Central European high-resolution gridded daily data sets (HYRAS): Mean temperature and relative humidity

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Abstract

High-resolution (5 × 5 km\(^2\)) gridded daily data sets of surface air temperature (DWD/BfG-HYRAS-TAS) and relative humidity (DWD/BfG-HYRAS-HURS) are presented in this study. The data sets cover Germany and the bordering river catchments and last from 1951 to 2006. Their data bases consist of daily station observations from Austria, Belgium, Czech Republic, France, Germany, Luxembourg, the Netherlands and Switzerland. The interpolation of the measurement data to the regular grid is performed using a method based upon Optimal Interpolation. A first climatological analysis for Germany and Central European river catchments of first and second order is performed. For the Rhine river catchment a summer mean temperature of 16.1 °C and relative humidity of 74% are found. In contrast, the mean temperature of heat summer 2003 amounts to 19.9 °C with a related relative humidity of 65% in this river catchment. The extreme character of this summer is also remarkable in the presented climate indices, e.g., the increased amount of summer hot days. The first validations of both data sets reveal a bias within the range of the provided data precisions. In addition, an elevation dependency of error scores is identified for temperature. Error scores increase with an increasing station height because height differences between station and grid cell increases with height. A comparison of HYRAS-TAS to another gridded temperature data set reveals a good agreement with again fewer differences at lower altitudes. The presented DWD/BfG-HYRAS data sets have a high spatial and temporal resolution which is unique for Germany and the bordering river catchments so far. They have a high potential for detailed studies of smaller scale structures in Central Europe and are already used as input for hydrological impact modelling, as climatological reference and for bias correction of regional climate models within the German research project KLIWAS. HYRAS-TAS and HURS are part of the DWD/BfG-HYRAS data set which will finally include high-resolution gridded daily data of precipitation, temperature, relative humidity, solar radiation and wind speed.

Keywords: temperature measurement, relative humidity measurement, daily interpolation, climate, KLIWAS

1 Introduction

In the framework of climatological research highly resolved climatological reference data sets of meteorological parameters are required. They are prerequisite for climatological analyses, impact modelling, monitoring of climate change and the validation and bias corrections of regional climate models. Meteorological parameters such as surface air temperature (TAS) and surface relative humidity (HURS) are measured at weather stations distributed irregularly in space. Interpolation methods are applied to generate the desired regular gridded climate reference data from these measurements. As described by Haylock et al. (2008), gridded data is fundamental for climate research and has been used extensively in the past and will be in the future due to its broad scope of applications.

The current study focusses on the generation of a daily mean temperature and a daily mean relative humidity high-resolution gridded data set for Germany and the bordering river catchments. The corresponding precipitation data set has already been presented by Rauthe et al. (2013). In fact, several surface temperature and surface humidity data sets have been developed for several decades. Nevertheless, the two presented surface data sets are the first ones covering Germany and the bordering river catchments on a daily base with a high spatial resolution of 5 × 5 km\(^2\) from 1951 to 2006. They have been developed by the German Weather Service (Deutscher Wetterdienst, DWD) within the context of the German research programme KLIWAS (Impacts of climate change on waterways and navigation - searching for options of adaptation) funded by the Federal Ministry of Transport, Building and Urban Development (BMVBS) and the Federal Institute of Hydrology (BfG).
High resolution data sets of precipitation, surface temperature, relative humidity, wind speed and solar radiation are required as input for hydrological modelling, used as climatological references and for bias correction of regional climate models. The presented DWD/BfG-HYRAS data sets of surface temperature and relative humidity, in combination with the corresponding precipitation data set (Rauthe et al., 2013), allow detailed hydrological and climatological studies, e.g., for river catchments from first to third order.

For the interpolation of irregularly distributed observations to a regular grid, also called gridding, several interpolation methods are available, e.g., Optimal Interpolation (Gandin, 1965) or Kriging (e.g., Stein, 1999; Chilès and Delfiner, 2012). An overview of common objective interpolation methods and gridding in general is given by Haterkamp et al. (1999). In general, the advantages and disadvantages of each interpolation method, the application of the resulting data set, the interpolated parameter and the desired grid resolution should be considered to choose a specific interpolation technique for the addressed problem. As suggested by Hofstra et al. (2008), the choice of the interpolation method modifies the resulting skill of the gridded data set less than station density. In this study, Optimal Interpolation is performed for the gridding of daily temperature and relative humidity following Gandin (1965). This method uses a spatial correlation function to obtain the interpolation weights for each grid cell and has already been successfully applied at DWD.

A data set of monthly mean temperature from 1950 to 2000 has been presented by Humans et al. (2005). They used the thin-plate smoothing splines procedure of Hutchinson (1995) for the interpolation of the measurements to a $1 \times 1$ km$^2$ grid. The data sets of Auer et al. (2008) and Hiebl et al. (2009) are also only available on a monthly base. In contrast, Haylock et al. (2008) developed a daily mean temperature data set for the European land mass (E-OBS) from 1950 to 2006 but only provide a spatial resolution of 0.25°, approximately $17 \times 28$ km$^2$ in Central Europe (see also Hofstra et al., 2009, 2010). Frei (2013) presented a daily mean temperature data set on a $1 \times 1$ km$^2$ grid for Switzerland from 1961 to 2010. He introduced an interpolation method especially developed for complex and mountainous terrain. The usage of nonlinear profiles and of a non-Euclidean distance accounts for the strong elevation dependency of surface temperature and the vertical thermal structure of the atmosphere.

There are many fewer gridded humidity than temperature data sets available. van Maanen (1981), Sinha et al. (1987) and Peixoto and Oort (1996) used radiosonde data to estimate humidity fields at specific pressure levels. Surface measurements of weather stations were used by New et al. (2002), Willett et al. (2008), and Willett et al. (2013). The monthly mean gridded surface data set of New et al. (2002) is provided in a resolution of 10° while Willett et al. (2008) provide a resolution of 5°. Both data sets are on a monthly base. There are several global reanalyses data sets available that provide surface humidity, e.g., ERA-Interim (Dee et al., 2011). Nevertheless, none of the mentioned temperature and humidity data sets satisfies the desired spatial and temporal resolution for Germany and the bordering river catchments to be used as input for hydrological impact modelling and as climatological reference for regional climate models.

In this study we present the development of the spatial and temporal high-resolution HYRAS (HYdrologische RASterdaten) gridded data sets for surface air temperature and relative humidity which are part of the DWD/BfG-HYRAS data set and based upon station measurements. The DWD/BfG-HYRAS data set will finally include gridded data of precipitation (Rauthe et al., 2013), temperature, relative humidity, solar radiation and wind speed. The two data sets, DWD/BfG-HYRAS-TAS for temperature and DWD/BfG-HYRAS-HURS for relative humidity, are presented in version 1.01 which refers to the data base and the interpolation method and is the first published version. Modifications of the data base will raise the third number, while a raise of the second number refers to smaller modifications of the interpolation algorithm. New official releases or fundamental changes are indicated by a raise of the first number. The available data sets of DWD/BfG-HYRAS and the corresponding contact person can be found in the Climate Data Centre of DWD (http://cdc.dwd.de/catalogue). Unfortunately, the use of the data is restricted differently by the different institutions and the possibility of dissemination has to be checked individually.

