

# Quantifying the urbanization induced temperature effect of weather station De Bilt (Netherlands) between 1900-2000

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## Abstract

Many cities around the world have spatially expanded during the 20<sup>th</sup> century. Consequently, some weather stations are currently located closer to cities than before. Since most cities experience urban heat island effects, it has been hypothesized that those weather stations show a positively biased temperature trend due to urbanization. In this study, we estimate this effect for WMO station De Bilt, using the mesoscale model WRF. This station has been selected because it has a long and accurate historical record and is located close to the city Utrecht, which substantially expanded in the 20<sup>th</sup> century.

The temperature rise due to urbanization is determined by conducting model simulations for the land use situations for both the year 1900 and 2000. This is repeated for four different episodes lasting a week, each representing a typical large-scale flow regime. By using frequency distributions of the Grosswetterlagen, an average temperature rise is estimated.

The results indicate that the urbanization during the 20<sup>th</sup> century has resulted in a temperature rise of  $0.32 \pm 0.06$  K. This rise is much higher than estimated by comparing observed temperature records close to De Bilt, which suggested only  $0.11 \text{ K} \pm 0.06$  K. The modeling study also reveals a larger temperature rise in the winter, due to the contribution of anthropogenic heat.

Keywords: Urban heat island; climate trend detection, urbanization.

## 1. Introduction

Many observational studies report a rise of the global 2 m temperature in the last century (e.g. Hansen and Lebedeff, 1987; Smith et al, 2008). The IPCC estimates  $\sim 0.74$  K of warming which is attributed to enhanced GHG concentrations. However, observational temperature records close to urban areas might be influenced by nearby city expansion and consequent heat advection from the city (Oke, 1982, Fall et al, 2010). This signal might be of similar magnitude as the GHG effect for such stations (Karl et al, 1988; Balling, 1998).

In the Netherlands, the surroundings of the central weather station in De Bilt (henceforth DB) have been gradually urbanized during the 20<sup>th</sup> century. De Bilt's most nearby city, Utrecht, had a surface area and population of respectively 22% and 44% in 1899 compared to 2003 (Brandsma et al, 2003). In that century, the screen level temperature increased significantly by 1.2 K in DB.

The observations in DB have a high scientific value for climate research, because DB has a long and relatively homogeneous data record (Brandsma, 2010). DB is also the main Dutch weather station, particularly for the general public. From DB monthly and yearly surveys are composed, which are often adopted by the media. Hence it is important to estimate the urbanization induced temperature effect (UITE).

So far, the UITE for DB has solely been studied by comparing observations from other weather stations. This observational study found a maximum nocturnal UITE of 0.5 K (Brandsma, 2010). However, in the comparison study between DB and nearby weather stations the yearly averaged UITE is estimated to be 0.11 K.

Here we extend the earlier studies by estimating the UITE using a modeling approach. Its main advantage is that model results suffer less from local signals as soil type, topography and roughness, which arise with comparing weather stations (Van Weverberg et al, 2008; henceforth VW08). In addition, modeling allows us to reconstruct the UITE where observations are lacking. We

follow the modelling study by VW08, who estimated the UITE for weather station Uccle, next to Brussels, by modelling four weather situations for both the land use in 1900 and 2000. Depending on wind direction, they found the UITE equals 0.37-1.13 K, while the observed temperature trend is 1.4 K during that period. A key difference between urbanization in Uccle and DB is that Uccle is fully surrounded by urbanized areas, while for DB only Utrecht and the village De Bilt are expected to contribute to the UITE (Brandsma et al., 2003).

## 2. Methodology

This section summarizes our research methodology that consists of a case selection, model and land use set-up and statistical analysis.

### a) Case selection

In order to cover a wide and representative range of weather situations four episodes have been selected, as inspired by VW08. Each of these weather conditions consists of 7 consecutive days, and each representing a specific Grosswettertype (Werner, 2009):

- Case WW: 1-7 December 1999. This event is characterized by a strong westerly circulation and above normal temperatures. Near the surface this results in south-westerly winds.
- Case SW: 1-7 December 2000. A southerly circulation with above normal temperatures characterizes this period.
- Case NW: 1-7 May 2001. During this period a north(easterly) flow dominates. For this case the wind blows especially over city De Bilt.
- Case CW: 23-29 July 2001. This case has variable light winds with a slight preference for NE. All days show above normal temperatures and are relatively sunny with little developing cumulus clouds in the afternoon.

