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On the relationship between global warming, local warming in the Netherlands and changes in circulation in the 20th century

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Abstract

The temperature in De Bilt in the Netherlands has risen by 1K over the 20th century. This rise parallels the rise in global temperature quite closely, albeit with a slightly higher amplitude. A linear relationship between the two, with a regression coefficient close to one, is an obvious first-order approximation. This is supported by the spatial homogeneity of global warming during the twentieth century, the lack of seasonality in the temperature rise, and the residuals being almost white in time.

The wind direction is used as a proxy for circulation type. Locally measured wind direction gives the same results as geostrophic wind direction from pressure stations, so that systematic errors are not likely to be large. The temperature in the Netherlands, on the edge of the continent, strongly depends on the wind direction. For most wind directions and seasons the average temperature per wind direction has increased. The exception is north-easterly winds in winter, in which the variability is too large to observe a trend. The increased temperature for each wind direction can explain the observed temperature rise in all seasons within the 95% error estimates.

Changes in the distribution of wind directions explain most of the interannual variability of temperature. On longer time scales, these changes have led to cooler weather in the middle of the century, but no trend is discernible over the whole century. However, in late winter and spring there is clear evidence for a change in the frequency distribution of circulation patterns affecting the Netherlands over the second half of the twentieth century. During the months of February to April more days with southwesterly wind and fewer with northeasterlies have increased the temperature even more than the observed increase in temperature per wind direction.

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1 Introduction

Like most of the world, the Netherlands has experienced a rise in temperature over the twentieth century. This study addresses the statistical relationships of this rise to global warming (IPCC, 2001) and to changes in circulation, which itself may also be connected to global warming. The temperature in the Netherlands depends strongly on the circulation, with continental easterlies associated with cold weather in winter and warm weather in summer, whereas the maritime westerlies are more temperate. There has been speculation that the winter westerlies increased due to global warming (e.g., Corti *et al.*, 1999), but other results point to rather small changes in the distribution over the twentieth century (Giorgi, 2002). The type of relationship between global and local warming strongly influences the way that future warming is expected to affect the weather in the Netherlands.

As a reasonably homogeneous proxy for circulation type we use the wind direction, as also used by van Veen (1940); Labrijn (1945); Jönsson and Holmquist (1995). Previous studies for the Netherlands used the Großwetterlage subjective daily classification scheme (Wessels *et al.*, 1994) or constructed analogs based on reanalysis data (Schuurmans and van den Dool, 2001). The first suffers from large inhomogeneities, e.g., in winter the class Hm drops from 591 days in 1901-1950 to 302 in 1951-1998. A reasonably homogeneous reanalysis is only available for the second half of the period. The homogeneity of wind speed measurements is problematic, for De Bilt a homogenized (hourly) wind speed series is only available from 1961 onward. Wind direction measurements with acceptable uncertainties have been performed since 1904.

A statistical analysis like this complements model results, which have large uncertainties. However, it is also not without pitfalls. Analyzing the whole century as statistically homogeneous gives the highest statistical significance. However, the warming from 1900 to about 1940 most likely had natural causes, whereas the warming from 1970 onward is likely due to anthropogenic influences (IPCC, 2001). Separate analyses of the periods 1901–1950 and 1951–2002 give insight into possible changes, but suffer from larger uncertainties due to the smaller number of years.

Another problem is the homogeneity of the observations. Observations of the twentieth century are relatively good. Still, measurement methods have changed several times. Also, the environment of meteorological stations has changed due to station relocations, urbanization and tree growth. The monthly mean temperature observations at De Bilt over the period 1901–2002 have recently been corrected for most of the known inhomogeneities (Brandsma *et al.*, 2002). The wind direction series has been compared with a geostrophic wind direction as proxy for circulation type. This substitution results in the same conclusions (albeit with more noise), showing that the inhomogeneities in the wind direction series do not affect the results.

There have been many investigations into the relationships between local temperature or precipitation, circulation patterns and global warming (or trends) for different regions of Europe, mainly using EOFs of sea-level pressure as predictands. Werner and von Storch (1993) find a warming trend in Jan–Feb in 11 central European stations that is independent of circulation patterns, unfortunately without an error estimate. In an analysis similar to the current one, Hanssen-Bauer and Førland (2000) find an unexplained increase in temperature in Norway, mainly in the first half of the century. In the second half the observed warming was explained by the increasingly westerly circulation. Osborn and Jones (2000) find that the trends in 1950–1999 annual, spring and fall Central England Temperature are made (more) significant after subtraction of the effects of circulation, in his case flow strength, vorticity and flow direction, derived from sea-level pressure.

Apart from the regional focus, this study differs from (some of) the previous in the following points. Local wind direction is used as a homogeneous proxy for circulation types. The analysis uses continuous functions and not binning to increase the statistical significance and reduce the sensitivity to systematic errors. We do not search for linear trends, but for changes proportional to the globally averaged temperature, which did not increase linearly over the twentieth century. The signal is not only seen as a residual unexplained by circulation, but also as trends in the statistical model parameters when these are determined for shorter periods. Finally, estimates of (symmetric) 95% confidence intervals are given for all numbers.

The data are discussed in section 2. Next the statistical relationship between local temperature in the Netherlands and globally averaged temperature is discussed in section 3. Section 4 discusses changes in the temperature per wind direction. The opposite, changes in the frequency distribution of wind direction that lead to temperature trends are discussed in section 5. In section 6 the combined effect is described, followed by discussion and conclusions.

2 Data

The station De Bilt (52.10°N, 5.18°E, 2.0m) is representative for the mean climate conditions in the Netherlands. Its temperature and wind direction records are considered the most homogeneous long-term records of the Netherlands. The daily mean temperature series of De Bilt starting from 1901 is available from the KNMI web site and the European Climate Assessment dataset (Klein Tank et al., 2002). The daily values were used directly, the monthly means of this series have recently been homogenized (Brandsma *et al.*, 2002) for the effects of a relocation and change of the thermometer screen in 1950, another relocation in 1951, the lowering of the screen from 2.20 m to 1.50 m in 1961 and urbanization effects. For the period 1951–1970 the monthly mean temperature is now derived from hourly ‘climatological measurements’. The ‘synoptic measurements’ that have been used up to now for practical reasons for that period are inferior in quality. The size of these corrections is about 0.2 K, a few months in the period 1950–1960 have corrections of more than 0.4 K. Changes in the measurement screen in 1980 (wood to plastic) and 1993 (Stevenson to unventilated saucer) have not yet been corrected for, but are estimated to be much smaller.