In Section 2 of this study the data base for both parameters are presented. The grid and the interpolation method for the data sets are described in Section 3. In Section 4 the validation of both data sets is presented. Section 5 focuses on a first climatological analysis for Germany and the bordering river catchments. Finally, a conclusion of the features and characteristics of the two HYRAS data sets is presented.

## 2 The DWD/BfG-HYRAS data base

### 2.1 Temperature

The HYRAS gridded temperature data set DWD/BfG-HYRAS-TAS is based upon daily mean temperature data of Central European weather stations between 1951 and 2006. Station data from Austria, Belgium, Czech Republic, France, Germany, Luxembourg, the Netherlands and Switzerland contribute to this cross-border data base. All countries and data providing institutes are listed in Table 1. The presented data base ends in 2006 because we do not have subsequent station data for each country so far. An update till 2013 is planned as soon as
Table 1: The countries and institutes contributing to the cross-border data base of HYRAS-TAS. Details about the averaging methods are discussed in Section 2.1.

| Country       | Institute                                                                 |
|---------------|---------------------------------------------------------------------------|
| Austria       | Zentralanstalt für Meteorologie und Geodynamik                            |
| Belgium       | Royal Meteorological Institute of Belgium                                 |
| Czech Republic| Czech Hydrometeorological Institute                                        |
| France        | Météo France                                                               |
| Germany       | Deutscher Wetterdienst                                                    |
| Luxembourg    | Administration des Services Techniques de l’Agriculture and Centre de Recherche Public |
| The Netherlands| Koninklijk Nederlands Meteorologisch Instituut                            |
| Switzerland   | Bundesanstalt für Meteorologie und Klimatologie MeteoSchweiz              |

Figure 1: Monthly change of available temperature stations utilized for the generation of HYRAS-TAS. The different countries are represented by different colors. Luxembourg only provides one station (Findel airport) and thus cannot be displayed.

The acquired data is no raw data but has been quality controlled by the providing institutes. Nevertheless, several tests of homogeneity have been performed as suggested by HERZOG and MÜLLER-WESTERMEIER (1998) and applied by RAUTHE et al. (2013), i.e. a modified version of the Mannheim method is applied by the Netherlands, France and average the daily maximum and minimum temperatures, i.e., \( \frac{(T_{\text{min}} + T_{\text{max}})}{2} \), while the remaining countries use the so-called “Mannheim hours” (7, 14 and 21 local mean time) for averaging, i.e., \( \frac{(T_7 + T_{14} + 2 \cdot T_{21})}{4} \). For West Germany, LMT (local mean time) was used for the “Mannheim hours” till 1986 but from then on till 1990 CET (central European time) +30′ was applied to calculate the mean daily temperature. CET is one hour ahead of the coordinated universal time (UTC), i.e., \( \text{CET} = \text{UTC} + 1 \). For Germany, LMT is equal to CET during winter and is one hour ahead of CET during summer. For East Germany, LMT was used till 1961 and CET from then on till 1966. Afterwards, an average of four or eight circadian temperature measurements was applied till 1990. Since 1991, all German stations used the “Mannheim hours” with CET + 30′ to obtain the daily mean temperature. In April 2001, averaging started to switch continuously from the “Mannheim hours” to the true mean in Germany due to automatization of weather stations.

The applied different temperature averages might lead to some discontinuities especially along national borders, e.g., between Austria and Switzerland. SIOGAS (1972) tried to quantify the effects of different averaging methods on monthly and yearly temperature means. It turned out that the annual mean temperature of the “Mannheim hours” overestimates the true annual mean temperature by about 0.23 °C while using the minimum and maximum temperatures leads to an overestimation of approximately 0.67 °C. HIEBL et al. (2009) investigated the greater Alpine region and also discussed the deviations of different averaging methods from the true monthly mean. They found deviations between −0.2 and 0.3 °C for the “Mannheim hours” and between −1.4 and −0.5 °C for the usage of minimum and maximum temperatures. They concluded that using different averaging methods causes non-negligible discontinuities. In contrast, they stated that the usage of different time conventions causes smaller and therefore negligible errors. The HYRAS-TAS data base is chosen to be as broad as possible and includes all available station data. Possible discontinuities are neglected, as well as different time conventions, but should be kept in mind for the validation and usage of the data set. Additional inhomogeneities might occur due to, e.g., the usage of different measuring instruments in different countries or at different stations. Considering only one station, discontinuities might arise from, e.g., changes in station position, measuring time, measuring instrument and land use around the station. This should be kept in mind by looking at long-term trends.

The acquired data is no raw data but has been quality controlled by the providing institutes. Nevertheless, several tests of homogeneity have been performed as suggested by HERZOG and MÜLLER-WESTERMEIER (1998) and applied by RAUTHE et al. (2013), i.e. a modified
Buishand test (Buishand, 1982), the Pettit test (Pettitt, 1979) and the standard normal homogeneity test (Alexandersson, 1986). As a major result, a quarter of the examined station time series were classified as useful and a half as doubtful. Consequently a quarter of the time series has been classified as suspect. The main reason for the large number of doubtful or suspect time series is a break in 1987 where measuring time changed in Germany. Breaks like that have also been detected for time series in other countries. A manual control of the yearly mean time series of the stations revealed very similar results for all stations and therefore none has been removed from the data base. As already mentioned by Rauthe et al. (2013), we refrained from using relative homogeneity testing due to the large effort required for a voluminous daily data set as used in this study. They also mention that there are general difficulties with the homogenisation process and that it requires large efforts to homogenise all time series. As described by Venema et al. (2012), there exist several homogenization techniques and their development and improvement is still work in progress. Therefore, most available gridded daily data sets are entirely or partially based on non-homogenised time series (e.g., Frei and Schär, 1998; Haylock et al., 2008).

In the presented data base, an additional quality control was performed by eliminating daily mean temperature values above 35 °C. This value is distinctly too high for the daily mean temperatures in the investigation area. In fact, only 16 values above this threshold have been detected within the entire investigation period and for all stations. In more detail, 15 of these values correspond to the mountain station Titlis at a geographical height of 3040 m and are consequently classified as measurement errors. This quality control finalizes the initial data base for the generation of HYRAS-TAS which is provided in monthly data files including all stations with a minimum of one valid measurement in this month.