### b) Model set up

Our model simulations employ initial and boundary (6

hourly) conditions (at pressure levels) from the 0.5° ECMWF reanalysis. We have set up four two model domains (Table 1) (Fig. 1). Three of them, WW, SW and NW are two way nested. Only the set up for the July case (CW) is one way nested, because it appears that the difference in convection in the inner domain causes strong divergent behaviour in the other domains. Vice versa, the different meteorology in the outer domains causes different circumstances in the inner domain. The consequence is, the UITE cannot be determined.

Utrecht is a relatively small city, a high horizontal model resolution is required (Brandsma et al., 2003). Thus, a resolution of 500 m was used in the inner domain. We use 35 vertical sigma levels, with the first model level at 15 m (similar as in VW08. Two days of spin up was applied.

Table 1 Four domains used in the WRF model

	Resolution (km)	Number of grids
Domain 1	62.5	24 * 24
Domain 2	12.5	30 * 30
Domain 3	2.5	30 * 30
Domain 4	0.5	40 * 40

The UITE is a typical boundary-layer (PBL) phenomenon and the selected PBL parameterization is of key importance. Thus, this study evaluates the non-local first order MRF (Hong and Pan, 1996), and the 1½ order TKE scheme MYJ (Janjic, 2002). Overall, the literature suggests that MRF performs better than MYJ for the urban climate (Pino et al. 2004). The focus on the role of urbanization on a temperature record means the urban surface energy balance should also be well represented. The characteristics of the city surface require special treatment in terms of modeling.

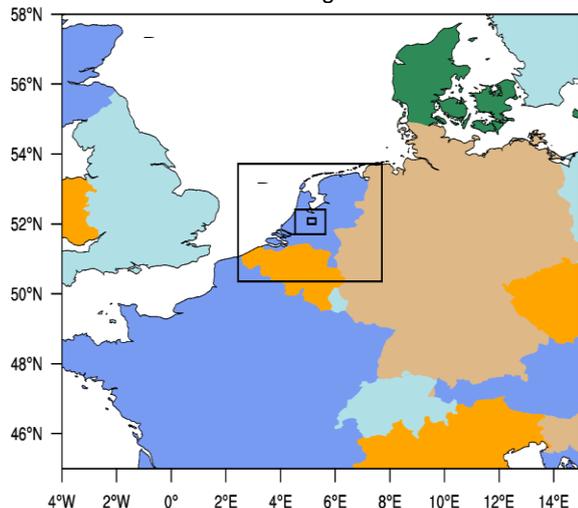


Figure 1 Overview of the location of the 4 domains. De Bilt is in the center of the smallest domain. Domain4 is the smallest domain.

Therefore, the single layer urban canopy model is used in WRF (Kusaka et al 2001; Chen et al 2010), which has been validated for e.g. Osaka (Shresta, 2009), Phoenix (Grossman-Clarke, 2009) and Rotterdam (Ronda et al. 2011). It consists of parallel infinite street canyons where the energy balance of three components (i.e. walls, street and roof surfaces) is solved. Subsequently, surface temperatures for each of the components are estimated. In this urban canopy model, the anthropogenic heat source is specified using values obtained in section d).

Moreover, we use the Grell (1991) cumulus parameterization (two outer domains only), the NOAH land surface model and the Monin-Obukhov similarity surface layer. Finally, we selected the RRTM and WSM3 radiation and microphysics schemes, respectively.

### c) Land use

To model the meteorology of the region around Utrecht, the land use should be correctly represented. The USGS land use map is used for the three outer domains, while the CORINE land use map (last modified in 2007) is used in the innermost domain. It was reclassified such that it corresponds to the USGS classification. CORINE has the advantage of a higher resolution (250 m) than USGS (900 m). The initial source of the constructed land use map from 1900 is the topographic map of the province Utrecht produced around 1905 (Knol et al., 2004; Breedveld et al, 2005). A raster was drawn over this scanned map corresponding to the location of the innermost domain in WRF. In this way the present and historical landuse maps are designed (Fig. 2). The latter shows a more patchy structure of different land use types than for the present land use, because the land use in the historical map is determined per grid cell.