The daily mean wind direction of De Bilt is also available from the KNMI web site from 1904 onward. The data for April 1945 are missing. This series has not been corrected for known inhomogeneities due to changes in measurement height and environment. The original tower (37m) on the KNMI building was demolished in 1916 and rebuilt half a metre higher in 1917, this site was surrounded by tall trees (Braak, 1942). In 1961 the measurement site was moved to a 10m tower in a meadow behind the institute, which was raised to 20m in 1993 (Verkaik, 2001). The importance of these inhomogeneities for our analysis has been assessed by a comparison with the geostrophic wind direction computed from daily mean sea-level pressures at the stations De Bilt, Groningen/Eelde and Den Helder/De Kooy (Können, 1999). This series has completely different systematic errors and inhomogeneities, but can also serve as a proxy for the weather type in the Netherlands. The major results of this study remain unchanged when the geostrophic wind direction is used instead of the locally observed wind direction, except for somewhat larger uncertainties, because variations in the large-scale geostrophic wind correspond less closely to local temperature variations than the locally observed wind direction. Note that the agreement between the effect of local wind direction and geostrophic wind direction on temperature does not mean the inhomogeneities in the De Bilt wind direction series are small, it just means they are not important for this particular analysis.

As an estimate of global temperature the monthly anomalies relative to 1961–1990 of Jones *et al.* (2001) are used. This series is also used extensively in IPCC (2001). The Northern-Hemisphere mean temperature has also been considered, as it reflects the effect of aerosols better than the globally averaged temperature. It is indeed correlated better with dutch temperature than the global average, but the difference is well withing the error margins due to the limited number of years. All conclusions remain unchanged. The 5×5° HadCRUT SST and 2-meter temperature dataset from the same source is also used.

3 Local and global warming

The temperature changes 1901–2002 in De Bilt and globally averaged are shown together in Fig. 1. The decadal changes are obviously correlated, both for the warming from 1900 to 1940 and for the period 1970 to 2002. For the last 20 years the warming in De Bilt was faster than the globally averaged warming. The best fit straight line over the whole period is $\Delta T_{\mathrm{DeBilt}} = (1.52 \pm 0.49)\Delta T_{\mathrm{global}}$, where the errors denote the 95% confidence interval. On average the Netherlands have warmed slightly faster than the global average: a value of one can just be excluded at a 95% confidence level. Over 1901-1950 the regression coefficient is 0.83 ± 0.85, over 1951-2002 it is 2.17 ± 0.91. These values are incompatible with each other at the 95% confidence level: the rise of local temperature has been faster in the second half of the century. Possible reasons for this will be explored in section 7.

It could be argued that the agreement between the local and global temperature series is a coincidence. The dangers of correlating trends are well-known (e.g. Sies, 1988). However, in this case there are supporting arguments for a causal relationship. It is not only the trend: the detrended series are still correlated ($r = 0.28$, 99% significant if all points are independent). The remaining noise is almost white in time.

More significantly, one would expect there to be a relationship between the temperature at any station and the global temperature, as the latter is just the average of all stations. (The direct influence of De Bilt and the area that varies with it is very small in this average.) A map of regression coefficients of local versus global temperature (as in Jones and Kelly, 1983) should have average one. The question is how large the spatial variations around this value are: has the world warmed homogeneously or inhomogeneously over the twentieth century? This map, computed from data of the HadCRUT dataset, is shown in Fig. 2. One sees that the warming has been relatively homogeneous: 75% of the grid points with enough data (at least 30 years) have a regression coefficient between 0.5 and 2. Most exceptions are well-understood. High-latitude continental regions have larger regression coefficients because of the snow-albedo feedback (Arrhenius, 1896). The equatorial Pacific shows up because the high-frequency El Niño signal can also be found back in the global temperature series. The northern central Pacific pole of the Pacific Decadal Oscillation was in a cooling phase for most of the decades with data in this area, this may be unrelated to the global warming signal. Finally, the reason behind the absence of warming around Greenland is not clear.

Similar conclusions can be drawn from the trend maps in the IPCC report and the area averages studied by Giorgi (2002). De Bilt is clearly no exception in its relationship between local and global warming during the twentieth century. A map of the last 50 years only does not show large differences, although there

