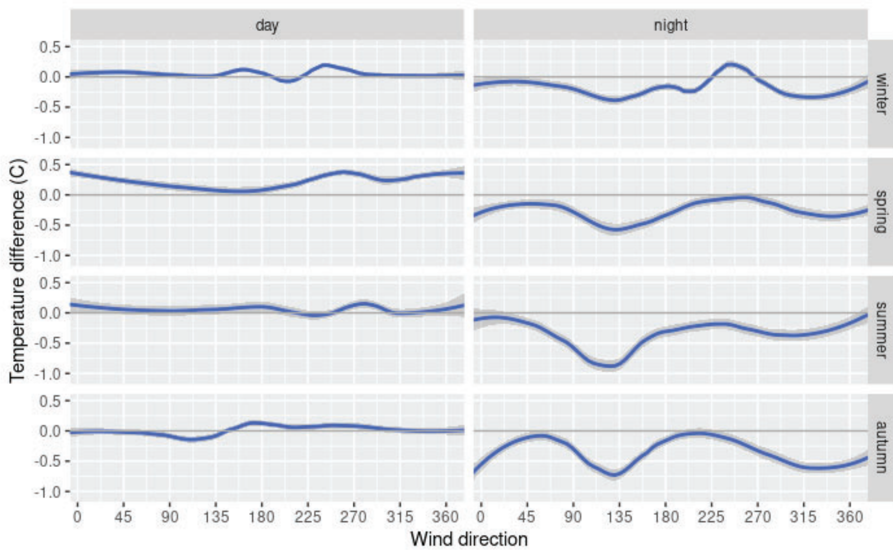


Figure 3.4: Smoothed hourly temperature differences (Voorschoten – Valkenburg) as a function of wind direction for each season and for daytime (10-16 UTC) and nighttime (20–4 UTC) hours. The shaded areas surrounding the curves present the 95% confidence intervals.

Valkenburg has been used. Temperature differences have been calculated for daytime and nighttime conditions and for each season.

Figure 3.4 shows the the smoothed temperature differences (Voorschoten–Valkenburg). We use smoothed differences as this helps the eye to pick up the trends. To prevent a jump between 360° and 10° we added 10-30° values after 360° and the 340-360° values after before 10°. Especially for nighttime conditions the figure shows a clear relationship with wind direction which is consistent throughout the seasons. It seems, however, difficult to attribute individual temperature differences to specific characteristics of the surroundings. The observed temperature differences are likely caused by a combination of distances to the coast and to nearby urban areas and differences in characteristics of the surrounding rural areas.

## 3.3 Humidity

For humidity we consider the absolute humidity instead of relative humidity. The latter is strongly correlated with temperature and therefore less suitable for comparing several sites. Absolute humidity (or vapor density) is calculated as follows.

For the water the saturation vapor pressure $e^*$ is defined as [1]:

$$e^* = 6.112 e^{\frac{17.62 T_c}{T_c + 243.12}} \tag{3.1}$$

where $T_c$ is air temperature in Celsius. Vapor pressure $e$ is then calculate as

$$e = RHe^*/100 \tag{3.2}$$

where $RH$ is relative humidity in %.

Finally the vapor density $\rho_v$ (absolute humidity) is calculated as

$$\rho_v = 2.17e/T_k \tag{3.3}$$

where $\rho_v$ in gm$^{-3}$, $e$ in Pa and $T_k$ is air temperature in Kelvin.

Figure 3.5 (top) shows the diurnal cycle of absolute humidity in Valkenburg. Compared to temperature, absolute humidity exhibits only a small diurnal cycle with the daytime values slightly larger than the nighttime values. There are however large seasonal differences, with the largest values in summer and autumn and the smallest values in winter and spring.

The diurnal cycle differences Voorschoten–Valkenburg (bottom) are generally small. Only the daytime values in summer and autumn show clear differences with Voorschoten having up to 3% larger absolute humidity than Valkenburg.