2.2 Relative humidity

The HYRAS gridded relative humidity data set DWD/BfG-HYRAS-HURS is based upon daily measurements of Central European weather stations available from 1951 to 2006. Fig. 3 shows all available stations for January 1971 and January 2001 providing relative humidity data. Station data from Austria, France, Germany, Luxembourg, the Netherlands and Switzerland contribute to the cross-border data base. The provided mean daily relative humidity values are obtained as described for temperature (Section 2.1). The interpolation procedure will extrapolate into regions without station data which should be kept in mind. The temporal change of station quantity is shown in Fig. 4. The maximum station number is reached in spring 1995 with more than 800 utilized stations for the generation of the HYRAS-HURS data set in this month.

As with temperature data, the acquired data is no raw data but has been quality controlled by the providing institutes. Nevertheless, an additional quality control is performed by ignoring station values lower than 0 % or larger than 101 % relative humidity. These values are out of the physically plausible range of relative humidity and are therefore consequently classified as measurement errors. The relative humidity values are provided in a data precision of 1 %. This relatively coarse precision should be kept in mind for the validation of HYRAS-HURS in the next section. As with temperature data, the
Figure 3: Spatial distribution of relative humidity stations (black dots) in January 1971 (left) and January 2001 (right). The grey shading indicates the KLIWAS investigation area for which the HYRAS-HURS data set is generated based upon the presented data base.

Figure 4: Monthly change of available humidity stations utilized for the generation of HYRAS-HURS. The different countries are represented by different colors. Luxembourg only provides one station (Findel airport) and thus cannot be displayed.

initial data base for the generation of HYRAS-HURS is provided in monthly data files including all stations with a minimum of one valid measurement in this month.

3 Interpolation procedure

For the generation of the presented DWD/BfG-HYRAS data sets, an available interpolation module is used. The module has been developed by DWD and is based upon Optimal Interpolation (Gandin, 1965). It is part of the energy- and mass balance SNOW model in version 4 (Reich et al., 2012), which is operated operationally at Deutscher Wetterdienst to forecast snow melt. This interpolation method and module have been used for the generation of HYRAS-TAS and HURS because they already produce reliable results operationally within the SNOW model and are successfully used in the DWD for many years. As suggested by Hofstra et al. (2008), the choice of the interpolation method modifies the resulting skill of the gridded data set less than station density.

The desired and finally provided spatial resolution of HYRAS-TAS and HURS is 5 × 5 km². The applied projection type for the gridded data is the Lambert conformal conic (LCC) projection for Europe based upon the European Terrestrial Reference System 1989 (ETRS89). The ETRS89-LCC Europe projection uses the standard parallels 65 °N and 35 °N with the reference coordinates 52 °N and 10 °E and has the advantage of a nearly equidistant grid which is a necessary requirement for the applied interpolation algorithm.

As described, a final grid resolution of 5 × 5 km² is desired. Nevertheless, the applied module has been developed for the interpolation of irregular measurements to a regular grid with a 1 × 1 km² resolution. Therefore, we perform the interpolation to this narrow grid and average to the coarser one subsequently. The height mask of the 5 × 5 km² grid is obtained by averaging the 1 × 1 km² interpolation height mask.

3.1 Interpolation module

For the generation of the gridded data sets, the applied interpolation method is performed separately for each day of the investigation period. The interpolation process starts searching the 15 to 30 stations influencing the currently considered grid cell. Before starting the
Gandin (1965) algorithm, each of these station measurements \( z \) is decomposed into a background \( z_b \) and an anomaly \( z_a \) value:

\[
z = z_b(x, y, h) + z_a \tag{3.1}
\]

with \( x \) and \( y \) for the horizontal position and \( h \) for station elevation. Thereby the procedure performs a preliminary Trend Surface Analysis as an equivalent to Universal Kriging (e.g., Stein, 1999; Chilès and Delfiner, 2012). The background value \( z_b(x, y, z) \) of each station and of the considered grid cell are derived by multiple linear regression. If regression fails, e.g., the estimated slope is to steep, \( z_b \) is reduced to the arithmetic mean of the influencing stations and the interpolation procedure becomes equivalent to Ordinary Kriging.

In the second step of the Optimal Interpolation procedure, the spatial correlation function \( r \) of all station anomaly values \( z_a \) is derived by using a simple hyperbolic form as

\[
r(d) = \frac{1}{1 + pd^2} \tag{3.2}
\]

with the empirical parameter \( p \) estimated from the current data using Canberra metric to represent similarity. Distance \( d \) (station to station or station to grid cell) is three-dimensional and takes height difference into account. A height difference accounts stronger to distance \( d \) than a horizontal displacement, i.e., a station with a height difference of 50 m has the same distance \( d \) as a station with a horizontal displacement of 1 km. This approach considers the strong height dependency of temperature and humidity and the resulting dissimilarity between stations at different heights.

In the third step, the correlation function \( r \) is used to form the following linear equation system

\[
R w = r. \tag{3.3}
\]

Therein \( R \) is the matrix of inter-station correlation and \( r \) the vector of station-gridpoint correlation both derived from Eq. (3.2) above. The solution vector \( w \) contains the interpolation weights.

The elements of the principle diagonal of \( R \) are enlarged by a factor considering the so-called “nugget effect” (e.g., Clark, 2010; Chilès and Delfiner, 2012) or observational error. On the one hand this “nugget effect” produces more numerical stability at the solution of the equation system, on the other hand it causes a slight smoothing of the interpolated field growing with the specific amount of the nugget factor. For the generation of the HYRAS data sets, this factor is set to \( 2/n \) where \( n \) is the relevant station quantity, i.e., the rank of matrix \( R \).

Finally, the interpolation weights are normalized to a total of 1 and used to calculate \( z_a \). At the last step \( z_a \) and \( z_b \) are re-composed for the considered grid cell as shown in Eq.n (3.1).

### 3.2 Special considerations for humidity interpolation

For the generation of the gridded relative humidity data set HYRAS-HURS some additional efforts are necessary. As already mentioned by Van Maanen (1981), when handling atmospheric humidity, one has to figure out first which humidity parameter is best for the intended purpose.

Humidity measurements used in this study are given in relative humidity (Section 2.2) which is, in fact, the measurement parameter and the desired parameter of HYRAS-HURS because of its direct relation to evaporation and its common application in hydrology. Unfortunately, relative humidity is not only depending on the moisture content of the atmosphere but also on temperature. For the usage of the described interpolation method, the temperature dependency has to be eliminated because it covers the essential underlying spatial trend \((x, y, h)\) of humidity needed for background interpolation (Eq. 3.1). Peixoto and Oort (1996) mentioned that specific humidity and vapor pressure can be regarded as humidity parameters independent of temperature. They also demonstrated that dewpoint temperature and vapor pressure are humidity parameters giving equivalent information. Therefore, it is valid to use specific humidity, vapor pressure or dewpoint temperature for the described interpolation. Lanciani and Salvalati (2008) decided to use the dewpoint temperature for interpolation within the FORALPS project. They used station relative humidity and temperature to obtain the dewpoint. Subsequent to interpolation, gridded dewpoint temperatures are reconverted to relative humidity by using gridded temperature data.