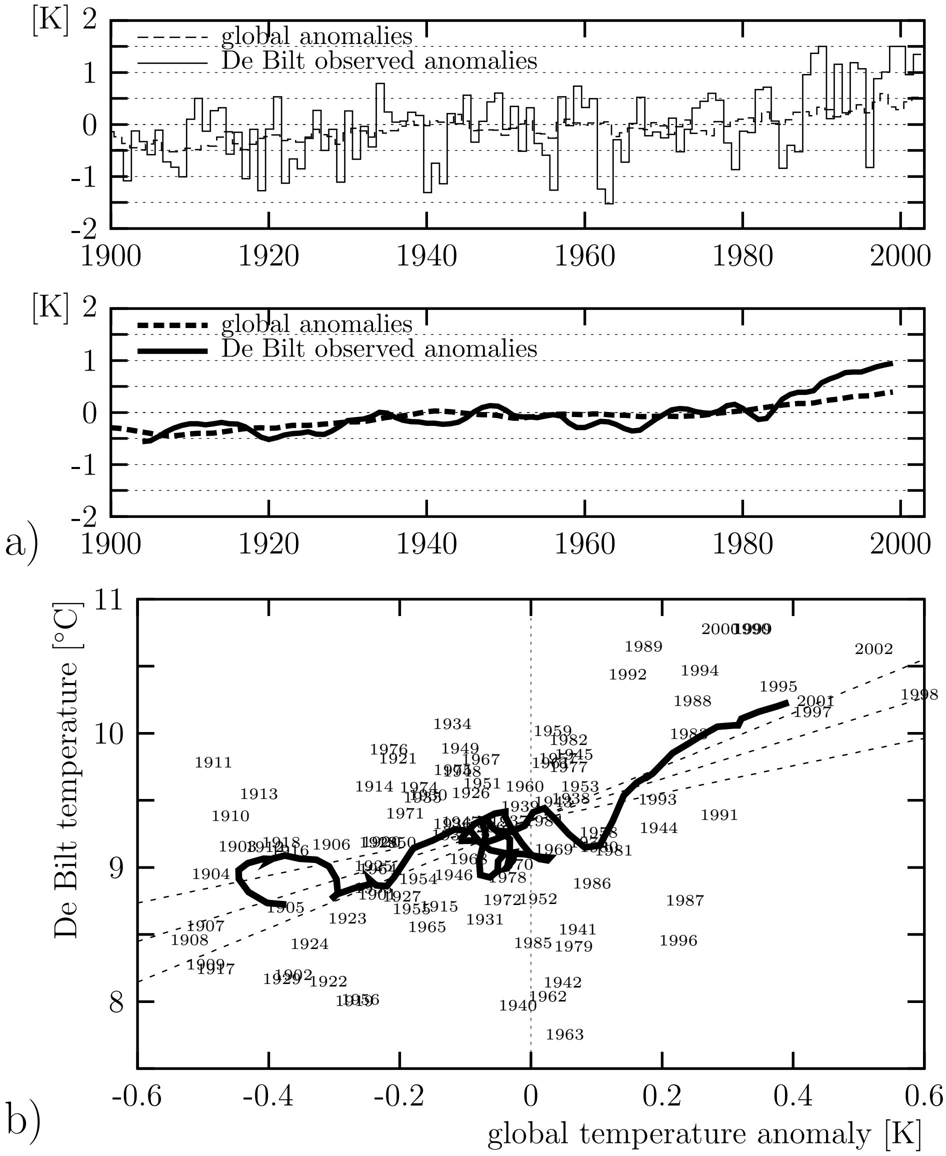

Figure 1: Comparison of the yearly temperature in De Bilt and the globally averaged yearly temperature (a), and a scatterplot of these two (b) with best straight-line fit and 95% confidence level estimates on the regression coefficient. The thick lines denote ten-year running means.

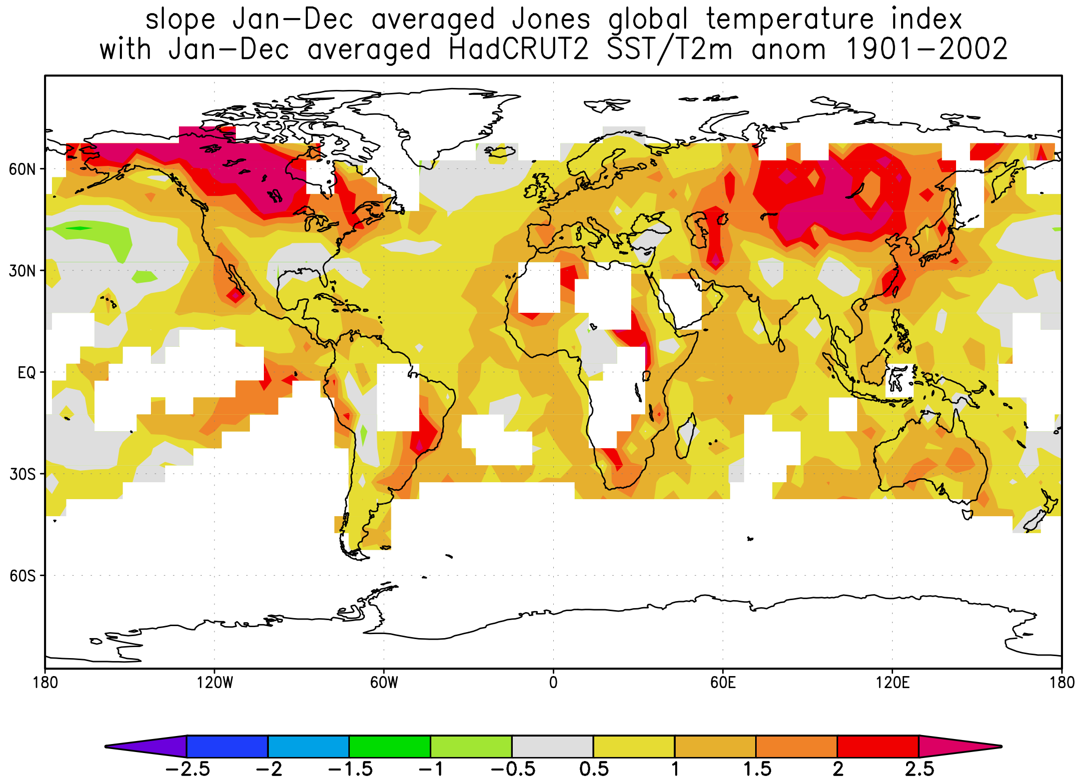

Figure 2: Map of regression coefficients of local with global temperature. White areas have fewer than 30 years of data in the HadCRUT dataset.

is a more pronounced warming trend in central and eastern Europe that extends westward to the Netherlands.

A final point is the seasonality of the relationship. The same relationship can be shown to exist in the four meteorological seasons (Table 1). In winter (Dec–Feb) the temperature variability is a factor two higher, so that the 95% confidence interval only barely excludes zero. The most significant change between the first and second halves of the twentieth century occurred in spring (Mar–May), when the temperature in De Bilt rose more than twice as quickly as expected from the globally averaged temperature rise. The regression coefficient increased even more in winter (Dec–Feb), but due to the high natural variability this change is not significant.