Figure 3.6 shows the mean monthly humidity differences. In the period June-October Voorschoten is more humid than Valkenburg. The largest monthly difference in absolute humidity equals 0.37 gm$^{-3}$ and is found in July (corresponding to a relative humidity difference of 77.1–74.7 = 3.0%).

The reason for Voorschoten being slightly more humid than Valkenburg in summer and autumn might be the results of local groundwater level differences and/or differences in soil type in the neighborhood of the sites. The position of the groundwater level in combination with soil type, determines to a great extent whether or not a soil dries out. In the Netherlands, this normally only occurs in dry summers. Drying out of the soil causes a decrease of the latent heat flux and an increase of the sensible heat flux, thus increasing the local temperature. Local vapor pressure differences may be an indication of differences in soil dryness. Dune areas are sensitive to drying out in summer and autumn. The situation of Valkenburg along the dune area may be an explanation for the observed differences.

## 3.4 Wind speed

Wind speed in the Netherlands decreases inland. Both Valkenburg and Voorschoten are close to the coast with Voorschoten 2.2 km further inland. The

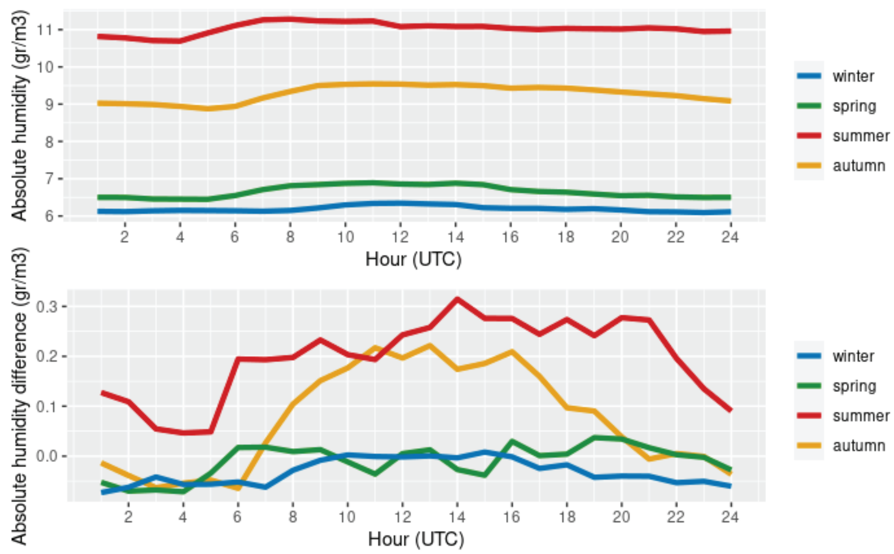


Figure 3.5: Seasonal mean diurnal absolute humidity cycle of Valkenburg (top) and the differences Voorschoten – Valkenburg (bottom) in the August 2014–April 2016 period.

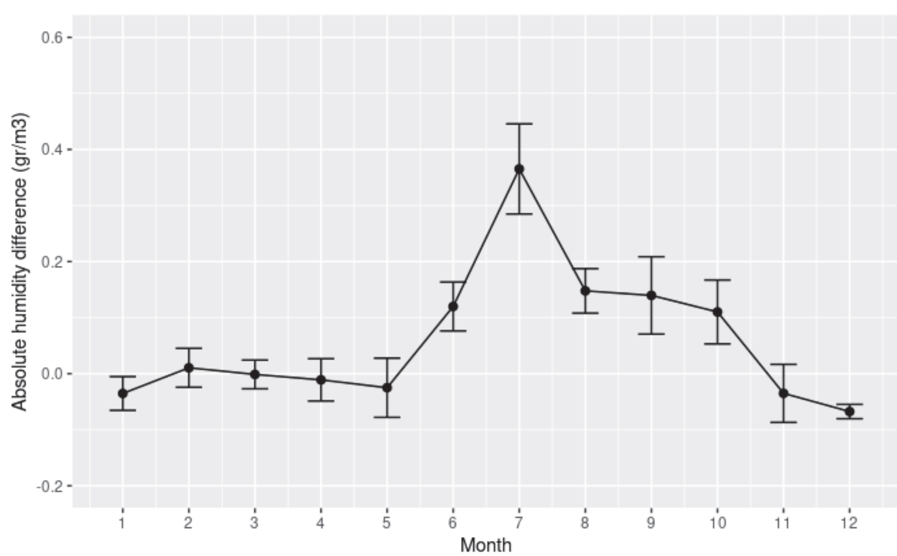


Figure 3.6: Monthly mean humidity differences (Voorschoten – Valkenburg) in the August 2014–April 2016 period. The error bars present the 2xse* values.