### d) Anthropogenic heat

The anthropogenic heat production is a substantial contributor to the urban energy budget, especially in winter. Anthropogenic heat consists of four components, i.e. natural gas consumption, electricity, transport and human metabolism (Table 2).

The natural gas consumption is hard to estimate for Utrecht, due to the commercialisation of the gas market. Therefore, following Klok et al. (2010), we assume the gas consumption of the total country is representative for the city of Utrecht, which appears to be 8.6 Wm<sup>-2</sup>. In summer, gas consumption is smaller than in winter, and therefore we account for the annual cycle of gas consumption (CBS, 2001).

As for the gas consumption, the CBS (2001) also has monthly values for electricity consumption. For the public network and companies this amounts to 387.7 PJ, i.e. 4.0 Wm<sup>-2</sup>. This study assumes that the electricity consumption ends up as heat in the local environment as assumed in Klok et al (2010) and VW08. In order to estimate the contribution of traffic, the same heat contribution is taken as for Rotterdam (Klok et al, 2010), i.e. 4.7 Wm<sup>-2</sup>. Finally, the metabolic rate amounts ~175 W per person (Sailor and Lu, 2004; Klok et al, 2010). With a population density of 5155 inhabitants per km<sup>2</sup>, this results in 0.90 Wm<sup>-2</sup>. The anthropogenic heat contribution for 1900 is set to the same value as for 2000. At first sight, this looks surprising, because the energy consumption per capita fivefold in a century (CBS, 2001). However, the four times larger population density around 1900 in Utrecht compensates this completely. As such, the metabolic rate raised a factor four, and the energy consumption per m<sup>2</sup> does not differ much with the present. Due to the small differences (Table 2, 3) the same anthropogenic heat values are used for the 1900 run as the 2000 run (henceforth R1900 and R2000).

Table 2: Estimate of anthropogenic heat production (2001)

Anthropogenic heat	Heat (Wm <sup>-2</sup> )
Gas consumption	8.6
Transit	4.7
Electricity	4.0
Metabolic rate	0.9
Total	18.2

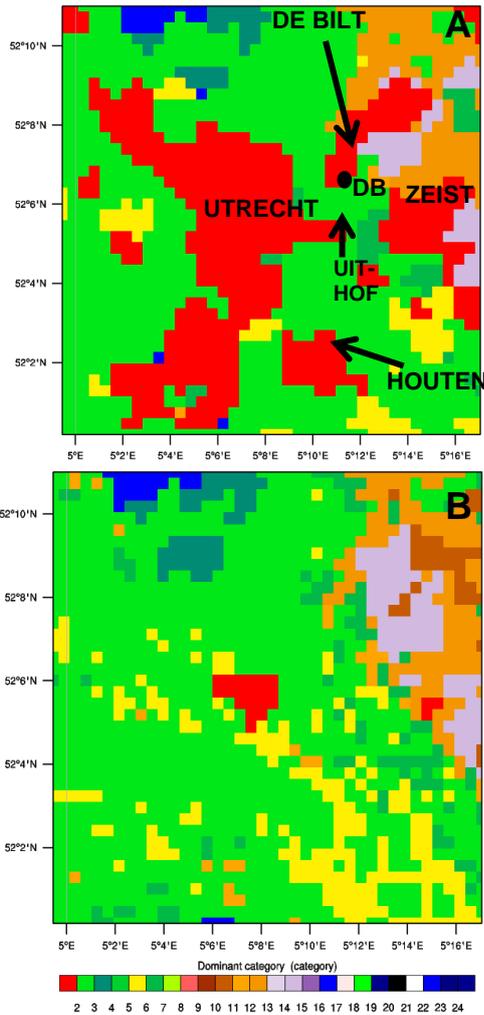


Figure 2 Land use map in 2000 (A) and 1900 (B).