4 Changes in temperature per wind direction

Using the daily temperature and wind direction records over 1904–2002 it can be studied how much of the trends in temperature are due to changes in the

		year	winter	spring	summer	autumn
1901–2002	corr	0.52 ± 0.16	0.20 ± 0.19	0.46 ± 0.17	0.50 ± 0.15	0.40 ± 0.16
	regr	1.5 ± 0.5	1.3 ± 1.3	1.6 ± 0.6	1.9 ± 0.7	1.6 ± 0.7
1901–1950	corr	0.27 ± 0.27	0.01 ± 0.31	0.27 ± 0.29	0.46 ± 0.21	0.26 ± 0.24
	regr	0.8 ± 0.9	0.0 ± 2.4	1.1 ± 1.1	2.0 ± 1.0	1.3 ± 1.4
1951–2002	corr	0.56 ± 0.18	0.32 ± 0.24	0.57 ± 0.15	0.39 ± 0.29	0.35 ± 0.19
	regr	2.2 ± 0.9	2.4 ± 2.1	2.6 ± 1.1	1.9 ± 1.3	1.7 ± 1.3

Table 1: The correlation and regression coefficient between temperature in De Bilt and globally averaged temperature. The errors denote 95% confidence intervals.

frequency distribution of the wind direction as a proxy for circulation type, and how much is due to an increase of characteristic temperature per wind direction.

To investigate the latter the wind directions could have been binned in 4 or 8 compass directions, as in Jönsson and Holmquist (1995). However, in order to minimize the effect of systematic errors and the number of free parameters in the fits, we choose to use a simple continuous daily temperature anomaly model. The temperature is described by a function of the wind direction ϕ (clockwise from north):

$$T_{\text{DeBilt}} = T_{\text{DeBilt,clim}} + \frac{1}{2}(T_w + T_c) + \frac{1}{2}(T_w - T_c)\cos(\phi - \phi_w) + \text{noise}. \qquad (1)$$

The daily climatological temperature $T_{\text{DeBilt,clim}}$ (defined over the full dataset) has been smoothed by applying a 7-day running mean four times. The temperatures T_w and T_c denote the characteristic anomalies for wind from the warm or cold direction respectively and ϕ_w is the wind direction associated with the warmest weather, the coldest direction is opposite in this first-order model. Higher-order terms in this Fourier expansion are small and their inclusion makes it harder to investigate the time-dependence of the model parameters.

In Fig. 3 the daily data in 1904–1913 and 1991-2000 are shown, together with fits of Eq. 1 to these data. The dominance of southwesterly wind directions is clearly visible. In summer (Jun–Aug) the highest temperatures occur when the wind comes from the continental southeast, in winter this is the maritime southwest. Between the first and last decade the temperature increased by about 1 K for all wind directions in summer. The winter is more interesting: the mild south-westerlies became warmer, but there was no difference between the average temperature of the north-easterlies in 1904–1913 and 1991-2000.

The trend in the temperatures T_w and T_c over the whole century can be estimated by considering consecutive 90-day seasons separately. For each season from March–May 1904 to Sep–Nov 2002 the model Eq. 1 was fitted with ϕ_w fixed to the value found for the whole period. The resulting seasonal time series $T_w(t)$

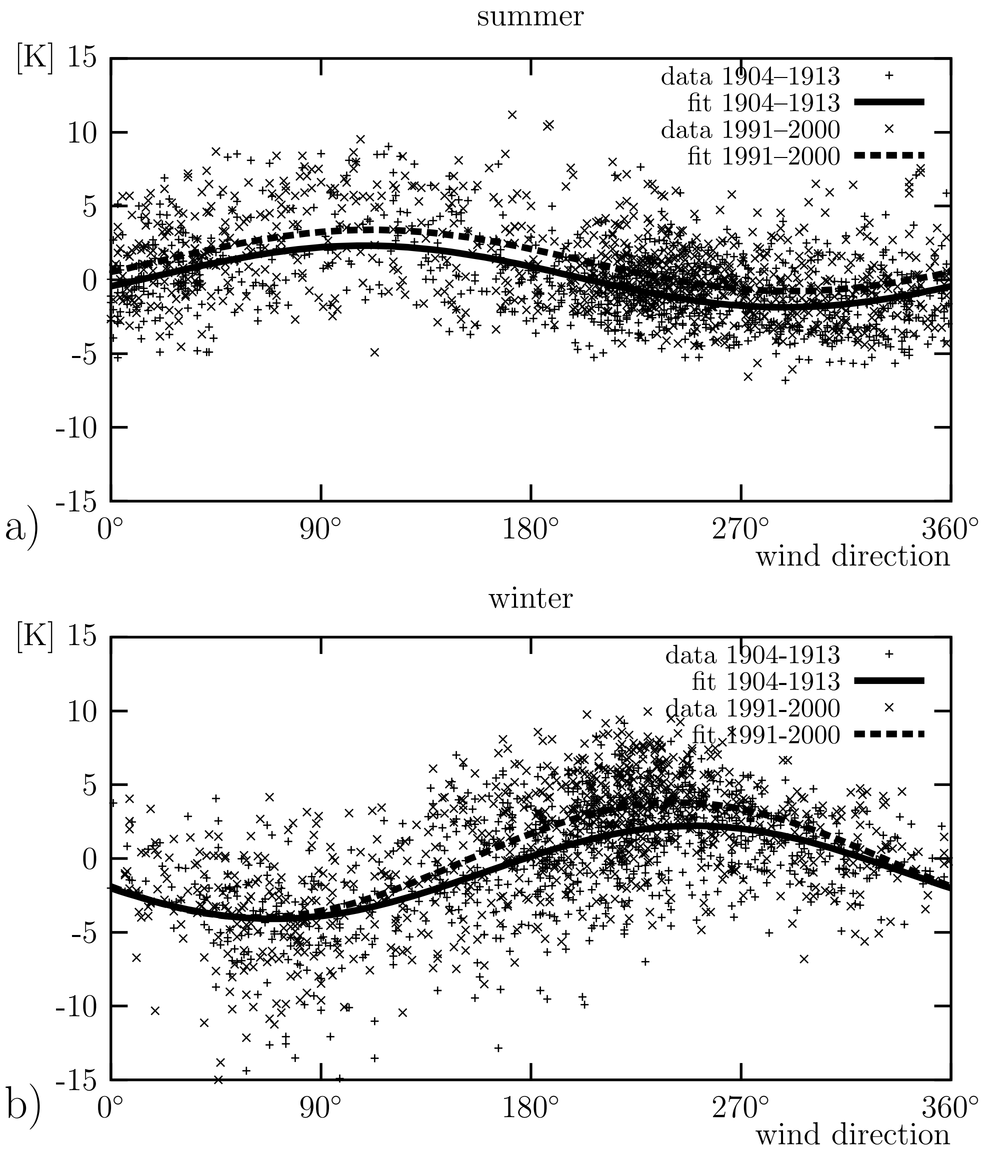

Figure 3: Daily temperature anomalies in summer (JJA) and winter (DJF) as a function of the wind direction in 1904–1913 (+) and 1991–2000 (×). The thick lines are fits to a sine curve for these decades. North corresponds to 0°, East to 90°.