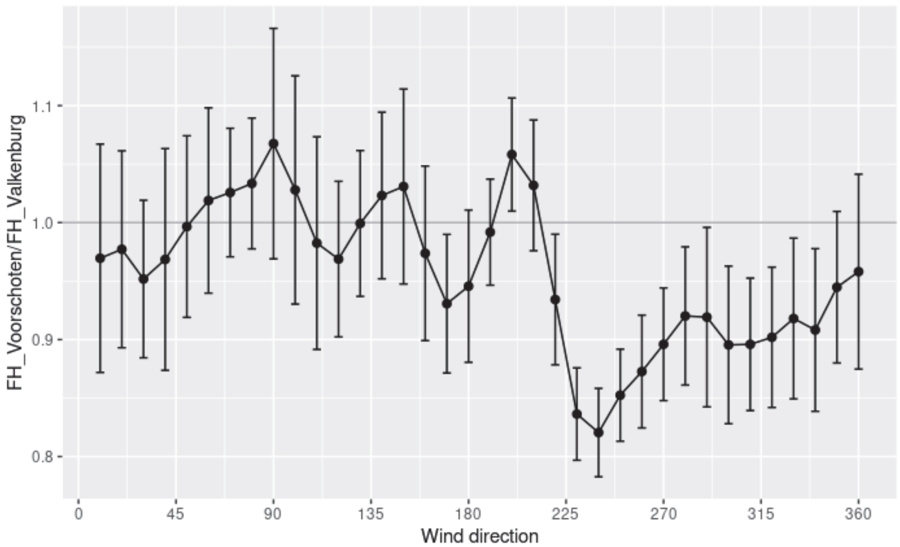


Figure 3.7: Ratio of the mean hourly windspeed of Voorschoten and Valkenburg in the August 2014–April 2016 period as a function of wind direction. The error bars present 2xse values.

mean wind speed differences between both sites are small. In 2015 e.g. the annual mean wind speed at the AWS of Valkenburg was 5.1 m/s and in Voorschoten 4.8 m/s. Our main interest here is to investigate if the wind speeds at the Valkenburg and Voorschoten locations differ with respect to wind direction. This is related to differences in upstream roughness at both stations.

Figure 3.7 compares the mean hourly wind speeds of Voorschoten with Valkenburg as a function of wind direction. The figure shows that wind speeds at Voorschoten and Valkenburg differ for wind from the North Sea (225–360°).

Another approach to compare both locations with respect to wind speed is to calculate the exposure correction factors. Wind direction dependent exposure correction factors have been used in the Netherlands for the calculation of potential wind speed. Potential wind speed is the wind speed at 10 m height when there are no obstacles (upstream surface roughness equals 3 cm). Multiplication of hourly wind speeds by the exposure correction factors yields the potential wind speed. Exposure correction factors are calculated here from all hourly mean wind speeds > 5 m/s and the accompanying hourly maximum wind gust as described by Verkaik [4]. In general, exposure correction factor > 1.2 are considered too large to calculate potential wind speeds.

Figure 3.8 shows the exposure corrections as a function of wind direction.