Table 3: Estimate of anthropogenic heat production (1900). The fossil fuel consumption covers transit, building heating, electricity

Anthropogenic heat	Heat ( $\text{Wm}^{-2}$ )
Fossil fuel	15.2
Metabolic rate	3.8
Total	19.0

#### d) Autocorrelations

In order to determine the significance of our findings a straightforward t-test or non-parametric Wilcoxon signed test is not appropriate. When working with time series on hourly intervals, autocorrelation needs to be accounted for (Wilks, 2006). This is substantial for all episodes. Without correction for strong autocorrelation, one overestimates the confidence. When calculated the error of the results autocorrelation will be corrected for.

### 3. Results

This section summarizes the model results. First the selected PBL schemes are evaluated, after which the model runs for 1900 and 2000 are compared. Finally, we scale the results from 4 cases up to a yearly mean effect.

#### a) Boundary-layer scheme performance

First, two PBL schemes i.e. MRF and MYJ are evaluated for four quantities (Figure 3). Next, we discuss the model performance for each modelled episode for MRF.

In the first case, July (CW), temperatures and specific

humidity are substantially underestimated by the model (a bias of  $-2.06 \text{ K}$  and  $-0.95 \text{ g kg}^{-1}$  respectively). The modelled 2-meter temperature of MRF is still better than that of MYJ (bias =  $-2.36 \text{ K}$ ). The too high soil moisture content in the model might explain these biases and the temperature at 850 hPa is up to 2 K too low. This is a reasonable limiter for the maximum temperature. Finally, the radiation is positively biased, which can be explained by the fact that in reality cumulus clouds developed, while this does not often occur in the model. Finally, the wind speed is well represented in the model with the largest positive bias at night (bias =  $0.4 \text{ m s}^{-1}$ )

The episode December 1999 (WW) is easier to model than the previously described summer case, because the PBL is more neutral because strong windy conditions. This results in a better representation of the temperature. Therefore, it is not surprising that the largest differences in temperature are observed in relatively calm evening on December 5. The observations were three degrees colder than modeled, especially because the wind vanishes in the observations, but not in the model. Over the full period wind speed is slightly underestimated. The specific humidity fits well with the observations with a bias of only  $-0.27 \text{ g kg}^{-1}$  and a RMSE of  $0.49 \text{ g kg}^{-1}$ . Global radiation is of minor importance in winter.

The case of December 2000 (SW) shows in reality higher temperatures than modelled for the first two days with a difference of 1.6 K. During the remaining days, the model really corresponds with the observations with a bias of 0.42 K and a RMSE=1.07 K. A small bias is found for humidity. Wind speed were also similar with a bias of  $0.23 \text{ ms}^{-1}$  and a RMSE<sub>s</sub> of  $0.42 \text{ ms}^{-1}$ .

Finally, in May 2001 (NW) the temperature is moderate negatively biased with  $-1.05 \text{ K}$ . A relatively large part of this bias is due to the modelled cold nights on the 5 and 6 May which were not correctly modelled by WRF. In particular, it was found that these nights were partly cloudy, while in the model. The specific humidity is almost every time negatively biased by  $-0.77 \text{ g kg}^{-1}$ . The radiation is slightly overestimated. The observed clouds on May 5 and 6 were hardly reproduced in the model. May 5 was a clear day in the model. The wind speed fits the observations reasonably with a RMSE of  $0.99 \text{ ms}^{-1}$  and a bias of  $0.14 \text{ ms}^{-1}$ .

Note that the RMSE<sub>s</sub> does not improve by taking the four best days (as in VW08). Therefore we concentrate on the entire 7 days period, which makes our results more significant.

#### b) UITE for the four episodes

Here, we determine the UITE by simply subtracting the average temperature from R1900 from R2000 (Table 4). In addition, a student-t test and the Wilcoxon signed z are utilized to determine the significance of the UITE signal. All episodes show significantly higher temperatures in R2000 when a confidence interval of 10% is assumed. The episodes are also broken down into mean day temperatures (sunrise–sunset) and mean night temperatures (sunset–sunrise). For both day and night temperatures, the present runs are significantly warmer. The differences for all periods are quite small. December 1999 (WW) shows a mean temperature difference of 0.38 K. R2000 and R1900 hardly differ in global radiation, clouds and precipitation occurrence. Hence, the mean UITE is not influenced by different meteorological factors in both runs.