		year	winter	spring	summer	autumn
T_w1904–2002	corr	0.51 ± 0.16	0.36 ± 0.20	0.39 ± 0.17	0.22 ± 0.21	0.44 ± 0.15
	regr	1.5 ± 0.5	1.3 ± 0.7	1.6 ± 0.8	1.3 ± 1.2	1.8 ± 0.8
T_c 1904–2002	corr	0.37 ± 0.17	0.07 ± 0.19	0.32 ± 0.19	0.50 ± 0.15	0.28 ± 0.18
	regr	1.2 ± 0.6	0.4 ± 1.1	1.3 ± 0.8	1.5 ± 0.5	1.7 ± 1.2

Table 2: Correlation and regression coefficients of the seasonally fitted temperatures of the warm and cold wind directions in De Bilt with the globally averaged temperature. The errors denote 95% confidence intervals.

and $T_c(t)$ were regressed linearly against the global temperature. The results are shown in Table 2.

All regression coefficients are compatible with the 1.52 ± 0.49 of the local versus global temperature. Their average, weighted with the seasonal frequency distribution of wind directions, is 1.42 ± 0.42. This means that the increase in temperature for a given wind direction can explain the full observed rise in temperature over the twentieth century. Almost all regression coefficients are significantly different from zero at the 5% level. The one exception is the temperature of cold wind in winter, which has hardly changed at all. This is in agreement with Fig. 3, which showed the difference between the beginning and end of the century.

Looking at the difference between the periods 1904–1950 and 1951–2002 (not shown), the only 95% significant change was in the cold wind in spring, which gets warmer more quickly after 1950. However, one should keep in mind that there is a 34% chance of finding at least one 95% significant number in eight random relationships. We therefore conclude that no information can be deduced from this analysis about changes during he century in he rate of local to global warming per wind direction.

5 Changes in wind direction

The other possibility to get a change in mean temperature is a change in the frequency of days with wind from warm or cold directions. On interannual time scales this is the dominant mechanism: a warm summer or a cold winter is dominated by easterlies, a mild one by westerlies. To quantify this Eq. 1 is used in reverse: the parameters T_w, T_c and ϕ_w are kept constant over the century and it is used to compute a wind-derived temperature from the wind direction. Rewriting it as

$$T_{\mathrm{DeBilt}} = T_0 - \Delta_{\mathrm{NS}} \cos\phi - \Delta_{\mathrm{EW}} \sin\phi + \mathrm{noise}, \tag{2}$$

it is seen to be a linear equation in the zonal and meridional components of the wind direction. Assuming the direction of warm wind ϕ_w to be constant over each month, the parameters Δ_{NS} and Δ_{EW} are a function of the calendar month only. Eq. 2 can therefore be fitted to the monthly temperature and wind direction data. The monthly mean wind direction is obtained by averaging the zonal and meridional components of the wind directions (not the wind vectors, the wind speeds are not used) separately, giving the vector $(-\overline{\sin\phi}, -\overline{\cos\phi})$. The length of this vector is a measure of the persistence of the wind direction.

The fitted parameters T_0, Δ_{NS} and Δ_{EW} are then used to compute a monthly wind-derived temperature series from the monthly mean zonal and meridional wind direction components:

$$T_{\mathrm{wind}} = T_0 - \Delta_{\mathrm{NS}}\overline{\cos\phi} - \Delta_{\mathrm{EW}}\overline{\sin\phi} \tag{3}$$

The inclusion of higher-order terms changes the seasonally averaged reconstructed temperature by no more than 0.1°C and does not affect the conclusions.

This wind direction signal series explains more than half the variance of the observed yearly mean temperature ($r = 0.78$). The amplitude underestimates the fluctuations in yearly averaged temperature, even when the trends have been removed, this was also noted in Wessels *et al.* (1994); Osborn and Jones (2000). The reason is that there is persistence in the temperature: warm months in summer and winter are more often followed by a warm month than by a cold month. In the following analysis the reconstructed temperature anomalies have been multiplied by an inflation factor to obtain a regression coefficient of one between the observed and reconstructed temperature. For yearly temperature this factor is 1.48 ± 0.20.

From the time series and scatterplots (Fig. 4) it is clear that the high-frequency part of the reconstructed and observed temperatures agree very well. However, the trends do not agree: the reconstructed temperature decreases by about 0.7 K from the beginning of the century until the early 1960s. Contrary to the extrapolation of Labrijn (1945) it increases again by the same amount until 1980. The trend in the wind direction signal over the whole century is virtually zero. The correlation with the globally averaged temperature is $r = 0.13 \pm 0.21$. This is the net effect of a slightly negative correlation, $r = -0.19 \pm 0.30$ for the first half of the century and a positive one, $r = 0.37 \pm 0.24$, for the second half.

Looking at the individual seasons, the wind direction explains a major part of the temperature variance in summer and in winter, when the land-sea contrast is largest (see Table 3). The wind direction signal is uncorrelated with the global temperature in summer and fall: there are no trends in those seasons. Over the whole century, only in spring there was a significant rise in temperature due to changes in circulation: more days with a warmer (more southerly) wind direction. This effect was only present in the second half of the century, when also the winter