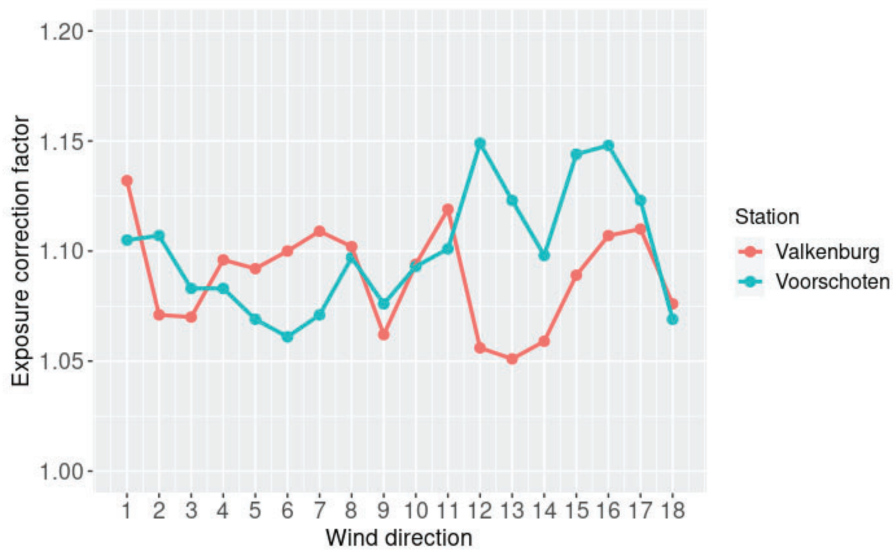


Figure 3.8: Exposure correction factor in the May 2015–April 2016 period. Wind direction is grouped in 18 categories (1 = 10–20, 2 = 30–40,..., 18 = 350–360 degrees).

The factors are < 1.2 for all wind directions. Mainly for wind directions ranging between 230–320° the upstream roughness of Voorschoten is larger than for Valkenburg. In worst case, the differences are up to 10% for the 230–240° category. This is of the same order as the achievable measurements uncertainty of 10% for windspeed > 5 m/s as defined in [5]. Station Voorschoten can, therefore, be considered as a continuation of Valkenburg when the series are connected by applying the exposure correction factors.

## 3.5 Global radiation

Just like wind speed, global radiation in the Netherlands decreases inland. Because of the small distance between Valkenburg and Voorschoten, the mean global radiation differences are small. In 2015 the mean global radiation at AWS Valkenburg was 128.3 W/m2 and and in Voorschoten 126.6 W/m2. This is a difference of about 1%. On average global radiation along the North Sea coast is about 10% larger than in the Eastern part of the country.

Figure 3.9 (top) shows the diurnal cycle of global radiation in Valkenburg. Just like temperature, global radiation exhibits a strong diurnal cycle during daytime but with zero values during the night. There are large seasonal differences, with the largest values in summer and spring and the smallest values

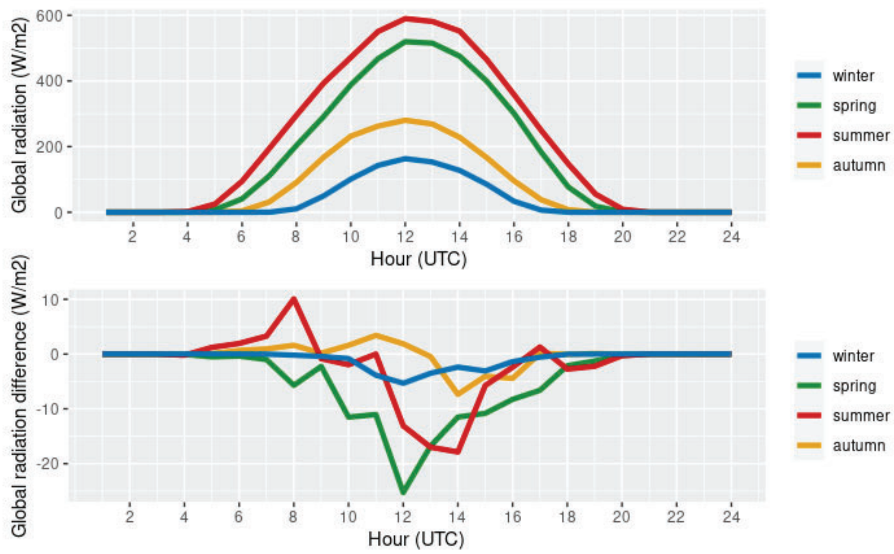


Figure 3.9: Seasonal mean daily global radiation cycle of Valkenburg (top) and the differences Voorschoten – Valkenburg (bottom) in the August 2014–April 2016 period.

in winter and autumn.