We follow this approach but use vapor pressure \( e_v \) instead of dewpoint temperature. Station data of relative humidity \( f \) is converted to vapor pressure \( e_v \) by using station temperature. If station temperature is missing, the height corrected HYRAS-TAS temperature of the corresponding grid cell is used. Height correction is described in more detail in Section 4.1.1 below. Vapor pressure \( e_v \) is calculated from temperature \( T \) and relative humidity \( f \) by

\[
e_v = \frac{f}{100} e_{v,s}(T) \tag{3.4}
\]

where \( e_{v,s} \) is the temperature dependent saturation vapor pressure given by the Magnus formula

\[
e_{v,s}(T) = c_0 \cdot e^{c_1 T/(c_2 + T)} \tag{3.5}
\]

with \( c_0 = 6.1078 \) and \( T \) in °C. For \( T > 0 \) °C we use \( c_1 = 17.08085 \) and \( c_2 = 234.175 \) °C and for \( T \leq 0 \) °C, i.e., supercooled water, we use \( c_1 = 17.84362 \) and \( c_2 = 245.425 \) °C (Letterer et al., 1997). Subsequent to vapor pressure interpolation (performed equivalent to temperature interpolation, see Section 3.1), we use HYRAS-TAS and invert Eq. (3.4) to obtain HYRAS-HURS.
4 Validation of the DWD/BfG-HYRAS data sets

In order to verify the quality of the provided gridded data sets DWD/BfG-HYRAS-TAS and HURS and to identify their characteristics, different validation methods are applied.

4.1 Temperature data set

DWD/BfG-HYRAS-TAS

4.1.1 Station validation

The HYRAS-TAS data set is validated with the original station data. Therefore, the coordinates of each data base station within the investigation area are related to the HYRAS grid cell enclosing the station. For one day, this approach leads to a set of HYRAS and station value pairs including all stations providing a temperature value at this day. Applied to each day of the investigation period a total number of about 16.9 million pairs of values is obtained. Different error scores for days, month, years, or specific stations can be calculated on the basis of these pairs.

Fig. 5 shows the development of the monthly bias, absolute error and root mean square error (RMSE) averaged over all stations in the entire investigation area. The bias is close to 0 °C with an evident tendency to positive values (see Table 2). The HYRAS-TAS grid cell values are in average 0.14 °C cooler than their corresponding station values, which is in the range of the provided data precision. The absolute error remains below 0.8 °C with an average value of 0.64 °C which is in the same range as the findings of Frei (2013). The RMSE, a measure for the scatter of the deviations between station and related grid cell values, averages to 1.2 °C for the entire investigation period. The mean yearly temperature for the entire investigation area and period accounts to 8.06 ± 0.72 °C, which is slightly below the mean value for Germany (Table 3). The identified RMSE of station validation exceeds the standard deviation of the yearly mean value clearly.

Additionally, Fig. 5 reveals an annual cycle in each error score with minimum values during winter months, meaning that deviation and scatter between data base and HYRAS-TAS are smallest in winter. One possible explanation is the reduced horizontal temperature gradient in these months which leads to a smoother temperature field and therefore to an improved representation of station data in the gridded data set.

The observed shift of the three error scores to slightly higher values in 1959 is related to a sudden increase of station number provided by Switzerland (compare Figs 5 and 1). Swiss station number jumped up from less than 40 stations in December 1958 to more than 60 in January 1959. The higher elevation of the Swiss stations and the height dependency of the error scores (see below) led to the observed increase of the error scores in 1959 while the increase of the provided Czech station number in January 1961 (from around 70 to nearly 100) had no such remarkable influence on the presented error scores.

The pairs of values for all days and stations are summarized in the next step. The resulting quantity distribution is presented in Fig. 6. The corresponding corre-
Table 3: Mean values for the long-term period 1952–2005 of mean daily temperature (± standard deviation) and relative humidity in Germany and the first-order river catchments Rhine, Danube and Weser (compare to Fig. 9). Provided are the mean values for the entire year, for summer (June, July and August) and winter (December of the previous year, January and February). Additionally, the heat summer 2003 (Section 5.2) is presented.

|                | 1952–2005       | 2003            |
|----------------|-----------------|-----------------|
|                | 2003            | summer          | summer          |
| temperature in °C |                 |                 |                 |
| Germany        | 8.46 ± 0.74     | 0.45 ± 1.75     | 16.55 ± 0.97    | 19.65           |
| Rhine          | 8.19 ± 0.70     | 0.37 ± 1.52     | 16.10 ± 1.04    | 19.90           |
| Danube         | 6.68 ± 0.69     | −1.98 ± 1.51    | 15.16 ± 0.97    | 18.79           |
| Weser          | 8.49 ± 0.78     | 0.83 ± 1.89     | 16.25 ± 1.04    | 19.15           |
| relative humidity in % |             |                 |                 |
| Germany        | 79.3 ± 1.4      | 85.3 ± 1.3      | 73.9 ± 3.0      | 66.0            |
| Rhine          | 78.6 ± 1.3      | 83.6 ± 1.3      | 73.8 ± 3.3      | 65.1            |
| Danube         | 77.4 ± 1.3      | 80.9 ± 1.5      | 74.5 ± 2.7      | 66.7            |
| Weser          | 79.9 ± 1.5      | 85.6 ± 1.4      | 73.8 ± 3.3      | 67.1            |

Figure 6: Quantity distribution of all station and corresponding grid cell values of HYRAS-TAS in the entire investigation period and area (total quantity of about 16.9 million pairs) squared in 0.5 × 0.5 °C boxes.

The regression coefficient of 0.988 is close to one, meaning that station values are realistically represented by the used interpolation method. The regression line (red) confirms the relatively weak bias and is close to a perfect match. The detailed investigation of the scatter and spread of the quantity distribution is presented in Table 2. More than 81 % of the analyzed grid cells deviate less than 1 °C from the related station data and less than 0.1 % differ more than 10 °C.

A closer look at stations with a difference between station and grid cell value larger than 10 °C shows that 92.9 % of them correspond to mountainous stations (station height $h_s > 2$ km). Thus, strong deviations between grid cell and station value seem to be related to high station elevations. Possible explanations are the lower station density, the complex orography, the horizontal resolution of the HYRAS grid and the underlying height field. To verify the effects of the latter possibilities on the results of the station validation, a height correction of the HYRAS-TAS grid cell values of the pairs is performed.