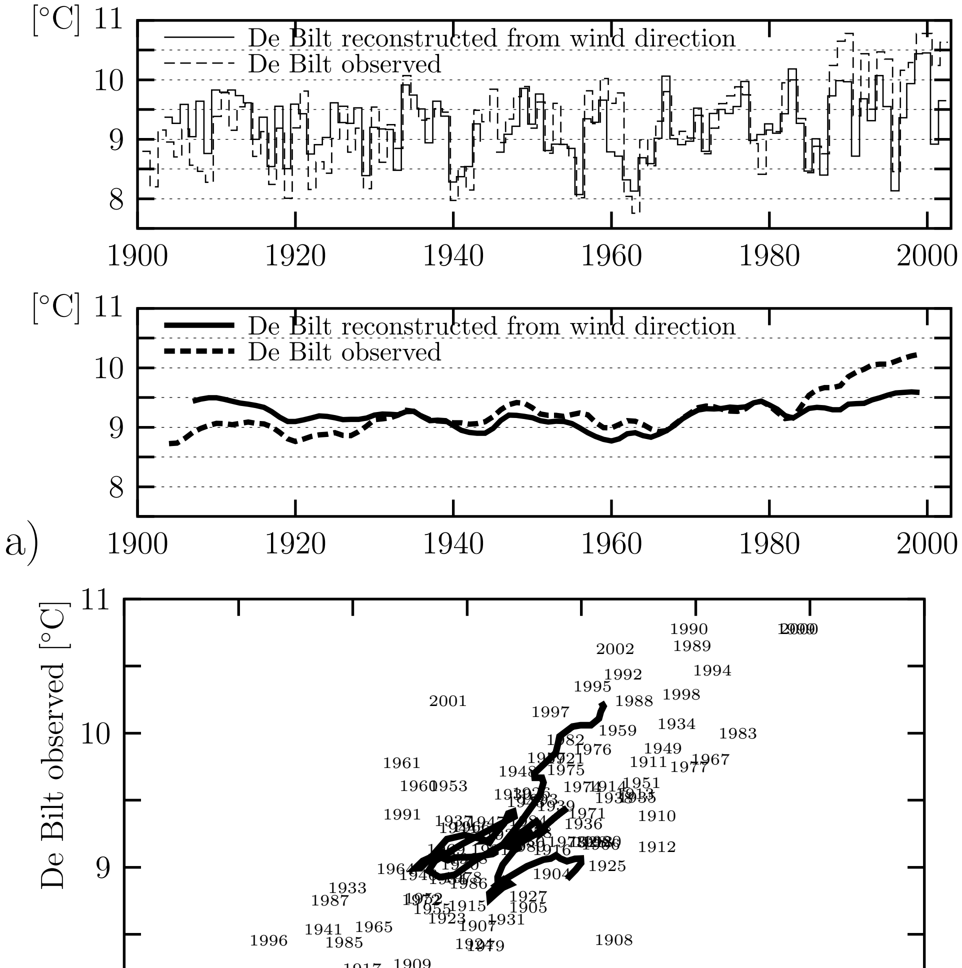

Figure 4: Comparison of the yearly temperature in De Bilt reconstructed from monthly wind direction measurements and observed (a), and a scatterplot of these two (b). The thick lines denote ten-year running means.

		year	winter	spring	summer	autumn
T_{DeBilt}						
1904–2002	corr	0.78 ± 0.09	0.86 ± 0.06	0.52 ± 0.15	0.76 ± 0.08	0.60 ± 0.13
	infl	1.48 ± 0.20	1.27 ± 0.15	0.91 ± 0.31	1.17 ± 0.20	1.06 ± 0.28
T_{global}						
1904–2002	corr	0.13 ± 0.21	0.09 ± 0.22	0.24 ± 0.17	0.12 ± 0.22	0.04 ± 0.19
	regr	0.3 ± 0.4	0.5 ± 1.1	0.6 ± 0.5	0.3 ± 0.5	0.1 ± 0.7
1904–1950	corr	-0.19 ± 0.30	-0.06 ± 0.32	0.02 ± 0.27	0.16 ± 0.28	-0.12 ± 0.30
	regr	-0.5 ± 0.7	-0.4 ± 2.1	0.0 ± 0.8	0.5 ± 0.9	-0.5 ± 1.2
1951–2002	corr	0.37 ± 0.24	0.29 ± 0.25	0.44 ± 0.21	0.05 ± 0.31	0.09 ± 0.21
	regr	1.1 ± 0.8	2.0 ± 1.8	1.7 ± 1.0	0.2 ± 1.0	0.3 ± 1.1

Table 3: The relationships between the wind-derived temperature and the locally observed temperature T_{DeBilt} and the trend as parametrized by the globally averaged temperature T_{global}. The errors denote 95% confidence intervals.

shows a trend. A monthly analysis (not shown) indicates that during the months of February, March and April changes in the average wind direction contributed to the observed rise in temperature during the second half of the century.

The February–April averaged south-westerly wind direction $\overline{\cos(\phi - 225°)}$ is shown in Fig. 5. The sharp rise starting in 1975 is clearly visible. The value of the average wind direction is related to the North Atlantic Oscillation (NAO) index ($r = 0.72$), but it describes the changes in the local temperature better.

6 Combined model

The low-frequency variability (30 years or more) of the local temperature in the Netherlands over the twentieth century was found to be described well by a term proportional to the globally averaged temperature. The remaining high-frequency variability is almost white in time and determined to a large extent by the local wind direction. A monthly fit to the global temperature and monthly mean zonal and meridional wind directions

$$T_{\mathrm{DeBilt}} = T_0 + A\Delta T_{\mathrm{global}} - \Delta_{\mathrm{NS}}\overline{\cos\phi} - \Delta_{\mathrm{EW}}\overline{\sin\phi} + \mathrm{noise}, \tag{4}$$

explains three quarters of the variance of the yearly averaged temperature (Fig. 6). The fit parameters are plotted in Fig. 7. The model fits the data best in winter ($r = 0.87$) and summer ($r = 0.84$). The coefficient A of the global temperature anomalies is somewhat lower in winter ($A = 0.74 \pm 0.41$) than in the other seasons. Its yearly average is 1.25 ± 0.40. This is somewhat lower than in the fit without wind direction dependencies due to the trend in the wind directions in spring.