The diurnal cycle differences Voorschoten–Valkenburg (bottom) are relatively small compared to the absolute values. The values are largest for spring, up to 25 W/m2 at 12 UTC (5%). In winter and autumn the differences are small.

## 3.6 Rainfall

Rainfall amount varies strongly in space and time. In addition, in the Netherlands the North Sea affects the regional distribution of rainfall amounts in some months. In May-June the relatively cold sea water suppresses rainfall development, yielding about 20% smaller amounts in the western part of the country compared to the eastern part of the country. On the other hand, in September-November the relatively warm sea water stimulates rainfall development, yielding about 30% larger amounts in the western part of the country compared to the eastern part.

Figure 3.10 shows the monthly rainfall amount, duration and intensity of both stations (where intensity equals amount divided by duration). The monthly amount of Voorschoten is greater than that of Valkenburg in 19 of the 21 months. On average the monthly rainfall amount of Voorschoten is


Figure 3.10: Monthly time series of rainfall amount (top), duration (middle) and intensity (bottom) for Valkenburg and Voorschoten in the August 2014–April 2016 period.

7 mm greater than that of Valkenburg (about 10%). This difference is strongly significant because the standard error of the monthly differences equals only 1.2 mm. The monthly rainfall duration of Voorschoten is also greater than that of Valkenburg but only in 14 of the 21 months. On average, monthly rainfall duration of Voorschoten is 1.2 hours greater than that of Valkenburg with a standard error of 0.8 hours. Considering a mean rainfall intensity of 1.3 mm/hour the 1.2 hours equal about 1.6 mm rainfall amount.

Finally, the monthly rainfall intensity of Voorschoten is greater than that of Valkenburg in 15 of the 21 months. On average the monthly rainfall intensity of Voorschoten is 0.09 mm/hours greater than that of Valkenburg with a standard error of 0.03 mm/hours. Considering a mean number of 60 rain hours, the 0.09 mm/hours equals about 5.4 mm of rainfall depth.

Summarizing, the monthly mean difference of 7 mm in rainfall amount is mainly (for 77%) a result of a greater rainfall intensity in Voorschoten in the period considered. The effect of rainfall duration is much smaller (2%).

## 3.7 Cloudiness and visibility

Cloudiness and horizontal visibility were not mandatory for the parallel measurements. Nonetheless, validated hourly values were available for the 7-

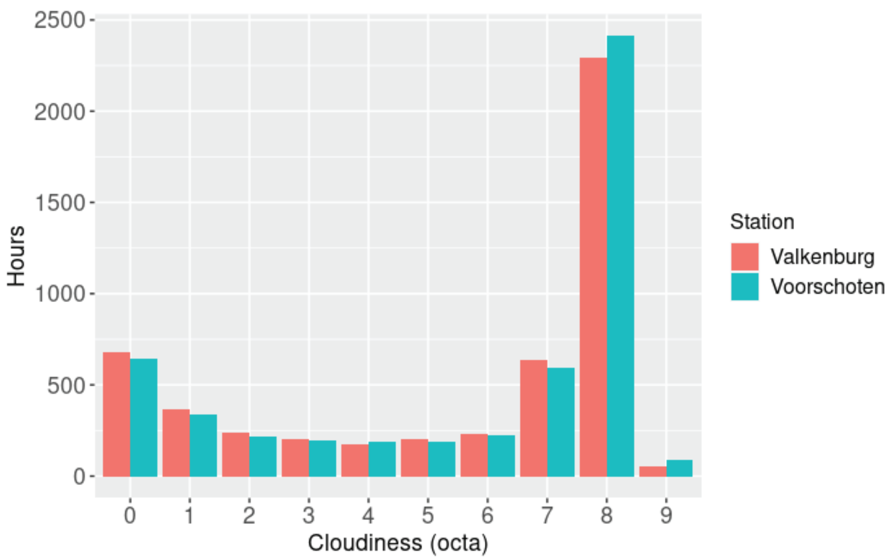


Figure 3.11: Frequency distribution of hourly cloudiness for Valkenburg and Voorschoten in the August 2014–February 2015 period. Okta values range between okta = 0 (clear-sky) and okta = 8 (overcast); okta = 9 means sky obscured.

month period August 2014 – February 2015 and will be considered here.