Regarding the temperature pairs, where $T_s$ stands for the station and $T_H$ for the grid cell daily mean temperature of a single pair, the different orographic heights of station and grid cell are an important aspect for station validation because temperature is a height dependent meteorological parameter. In addition to the two temperatures $T_s$ and $T_H$, the corresponding station and grid cell heights $h_s$ and $h_H$ are known. To obtain the height corrected grid cell temperature $T_{cH}$, the height difference $\Delta h = h_s - h_H$ is multiplied with the atmospheric temperature gradient ($\partial T/\partial h = −6.5°C/km$) and the product is added to the HYRAS grid cell temperature $T_H$:

$$T_{cH} = T_H + \frac{\partial T}{\partial h} \Delta h. \quad (4.1)$$

Applying this correction leads to a height corrected set of temperature pairs.

Averaging bias and absolute error of the height corrected and uncorrected set of pairs over the entire investigation period for different station height intervals leads to Fig. 7 and to a closer look on the height dependency of the error scores. For the uncorrected station validation, there is an evident tendency to an increasing absolute error with an increasing station height difference. Height correction reduces the slope of this relation.

For the uncorrected pairs, grid cells with a height more than 1 km above station height underestimate station temperature by 5.8 °C on average. In contrast, an overestimation of nearly 7.6 °C on average is found for grid cells with a height more than 1 km below station height. The bias is minimal for a minimal difference between station and grid cell height. For the height corrected pairs, the underestimation of 5.8 °C changes into an overestimation of 1.4 °C while the overestimation of 7.6 °C changes into an underestimation of 1.4 °C in average. After height correction, the bias is no longer significantly decreasing but is slightly increasing with an
increasing height difference. A perfect match can never be obtained due to two major reasons. First, the temperature gradient is only a constant approximation neglecting changing humidity conditions. Second, temperature inversions are neglected completely.

Averaging over all pairs of values leads to the height corrected station validation, presented in Table 2, which can be directly compared to the uncorrected validation. The elimination of height difference between the HYRAS-TAS grid cell and the related station reduces the mean bias significantly from 0.14 °C to −0.02 °C which is below the measurement error and precision of the investigated daily mean temperature. Absolute and root mean square error are also reduced by some tenths of a °C. The height correction also shows a remarkable improvement for the weak and strong deviations. The percentage of grid cells with less than 1 °C deviation to station data is increased from 81.3 % up to 89 % by height correction while the percentage of grid cells with a deviation above 10 °C is reduced. Additionally, less mountainous stations ($h_i > 2$km) are related to this large deviation. Their percentage is reduced from 92.9 % to 65.3 %. Also the correlation coefficient is slightly improved from 0.988 to 0.994.

The bias of the height corrected and the bias of the uncorrected station validation are split into single values for winter, spring, summer and autumn to obtain information about seasonal variability (Table 4). In the winter months, which have relatively weak temperature gradients, the uncorrected station validation produces only a weak bias compared to the other seasons. Therefore, the height corrected (−0.093 °C) bias of winter shows a higher deviation to zero than the uncorrected (0.075 °C) while the application of the height correction shifts the biases of spring, summer and autumn closer to zero.

By applying a height correction, station validation is improved significantly. The height difference between station and the corresponding grid cell is a non-negligible feature for the validation of the data set. For the usage of HYRAS-TAS it follows, that for investigations focusing on height or temperature dependent parameters the HYRAS height field should be considered, especially for warmer seasons.

### 4.1.2 Cross-validation

In this section, the interpolation method for the generation of HYRAS-TAS is investigated in more detail by performing a fivefold cross-validation. In this context cross-validations is applied to examine the capability of the interpolation method to represent the temperature field at grid points without a corresponding data base station.

First, five subsets of the initial data base (Section 2.1) are generated by leaving out randomly one fifth of the stations each month. These five subsets are named interpolation subsets. Each station is left out in one of the interpolation subset, i.e. is part of the corresponding validation subset which is the non-overlapping complement. This is a typical realization of cross-validation, because creating a number of subsets equal to the number of stations (in each subset exactly one station is left out) is very CPU-intensive and leads to a large amount of data. Fig. 2 illustrates the five generated data bases for the cross-validation performed for this study. All available stations for January 1971 (left) and January 2001 (right) are presented. Colors indicate the five validation subsets for these month. In short, the sum of the five validation subsets lead to the full data base including 100 % of station data.

Second, five HYRAS-TAS data sets are generated based upon the five interpolation subsets. Subsequently, each station measurement of the validation data base is related to the HYRAS-TAS value of the enclosing HYRAS grid cell. Merging the resulting five sets of

### Table 4: Seasonal biases and absolute errors for station validation and height corrected station validation for the entire investigation area for HYRAS-TAS.

|         | spring      | summer     | autumn     | winter     |
|---------|-------------|------------|------------|------------|
| bias    | 0.193 °C    | 0.165 °C   | 0.146 °C   | 0.075 °C   |
| height corrected bias | 0.027 °C | −0.002 °C | −0.020 °C | −0.093 °C |
| absolute error | 0.714 °C | 0.715 °C | 0.628 °C | 0.591 °C |
| height corrected absolute error | 0.405 °C | 0.418 °C | 0.480 °C | 0.517 °C |
station and corresponding HYRAS-TAS pairs of values leads to one set having the same dimension as the station validation set of pairs. Consequently, the obtained error scores and percentages are directly comparable to the results of station validation and lead to an assessment of the capability of the interpolation method to represent the temperature field where no station data for interpolation exists.

Fig. 8 shows the monthly error scores averaged over the entire investigation area and period for station and cross-validation. The missing underlying station data for interpolation has no significant influence on monthly bias, i.e., grid cell values without a related station in the interpolation subset neither tend to a consistent over-estimation nor underestimation of station temperature. While the bias is nearly the same for station and cross-validation, absolute and RMSE worsen without the underlying station data.

The detailed scores and values of cross-validation are listed in Table 2 and reinforce the findings of Fig. 8 with an overall bias equal to station validation. The overall absolute error is increased by 0.23 °C and RMSE by 0.19 °C compared to station validation and represent the enhanced variability and uncertainty due to the missing underlying station values. These errors are in the same range as the findings of Frei (2013). The percentage of grid cells with a deviation of less than 1 °C to the validation stations is reduced from approximately 81.3 % to 72.2 % while the percentage of grid cells with a deviation above 10 °C is slightly increased. The proportion of mountainous stations on the large deviations (ΔT > 10 °C) is reduced by approximately 3 % as a result of the general increase of uncertainty in cross-validation, i.e., more non-mountainous stations additionally contribute to the large deviations.

In summary, while variability and uncertainty is increased by missing underlying station data, bias is nearly unaffected. This is a very positive and desirable property because temperature values at grid cells without underlying station data are not systematically over- or underestimated. Additionally, changes in station quantity do not tend to produce systematic errors.