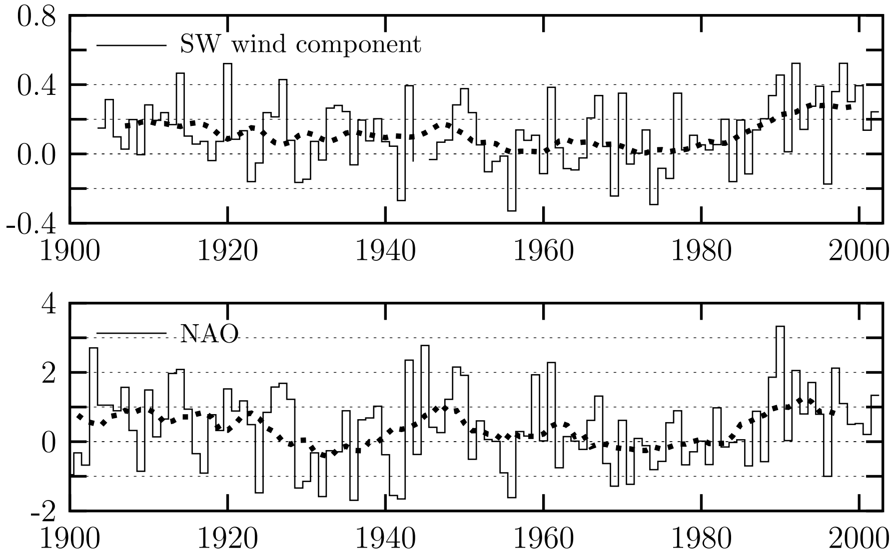

Figure 5: The southwesterly wind component $\overline{\cos(\phi - 225^\circ)}$ in Feb–Apr compared to the Iceland–Gibraltar NAO index averaged over the same months.

7 Discussion

The temperature in the Netherlands has risen over the twentieth century. A connection with the rise in globally averaged temperature is physically plausible. It is not just the trends that coincide: a detrended fit is still significant at the 95% confidence level. Similar relationships can be found for Europe, and in fact for most of the world. The regression coefficient between the local and globally averaged temperature is slightly larger than one, 1.52 ± 0.49 (95% confidence interval) over the whole century. The same connection with globally averaged temperature holds for all four meteorological seasons.

The low-frequency warming could either be due to a uniform warming of weather types, or due to changes in the frequencies at which unchanged weather types occur. This distinction has been investigated with the local wind direction in De Bilt as a relatively homogeneous proxy for the circulation type. To minimize the influence of errors in the wind direction observations, a sine curve approximation for the wind-temperature relationship was employed.

Over the whole century, the characteristic temperature for the warm and cold wind directions has risen with the global temperature in almost all seasons. The exception is cold (northeasterly) wind in winter. The large variability encountered during days with this type of weather means that neither no change nor a similar rise in temperature can be excluded at 95% confidence level for this season and wind direction. Averaging over all seasons and wind directions (weighted by

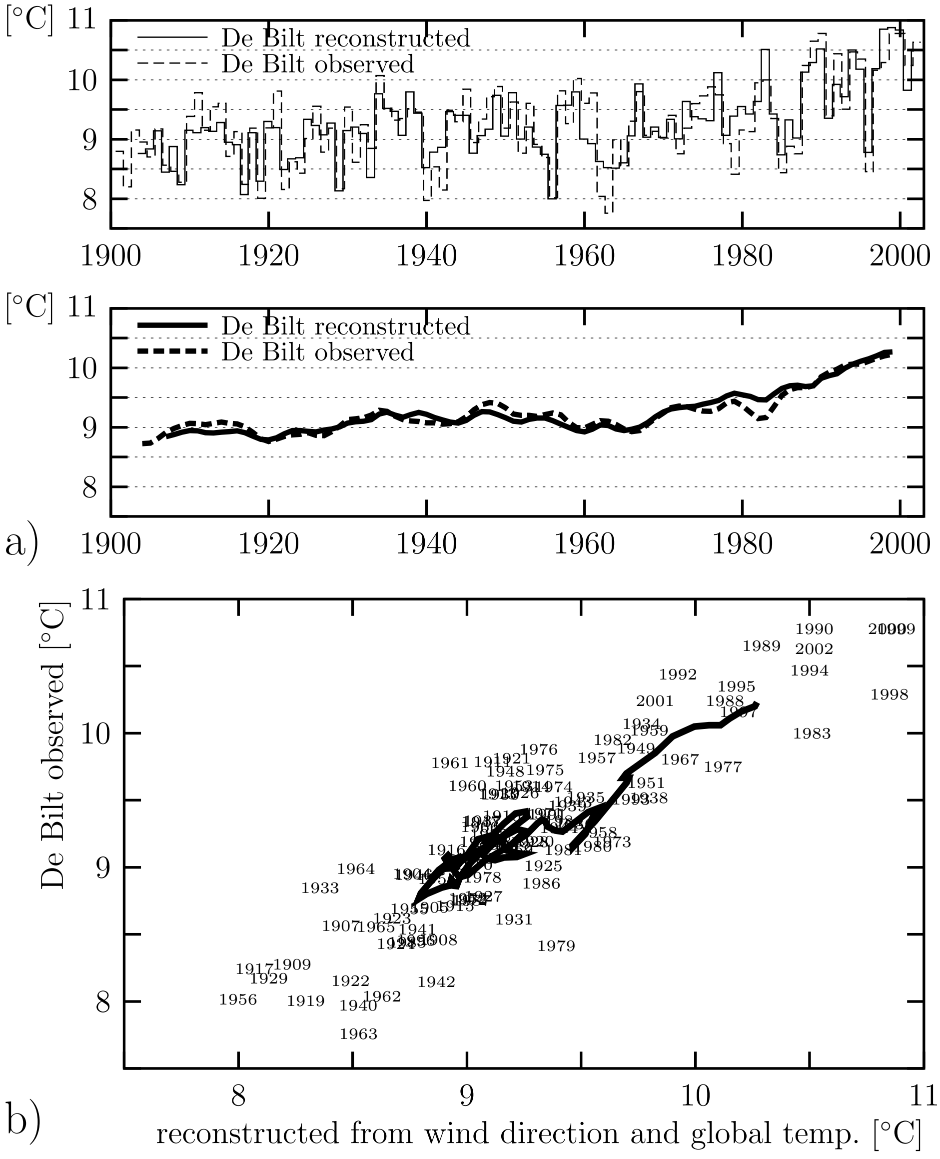

Figure 6: Comparison of the yearly temperature in De Bilt reconstructed from monthly wind direction measurements plus global temperature and observed (a), and a scatterplot of these two (b). The thick lines denote ten-year running means.