### Cloudiness

Figure 3.11 compares the cloudiness occurrences (ceilometer values) of Valkenburg and Voorschoten. The figure shows only small differences between the stations with Valkenburg 5% more clear-sky hours (okta = 0) and Voorschoten 5% more overcast hours (okta = 8). In spring and early summer the differences will probably be somewhat more pronounced because of the then relatively cold sea water.

### Visibility

Figure 3.12 compares the visibility (MOR) of Valkenburg and Voorschoten. Visibility is grouped in four categories where visibility $< 1.0$ km is defined as fog in the Netherlands. Fog situations are potentially dangerous e.g. for traffic. The figure suggest that Voorschoten has more fog conditions than Valkenburg. In Voorschoten 5.5% of the total number hours are considered as fog against 2.7% for Valkenburg. Although we only considered 7 months of

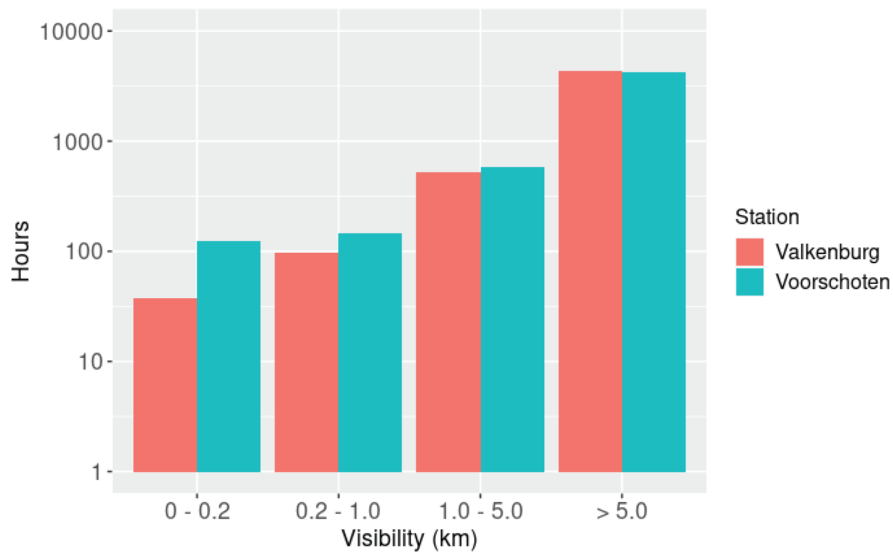


Figure 3.12: Frequency distribution of visibility for Valkenburg and Voorschoten in the August 2014–February 2015 period. Note the logarithmic scale of the y-axis.

data, this difference may be real and is also supported by the greater absolute humidity and lower wind speeds at Voorschoten.

# 4 Discussion

The results in this report show the differences between the measurements at the Valkenburg and Voorschoten location in the 20 month period August 2014 until April 2016. Although for most variables the differences are small, they are statistically significant. In addition, the differences are mostly larger than instrument measurement uncertainties in Table 2.3. Together this suggests a real climatological difference between the station locations Valkenburg and Voorschoten.

It is known that along the Dutch coast steep gradients exist in variables like temperature, wind speed and global radiation. For instance Slob [3] analysed 2 years of measurements in a cross section of 13 km perpendicular to the coast about 5 km north of Hoek van Holland. The study was restricted to temperature, wind speed, global radiation and long-wave radiation.