4.1.3 Comparison to the E-OBS data set

The presented HYRAS-TAS data set has been validated with station data so far. In this section, a comparison to an already existing temperature data set for Europe will be presented. Haylock et al. (2008) introduced the European land-only daily high-resolution gridded data set for mean surface temperature for the period 1950–2006, called E-OBS, which is provided on a regular 0.25 °C horizontal grid (a resolution of approximately 25 × 25 km²). In this study version 8.0 of the data set is utilized. It should be mentioned, that HYRAS-TAS and E-OBS are nearly based upon the same stations within the KLIWAS investigation area. Therefore, a comparison of both data sets will provide insight into the effects of the different interpolation methods, horizontal resolution and height fields.

For the comparison of the two data sets both should be present at the same horizontal grid. Thus, HYRAS-TAS is interpolated on the coarser grid of the E-OBS data set. The grid conversion is performed by bilinear interpolation using the Climate Data Operator (Schulzweida, 2013). Once, both data sets have the same resolution a grid by grid comparison is carried out.

Fig. 9 shows the spatial distribution of the mean bias of HYRAS-TAS to E-OBS averaged over the entire investigation period. Positive values indicate a colder HYRAS-TAS data set compared to E-OBS. Note, we now compare to gridded data sets which differs basically from previous comparisons to station data. The presented bias varies between −2.5 and 2.5 °C with maximum values in the Alpine region and typical values between −0.4 and 0.4 °C in the lowlands. As mentioned in the context of the height correction, gridded data sets are sensitive to the underlying height field. Due to the different original horizontal resolutions of HYRAS-TAS and E-OBS and the transformation of HYRAS-TAS to the E-OBS grid, differences in height dependent temperature are evident in regions with complex topography, e.g. in the Alpine region, the Black Forest, the Vosges, the Erz and Giant mountains. Averaged over the entire investigation area, a bias of 0.05 °C is obtained. The averaged deviation is very small, below the provided data precision, showing a weak tendency to a colder HYRAS-TAS data set.

In addition to the monthly averaged error scores of station and cross-validation, Fig. 8 shows also the results for the comparison of HYRAS-TAS to E-OBS. The bias stays positive for all month and never exceeds the data precision of 0.1 °C. The mean absolute error remains relatively constant through the year with an overall mean value of 0.43 °C. The RMSE has an average value of 0.60 °C. Overall, the differences between the two data
sets are in the same order as for the height corrected station validation (Section 4.1.1, Table 2). The correspondence between the data sets is high even though they were generated by different interpolation methods and for different horizontal resolutions.

4.2 Relative humidity data set
DWD/BfG-HYRAS-HURS

4.2.1 Station validation

HYRAS-HURS is validated with its own data base, as already presented for HYRAS-TAS, to obtain an insight into the quality of data representation. Station validation leads to a total number of about 13.6 million pairs of values. The monthly averaged error scores are presented in Fig. 10 and summarize the entire investigation area.

The bias is close to 0 % relative humidity with no evident tendency to an over- or underestimation of the station data base by HYRAS-HURS and no obvious annual cycle. Over the investigation period it averages to −0.03 % which is significantly below the provided data precision of 1 % relative humidity. The absolute error alternates between 3 and 5 % and averages to 3.2 % while RMSE averages to 5.5 % for the entire investigation period. An annual cycle is evident for both error scores with maximum values during the winter months. The mean yearly relative humidity for the entire investigation area and period accounts to 79.5 ± 1.2 %, which is slightly above the mean value for Germany (Table 3).

The identified RMSE of station validation exceeds the standard deviation of the yearly mean value clearly.

For the consideration of the errors scores, it should be kept in mind, that relative humidity station values are provided in a precision of 1 % and consequently HYRAS-HURS is provided with a data precision of 1 % relative humidity. Thus, the error score precision of a single pair of values amounts to 1 %.

The correlation coefficient obtained from all pairs of station and related HYRAS-HURS values is close to 0.9 which is significantly below the one of HYRAS-TAS and reflects the enhanced scatter of the differences. A closer look at the deviations reveals that 94.5 % of the pairs have an absolute error of less than 10 % and 80.9 % of less than 5 % relative humidity. A difference of 0 or 1 % relative humidity is achieved by 42.9 % of the pairs. Additionally, the regression line (not shown) reveals that station values below 80 % relative humidity are reproduced too wet while station values above 80 % relative humidity are reproduced too dry.

In contrast to HYRAS-TAS, there is no evident height dependency for the error scores of HYRAS-HURS. For deviations of minimum 10 % relative humidity only 10.5 % are related to mountain stations with a height above 2 km. The amount is increased to 17.6 % for deviations of minimum 15 % relative humidity. Compared to the results of HYRAS-TAS (Table 2) there is no clear evidence for a height dependency of the error scores even though HYRAS-TAS is used for the conversion to relative humidity after interpolation (Section 3.2).
The representation of station values in HYRAS-HURS is not as good as for HYRAS-TAS. One reason for the higher uncertainty is the available data precision of 1% relative humidity in the data base and the resulting data set. Another reason is the implicit usage of relative humidity for the generation of HYRAS-HURS. As described in Section 3.2, relative humidity station data is first converted into vapor pressure by using temperature station data or height corrected HYRAS-TAS. In a second step, the interpolation of the vapor pressure is performed. Finally, the vapor pressure gridded data is reconverted into relative humidity by using HYRAS-TAS. Thus, the process itself and the uncertainties of HYRAS-TAS lead to higher uncertainties in the final HYRAS-HURS data set.

To sum up, there is no clear tendency to a systematic over- or underestimation of the station relative humidity by the gridded data set and the error scores are in the magnitude of the provided data precision. Additionally, there is no height dependency of the error scores.

A comparison of HYRAS-HURS with other humidity data sets, as presented in the introduction, is not performed because there is no daily data set covering even partly the investigation area with a sufficient spatial resolution for a reasonable comparison (see Section 1).

5 The gridded DWD/BfG-HYRAS data sets

In this section, a first climatological analysis of the HYRAS-TAS and HURS data sets is presented with a specific focus on the summer heat wave of 2003 in the second part.

5.1 Climatological analysis

The long-term (1952–2005), years with incomplete winters are excluded) annual mean temperature for Germany is $+8.5 \pm 0.7 \, ^\circ C$ and for winter (summer) we find $+0.4 \pm 1.7 \, ^\circ C$ ($+16.5 \pm 1.0 \, ^\circ C$) as presented in Table 3 (mean value ± standard deviation). Winter stands for December, January and February (DJF). For a specific year, December of the previous year and January and February of the current one are used. Summer corresponds to June, July and August (JJA) of the current year. Fig. 11 illustrates the temporal evolution of the annual, summer and winter mean temperature for Germany. The coldest annual mean ($+6.9 \, ^\circ C$) and the coldest summer mean value ($+14.8 \, ^\circ C$) were detected in 1956. The coldest winter ($-5.4 \, ^\circ C$) was found in 1962/63, where Lake Constance on the German-Swiss border was frozen. Warmest annual conditions ($+9.8 \, ^\circ C$) were observed in the year 2000, warmest winter conditions ($+3.6 \, ^\circ C$) in 1974/75 and warmest summer conditions ($+19.6 \, ^\circ C$) in 2003, where the western part of Europe was affected by an outstanding heat wave (Section 5.2). These results agree with the warmest and coldest conditions found within the German Climate Atlas (http://www.dwd.de/klimaatlas).