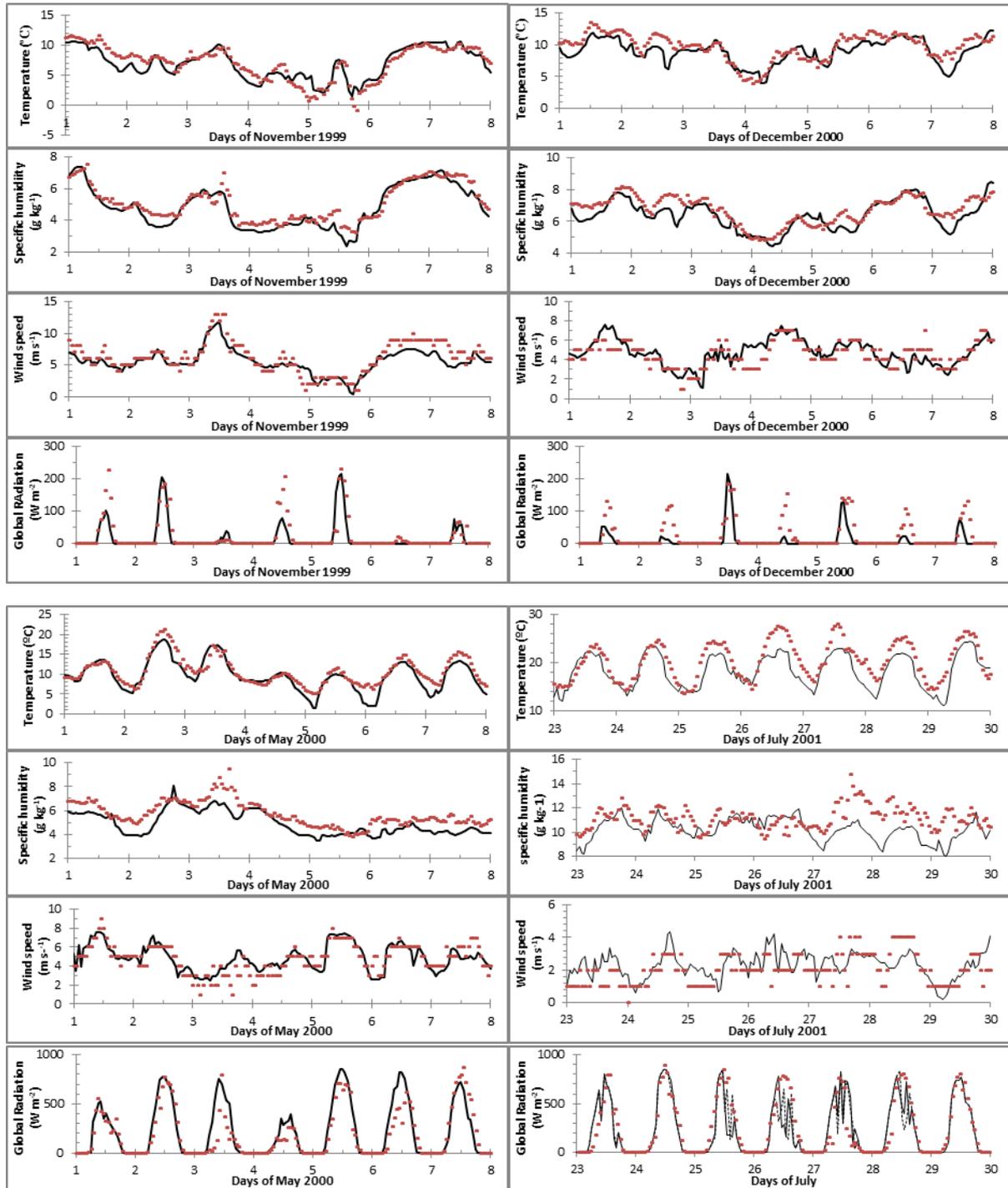


Figure 3: Simulated (line) and observed (asterisks) values of temperature, specific humidity, wind speed and global radiation for the four episodes. ((top left) WW, (top right) SW, (bottom left) NW, (bottom right) CW).