The mean temperature differences in Slob between a station 13 km from the coast and a station 0.7 km from the coast show the same seasonal patterns as found here for Valkenburg and Voorschoten, though the magnitude of the differences is somewhat smaller here. For global radiation, Slob found a annual difference of +3% between the coast and 10 km land-inward. The +1% differences between Valkenburg and Voorschoten are in line with the findings of Slob. Slob measured wind speed only at a selected set of stations. The decrease in annual mean wind speed of 0.3 m/s from Valkenburg to Voorschoten is of the same order of magnitude as the decreases found by Slob for a comparable inter-stations distance.

With respect to absolute humidity, Voorschoten is more humid than Valkenburg, especially in summer and autumn. The reason for the difference is probably a difference in groundwater level. Valkenburg is situated in the dune area and Voorschoten in pasture. Dune area's usually have deeper groundwater levels than pasture, where groundwater levels are generally artificially controlled. This is particularly relevant in summer and autumn when precipitation deficits are largest.

Rainfall amount in Voorschoten is about 10% larger than in Valkenburg. This is relatively large, considering the small difference in distance to the coast (2.2 km). The rainfall difference is the mainly the result of a greater rainfall intensity in Voorschoten. Rainfall duration is also larger in Voorschoten but this effect much smaller than the effect of rainfall intensity. It is known that in spring and early summer the relatively cold sea water suppresses rainfall development. This effect decreases with distance to the coast. In contrast, in September-November the relatively warm sea water stimulates rainfall development, stimulating rainfall along the coast. Apparently this effect has its maximum not directly on the coast but somewhat further inland.

For cloudiness, Valkenburg has 5% more clear-sky hours (okta = 0) and Voorschoten 5% more overcast hours (okta = 8). This is in line with the differences found in global radiation and rainfall amount. With respect to visibility, Voorschoten has more problems with fog than Valkenburg. In Voorschoten, 5.5% of the total number hours are considered as fog, against 2.7% for Valkenburg. This is supported by the greater absolute humidity and lower wind speeds at Voorschoten.

The observed climatological differences between Voorschoten and Valkenburg can mainly be attributed to their mutual differences in distance to the coast. However, differences in soil type, ground water levels, and situation with respect to surrounding urban areas may also play a role.

# 5 Conclusions and recommendations

In conclusion, the relocation of AWS Valkenburg to Voorschoten resulted in significant changes in the meteorological variables. As a result, for climatological studies, Voorschoten cannot be considered a continuation of Valkenburg. Depending on the type of study and the variable of interest, corrections have to be made for some or all of the seasons when the series of Voorschoten are begin used as a continuation of those of Valkenburg. These correction may be monthly mean corrections, daily or even hourly corrections. The data described in this study can be used to derive the corrections.

Below we give some general recommendations for trends studies of each of the investigated variables. In all cases, it is assumed that Valkenburg series are corrected to the corresponding Voorschoten series.

**Temperature** Tn differences between Voorschoten and Valkenburg are significant for each season and are much larger than the measurement uncertainty. For Tx and Tmean, the differences are much smaller and limited to specific seasons. When studying e.g. long term changes in annual mean temperatures, the inhomogeneity in Tn cannot be neglected. When considering seasonal trends, inhomogeneities in Tx and Tmean should also be considered. Smoothed monthly mean differences can be used as corrections.

For trend studies using daily indices (for instance the annual number of days with Tx $\geq$ 25°C), the series may be corrected with methods like percentile matching. However, the length of the parallel series may be too short for this purpose.

**Humidity** Absolute humidity differences between Voorschoten and Valkenburg are mainly significant in the period June–October, up to 3% in July. Trend studies for absolute humidity are not common, but if they are undertaken on the combined series, it is recommended to correct the monthly series using smoothed monthly differences.

**Wind speed** The direction dependent wind speed differences between Voorschoten and Valkenburg are small but have to be taken into account when both series are combined for trend studies or extreme values analysis. It is recommended to transform both series to potential wind series using the exposure correction factors before performing these studies or analysis.