The relative humidity long-term annual mean (1952–2005) is about $79.3 \pm 1.4 \%$ with lower values in summer ($73.9 \pm 3.0 \%$) and higher values in winter ($85.3 \pm 1.3 \%$). The temporal evolution of the annual, summer and winter mean relative humidity in Germany is presented in Fig. 11. The years 1959, 1976 and 2003 have the lowest annual mean relative humidities. Very dry summer seasons are related to high temperatures as perceived for the summers of 1976, 1983, 1992, 1994 or 2003. Most wet winters occurred within the first three decades of the investigation period.

The high-resolution and broad spatial coverage of the presented HYRAS data sets allows a detailed climatological analysis focusing on hydrological relevant regions. Therefore, mean values of temperature and relative humidity have been calculated exemplarily for the first-order river catchments Rhine, Danube and Weser (see black lines in Fig. 9). There are slight differences between the values of the river catchments and Germany (Table 3). In general, the Danube river catchment has lower temperature mean values than found for Germany, Rhine and Weser. A negative winter mean temperature is a special characteristic of the Danube region. The summer heat wave of 2003 led to the summer with the highest mean temperatures for Germany and the discussed three river catchments. For relative humidity, only the winter 1975/76 has a lower mean value than 2003 for Rhine and Weser.
Regarding the long-term trends, the lack of homogenisation of input station data should be kept in mind. Nevertheless, we find a long-term (1952–2005) linear trend of +1.3 °C for the yearly temperature mean for Germany and a decrease of the yearly mean relative humidity of −2 %. Both trends are larger than the standard deviation of the corresponding mean values (compare to Table 3). For summer (winter) we find a temperature increase of +1.4 °C (+1.7 °C) and a relative humidity decrease of −3.8 % (−1.9 %). For the first-order river catchments these trends differ sometimes more, sometimes less, e.g., the yearly mean relative humidity decreases −1.7 % for the Rhine and −3.5 % for the Danube river catchment and the summer mean temperature increases +1.4 °C for the Weser and +1.8 °C for the Danube river catchment.

The high resolution of the DWD/BfG-HYRAS data sets allows trend analyses even on smaller scales, i.e., for river catchments of the second order. Fig. 12 shows the regional varying trends of temperature and humidity for river catchments of the second order. Fig. 12 shows the regional varying trends of temperature and humidity for second-order river catchments completely covered by the data sets. For temperature, the maximum trends (above +1.6 °C) are found along the Rhine Valley and in the eastern Chzech Republic. The minimum trends (between +0.8 and +1.2 °C) are located in the eastern parts of Germany and in the coastal regions. A more homogeneous structure is found for winter with maximum trends (above +1.4 °C) in northern Germany. The maximum decrease of relative humidity in summer (below −4.4 %) is located in the Upper Rhine Valley. Minimum decreases are found in the alpine and coastal regions. Winter trends are weaker with maximum decreases in eastern Germany. Nearly all presented second-order river catchment trends for temperature and relative humidity have a significance level of above 95 %. For spring and autumn (not shown), the observed trends are weaker with slightly positive humidity trends in some river catchments. It should be kept in mind, that HYRAS-TAS and -HURS are not independent data sets because HYRAS-TAS is used for the calculation of HYRAS-HURS (see section 3.2).

In addition to the long-term (1952–2005) investigations for Germany and the river catchments, the WMO (World Meteorological Organization) climate normal period (1961–1990), which is typically used as reference period, is examined in more detail. The mean values of the normal period shows only slight differences compared to the long-term period in Germany (Table 3). The mean annual (summer/winter) temperature is 8.3 ± 0.7 °C (16.3 ± 0.8 °C/0.2 ± 2.0 °C) and the mean annual relative humidity 79.4 ± 1.3 % (74.0 ± 3.0 %/85.4 ± 1.3 %). The extended time period in this study keeps mean values nearly unaffected. Fig. 13 shows spatial distributions of some climate indices for the normal period, i.e. mean winter (bottom) and summer (top) values of temperature and relative humidity, hot summer days (c, amount of days with a mean daily temperature above 20 °C), winter frost days (g, amount of days with a mean daily temperature below 4 °C) and the amounts of days with a daily mean relative humidity below 70 % in summer (d) and above 90 % in winter (h). The indices are calculated for the 5 × 5 km² HYRAS grid resolution and allow a very detailed investigation of small scale structures.

In summer, the spatial pattern of mean daily temperature has a range of 5 to 20 °C with low values in the alpine region and high values in the Upper Rhine Valley. In general, temperature is decreasing with increasing height and largest temperature gradients are related to strongest height gradients, e.g., between alpine valleys and the Alps. Warm regions (Upper Rhine Valley, parts of the eastern lowlands and the tri-border region of Austria, Hungary and the Czech Republic) are related to regions with more hot days in summer. The majority of the investigation area shows only a few hot days, i.e. less than 15 days per summer. During winter season, mean daily temperatures vary from −10 °C up to +4 °C. Lower mean temperatures are connected to higher elevations (Alpine region, Giant and Erz Mountains, Thrugian and Bohemian Forest) and regions with continental climate (Czech Republic). The maritime influenced western and northern parts of the domain show higher mean temperatures (the Netherlands, Cologne Lowland, France and Upper Rhine Valley). Especially for frost days a temperature gradient from north-west to south-east becomes evident. In the Alpine region, mostly all winter days are affected by frost, while the Netherlands show only half of these amounts.

In summer, the mean relative humidity values show a spread from 65 to 85 % in different regions with the highest values located near the coast, in maritime influenced north-western parts of the domain and in the Alpine region where mountains are typically located at cloud height in contrast to the dryer valleys north and south of the alpine ridge (KIRCHHOFER, 1982). Southern and eastern parts of the investigation area and at low altitudes are characterized by the lowest values. Summer days below 70 % relative humidity show similar spatial patterns. The occurrence frequency of these days varies spatially: near the coastline of North and Baltic Sea only a few days exist, but the Upper Rhine Valley, East Germany and the Alpine valleys (i.e. Swiss Upper Inn, lee of Swiss Jura) show more than 50 days per summer. In winter, the mean relative humidity is slightly differently distributed compared to summer patterns. Coastal lowlands and Uplands (Eifel, Harz Mountains, Thrugian Forst) show mean values higher than 90 %, while the Alps show the lowest values.