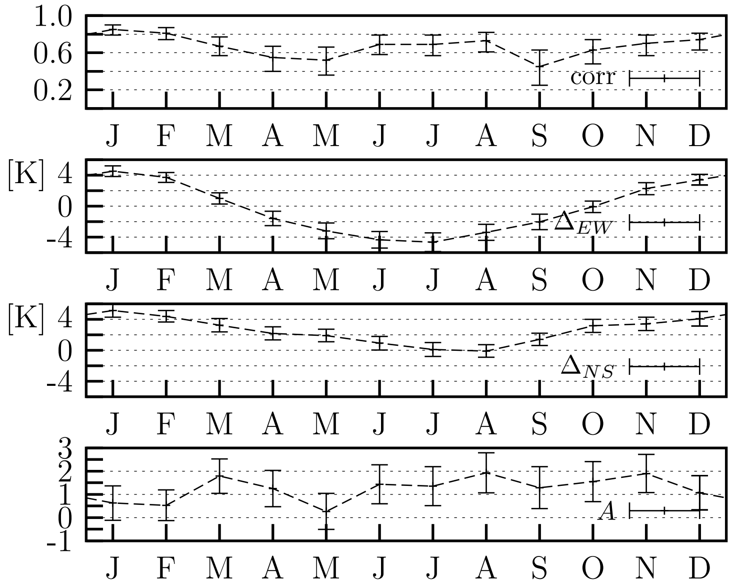

Figure 7: Yearly cycle of the correlation of the statistical model Eq. 4 per month and the fit parameters: the dependence on the monthly zonal wind direction (Δ_{EW}), meridional wind direction (Δ_{NS}) and globally averaged temperature anomalies (A).

their frequencies), the regression coefficient between the averaged characteristic temperature per wind direction and global temperature is 1.42 ± 0.42. There are no significant changes between the first and second halves of the century.

Changes in the frequency distribution of wind directions also give rise to temperature variability. Apart from the high-frequency variability mentioned before, there is also a low-frequency component. To investigate the influence of slowly varying changes in the frequency at which circulation patterns occur, a temperature series has been reconstructed from the wind direction with fixed parameters. It is necessary to include an inflation factor. This series, which explains 60% of yearly variance, shows a cooling trend of about 0.7 K from 1900 to 1960 and a similar warming trend since then, averaging out to zero over the whole century.

In summer and autumn the only trend is warming proportional to the globally averaged temperature. The influence of circulation on temperature is almost white in time and contains no long-term trends. In winter and spring there is the same uniform warming, but also a trend due to changes in circulation after 1950. Osborn and Jones (2000) find similar trends in the part of the Central England Temperature that is described by the circulation. However, their statistical model does not describe the recent spring warming as due to changes in circulation. After subtraction of the circulation-dependent effects, significant long-term trends remain in the spring and autumn Central England temperature as well as in the annual mean.

In the Netherlands, in the months of February, March and April the circulation has changed significantly over 1951–2002, giving rise to warmer temperatures than expected on the basis of a uniformly heating earth. Quantitatively, averaged over these months the temperature has risen 3.3 ± 1.4 degrees for each degree rise in the globally averaged temperature over 1951-2002. The warmer characteristic temperature per wind direction explains 2.0 ± 0.9 of this regression coefficient. The shift to more southwesterly wind directions is associated with another 3.1 ± 1.1. This partition overexplains the observed rise, but the difference between the observed and modeled regression coefficient is within the 95% error margins.

The extra warming is connected with the observed increase in south-westerly flows associated with the positive phase of the North Atlantic Oscillation (NAO) in late winter and early spring (Hurrell, 1995). This change has been attributed to the effects of increased sea surface temperature in the tropics (Hoerling *et al.*, 2001), stratospheric ozone depletion, increased greenhouse gas concentrations and increased volcanism (Hartmann *et al.*, 2000; Robock, 2000). At the surface the greenhouse warming forcing outweighs the cooling trend due to volcanic eruptions (Crowley and Kim, 1999; van Ulden and van Dorland, 2000). In the stratosphere, ozone depletion and greenhouse gases cool the polar stratosphere, whereas volcanic dust heats the tropical (lower) stratosphere. The increased temperature gradient leads to a stronger polar vortex, which would increase the south-westerly flow over Europe (Ambaum and Hoskins, 2002). Following the same reasoning, the predominance of southwesterlies in the beginning of the twentieth century might also be due to external forcings, but this is far from clear.

The rise in NAO index (the Gibraltar-Iceland normalized pressure difference series of Jones *et al.* (1997) was used) does not explain all the observed warming due to circulation changes. Regressed against global warming in Feb–Apr over 1951–2002 it increased $2.0 \pm 1.0\ \mathrm{K}^{-1}$. As each unit rise of this NAO index is associated with a temperature rise of $0.87 \pm 0.10\,\mathrm{K}$ in De Bilt in this season, the effect of the rise of the NAO explains 1.7 ± 0.9 of the regression coefficient of local versus global temperature. This is roughly half the observed effect of the circulation changes, 3.1 ± 1.1, the rest, 1.4 ± 1.4, is due to circulation changes unrelated to the NAO.

The 1990s were unusually warm in the Netherlands (see Fig. 6), as in a large part of Europe. Using the simple statistical relationships the difference between the period 1991–2000 and the 30-year period before this can be studied in some detail. The yearly averaged temperature increased by 0.78 K. About half of this is explained as a uniform warming, slightly more than the increase in globally averaged temperature, which is 0.29K. The increased frequency of southwesterly wind in February to April contributed about 0.25K. The remaining 0.2K is ascribed to other, random, weather variations. The sum of the circulation-induced terms, about 0.45 K, is more than two standard deviations of the 10-year variations over the earlier part of the century (0.2 K). However, viewing part of the early spring trend as a non-random effect brings the remaining term in line with earlier observed weather noise.

8 Conclusions

An analysis of the temperature in the Netherlands, local wind direction and global warming shows that the seasonally averaged temperature in De Bilt over the twentieth century is described well by

- a warming independent of wind direction proportional to the globally averaged temperature,
- an increase in south-westerly circulation in February–April after 1950 and
- almost white noise due to other variations in wind direction and other effects.

The first term explains most (0.8 K) of the observed trend over the twentieth century of 1K, the second one contributes about 0.2K. The last term has standard deviation 0.6 K in the yearly temperature.

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