**Global radiation** Global radiation differences between Voorschoten and Valkenburg are small on the annual scale (1%) and vary between −3.5% in April and 0.6% in October. For trend studies using the combined series, correction can be imposed using a smoothed version of the monthly differences

**Rainfall** The monthly mean rainfall amounts of Voorschoten are about 10% greater than the amounts of Valkenburg. For annual or seasonal trend studies on the combined series, it is recommended to correct the monthly series using smoothed monthly differences. For studies on daily indices, it is recommended to correct the daily values using the same monthly differences. As an alternative, percentile matching could be used to correct the series.

**Cloudiness and visibility** The results suggest both cloudiness and hours with fog being slightly greater in Voorschoten than in Valkenburg. Although the analysis was only for a 7-month period, it is recommended to be aware of possible differences for trends studies on cloudiness and fog when both series are combined.

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# A Monthly corrections

Table A.1 summarizes the monthly corrections needed to correct Valkenburg to Voorschoten (or the other way around). We advise to smooth the correction before applying them. A basic smooth for a specific month could be the sum of two times the correction for that month and one time the correction for the neighboring months and then dividing the result by four.

| | Jan | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|---|
| TN (C) | -0.35 | -0.54 | -0.38 | -0.65 | -0.37 | -0.15 |
| TX (C) | 0.06 | 0.13 | 0.27 | 0.34 | 0.10 | -0.11 |
| Tmean (C) | -0.10 | -0.06 | 0.00 | -0.04 | 0.00 | 0.07 |
| $\rho_v$ (g/m3) | -0.04 | 0.01 | 0.00 | -0.01 | -0.03 | 0.12 |
| Q (W/m2) | -0.51 | -2.07 | -3.42 | -6.71 | -3.86 | -2.60 |
| P ( / ) | 1.08 | 1.07 | 1.19 | 1.09 | 1.16 | 1.09 |

| | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|
| TN (C) | -0.39 | -0.69 | -0.66 | -0.54 | -0.31 | -0.37 |
| TX (C) | -0.33 | 0.10 | -0.02 | -0.02 | 0.05 | 0.10 |
| Tmean (C) | -0.16 | -0.21 | -0.26 | -0.19 | -0.10 | -0.06 |
| $\rho_v$ (g/m3) | 0.37 | 0.15 | 0.14 | 0.11 | -0.04 | -0.07 |
| Q (W/m2) | -1.74 | -1.72 | -1.06 | 0.39 | -0.08 | -0.20 |
| P ( / ) | 1.23 | 1.07 | 1.10 | 1.07 | 1.04 | 1.16 |

Table A.1: Monthly corrections (Voorschoten – Valkenburg) for temperature (TN, TX and Tmean), absolute humidity ($\rho_v$), global radiation ($Q$), and (Voorschoten/Valkenburg) for precipitation ($P$)

Table A.2 summarizes exposure correction factors (ECF) for Voorschoten and Valkenburg. After correcting each series using the ECFs they can be connected to form one series of potential windspeed.

| DD | ECF_215 | ECF_210 |
|---|---|---|
| 1 | 1.105 | 1.132 |
| 2 | 1.107 | 1.071 |
| 3 | 1.0831 | 0.070 |
| 4 | 1.083 | 1.096 |
| 5 | 1.069 | 1.092 |
| 6 | 1.061 | 1.100 |
| 7 | 1.071 | 1.109 |
| 8 | 1.097 | 1.102 |
| 9 | 1.076 | 1.062 |
| 10 | 1.093 | 1.094 |
| 11 | 1.101 | 1.119 |
| 12 | 1.149 | 1.056 |
| 13 | 1.123 | 1.051 |
| 14 | 1.098 | 1.059 |
| 15 | 1.144 | 1.089 |
| 16 | 1.148 | 1.107 |
| 17 | 1.123 | 1.110 |
| 18 | 1.069 | 1.076 |

Table A.2: Exposure correction factor for Voorschoten (ECF_215) and Valkenburg (ECF_210) in the May 2015–April 2016 period. Wind direction DD is grouped in 18 categories (1 = 10–20, 2 = 30–40,..., 18 = 350–360 degrees).

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