For December 2000 the WRF model estimates a UITE of 0.35 K. The high UITE of this episode is remarkable, because not many building areas are present in the south. Perhaps the outskirts (De Uithof) of Utrecht and Houten do influence the temperature in contrast to findings of Brandsma et al. (2003). During the first December days an additional four hours of clouds were calculated in the R1900 when compared to the R2000. These hours with clouds are associated with more incoming long wave radiation. By discarding these hours of different cloudiness, the UITE is only 0.03 K lower and still significant.

For May no discrepancies are seen between

R2000 and R1900 for relevant variables as cloudiness and global radiation. The nights of May 5 and 6 are coldest in R2000, due to lower wind speeds supporting surface layer cooling. However, the wind was directed from De Bilt only present in the R2000.

July shows an UITE of 0.25K. The small cumulus clouds which developed in the observations are also modeled in the R2000 and R1900 in a similar way. Hence, this doesn't cause substantial global radiation differences in both runs.

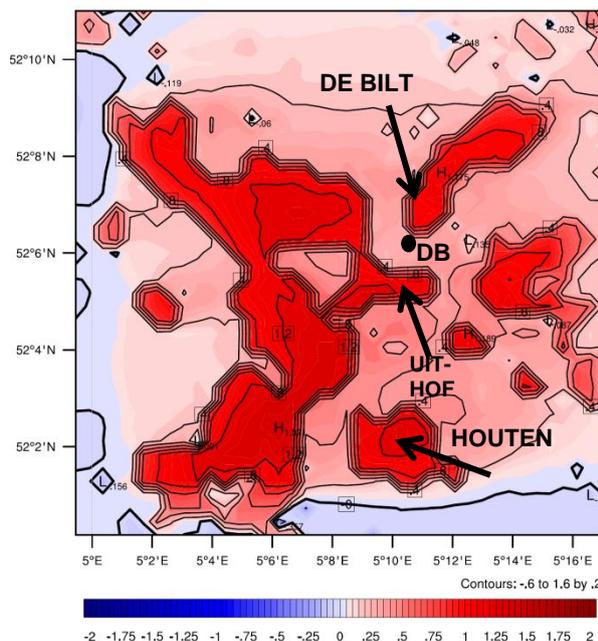
**Table 4: Modelled UITE per flow pattern and MRF PBL scheme.**

Case	UITE (K)	N (hours)	Freq. of occ
WW (Nov)	0.378	169	26.9 %
Daily	0.551	56	
Night	0.292	113	
SW (Dec)	0.354	169	5.0%
Daily	0.500	56	
Night	0.282	113	
NW(May)	0.229	169	8.3%
Daily	0.197	106	
Night	0.283	63	
CW (Jul)	0.253	169	16.6%
daily	0.138	112	
night	0.479	57	

**c) Yearly average UITE intensity**

From the four model simulations an average UITE for DB is calculated. The simulations represent a weather type for which the frequency of occurrence is known (Werner and Gerstengarbe, 2009). These frequencies are calculated during the period between 1951-2009. The modeled mean UITE is  $0.32 \pm 0.06K$  with MRF (Fig. 4), while UITE with MYJ amounts to  $0.28 \pm 0.08K$ . Note the reported standard error has been calculated accounting for autocorrelation, otherwise the error would only be 0.04 K. Not all weather types were simulated and thus 43% is unexplained. The modeled UITE of 0.3K during the 20<sup>th</sup> century is a factor 3 larger than reported in Brandsma et al. (2003) who found i.e.  $0.10 \pm 0.06 K$ .

Figure 4 shows the largest positive anomalies are not found close to the city center. This is because the city centre is also present in R1900. Another important result is that other locations between Utrecht, De Bilt, Zeist and Houten have similar anomalies as the location of DB. On the northern side of Utrecht anomalies are still seen at a large distance from Utrecht. The advection of heat on average has an influence more than 5 km away from the city.



**Figure 4** Difference temperature 2000\_run and 1900\_run averaged with frequencies over all periods using MRF.

**4. Conclusion**

This study quantifies the urbanization induced temperature effect (UITE) of Utrecht and its impact on weather station De Bilt (Netherlands). This is done by the mesoscale modeling of four 7-day cases with different large scale flow patterns and consequent upscaling via Grosswetterlage frequencies. We find that the UITE may amount to 0.38 K for a westerly circulation. Overall, the UITE may amount up to 0.32 K, which is about a factor 3 larger than found in earlier studies.

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