The presented analysis of temperature and relative humidity provides a broad overview of the recent climate conditions in Germany. Additionally, the specific characteristics of the new data sets allows trend analyses broken down to the first- and second-order river catchments providing important insight in the spatial variance of temperature and humidity trends. The DWD/BfG-HYRAS data sets have a great potential for even smaller scale analyses as presented by the analysis of climate indices for the WMO normal period in grid cell resolution.
Figure 12: Temperature (a and b) and relative humidity (c and d) trends for 1952–2005 summer (a and c) and winter (b and d) calculated for second-order river catchments completely covered by the investigation area. This type of analysis is possible due to the presented high-resolution gridded HYRAS data sets.

Figure 13: Climatological analysis of mean daily temperature and relative humidity for the WMO climate normal period (1961–1990). Presented are summer (top) and winter (bottom) climate indices. For both seasons, mean daily temperature (a and c) and relative humidity (b and f) are shown. Additionally, the amounts of days with a mean daily temperature above 20 °C (c, summer hot days) and of days with a mean daily relative humidity below 70 % (d) are presented for the summer season while the amounts of days with a mean daily temperature below 4 °C (g, winter frost days) and of days with a mean daily relative humidity above 90 % (h) are presented for the winter season.
However, the knowledge of the past climate is essential for the assessment to future climate and the validation of climate models.

5.2 The summer heat wave of 2003

In Germany as well as in most parts of Western Europe, the summer heat wave of 2003 was a record breaking extreme event and led to the warmest conditions since 1761 (e.g., Schönwiese et al., 2004; Schär et al., 2004; Fink et al., 2004; ProCLIM, 2005). Consequently, extreme low water levels were detected and led to an increase of the welfare loss of the inway waterway transport (e.g., Jonkeren et al., 2007). In summer 2003, a large-scale anomaly occurred which was mainly induced by a very stable atmospheric circulation pattern in form of an extended blocking high pressure system. With west and east flanking low pressure systems a quasi-stationary Rossby wave was present. As a result, surface air temperatures were rising to very high levels and established in some regions the hottest conditions ever measured. In this section, we shortly describe climate indices in summer 2003 and compare their characteristics to the ones of the WMO climate normal period (1961–1990) presented in the previous section (Fig. 13).

In comparison to the normal period mean summer temperature, an anomaly of $+3.3\, ^{\circ}\!\!\!\text{C}$ was detected for Germany in summer 2003. The entire investigation area was affected by this anomaly but the spatial distribution of the mean summer temperature (Fig. 14) is very similar to the distribution of the WMO climate normal period (Fig. 13). In 2003, the colder mountainous regions, e.g., the Black Forest, show temperatures comparable to the ones in the warm regions of the climate normal period, e.g., the Upper Rhine Valley. Very hot conditions are present especially in the Upper Rhine Valley and surrounding parts of the River Neckar (Heilbronn, Stuttgart) which show a mean daily summer temperature above $23\, ^{\circ}\!\!\!\text{C}$ in 2003. The number of hot days was higher than in the normal period. In southern parts of the domain the highest amounts of these days (50–80 days) were measurable. Less hot days, but still more than in the climate normal period, are visible in areas near the coast and at higher altitudes, e.g., Eifel, Harz, Erz and Giant Mountains.

The mean relative humidity of the heat summer 2003 was 8 % below the WMO period summer mean in Germany. A closer look on the amount of days with relative humidity below 70 % reveals that most regions show more than 60 to 70 of these days in summer 2003. Exceptions are present near the North and Baltic Sea and in the Alps. Overall, the summer heat wave of 2003 was not only characterized by extreme high temperatures but also by very low relative humidities.

The low precipitation amounts in summer 2003 were mostly generated by large-scale blocking high-pressure systems (e.g., Fink et al., 2004). Low water levels in rivers were reported (e.g., ProCLIM, 2005; BfG, 2006; Jonkeren et al., 2007) and soil moisture dropped to a record low (DWD, 2003) because of the low precipitation amounts and the co-occurring high temperatures. In fact, precipitation amounts for this summer were 30 to 60 % lower than in the WMO climate normal summer (obtained from HYRAS-PRE). Due to the positive relation between actual evaporation and moisture sources as lakes, rivers and soil, extremely low near-ground relative humidity occurred in summer 2003. The convective driven cycle of summer precipitation has a positive feedback leading from precipitation to soil moisture to evaporation to humidity back to precipitation and was considerably disturbed during the summer heat wave of 2003.
6 Conclusions and outlook

High-resolution (5 × 5 km²) daily data sets of surface temperature and relative humidity for Central Europe have been created, investigated and validated in this study. These data sets, namely DWD/BfG-HYTAS-TAS and HURS, in addition to the precipitation data set DWD/BfG-HYRAS-PRE (Rauthe et al., 2013), have been developed within the framework of the KLIWAS research project and are relevant for, e.g., climatological studies (Section 5), bias correction of regional climate models (e.g., Berg et al., 2012; KLIWA, 2012; Imbery et al., 2013), hydrological modeling and as climatological reference.

HYRAS-TAS and HURS are based upon measurements of daily mean temperature and relative humidity provided by several countries. After quality control, measurements are gridded using the interpolation method described in Section 3.1 following the Optimal Interpolation approach of Gandin (1965). The created gridded DWD/BfG-HYRAS data sets are validated using station validation. Additionally, a cross-validation is performed for HYRAS-TAS and it is compared to the E-OBS surface temperature data set (Haylock et al., 2008).

The obtained mean biases of all temperature validations are consistently in the range of the data precision of 0.1 °C. For relative humidity the mean bias of station validation is close to 0 %. Consequently, the developed high-resolution gridded data sets have in average no clear tendency for over- or underestimating the measured conditions. For temperature, a height dependency of bias and absolute error is identified with higher absolute errors found at higher altitudes. The HYRAS height field and the resulting height differences between stations and grid cells are identified as the major reason. These differences lead to a systematic temperature underestimation for grid cells allocated at higher altitudes than the corresponding station and vice versa. Therefore, the underlying height field should always be considered by the usage of HYRAS-TAS.

A climatological analysis of the two data sets gives an overview of the past climate in Central Europe. Mean values and trends for Germany and first- and second-order river catchments represent the past climatic conditions and show regional differences, e.g., positive temperature trends in summer are minimum in Eastern Germany and maximum in the Danube and Rhine river catchments. Additionally, the spatial distributions of some climate indices for the climate normal period and the entire investigation area are presented in grid cell resolution. In this context, the summer heat wave of 2003 is identified as the summer with the highest mean daily temperatures (19.6 °C) in Germany for the entire investigation period and was related to a very low mean relative humidity (66 %). Consequently, the climate indices are significantly affected, e.g., about 80 summer hot days in summer 2003 in the rhine valley compared to the long-term average of 30. HYRAS-TAS and HURS have a high potential for further detailed studies of smaller scale structures, in time as well as in space, and are available for free for research projects from the authors.

Besides the mean daily temperature and relative humidity, a corresponding precipitation data set has already been presented (Rauthe et al., 2013) and is applied for serveral purposes (e.g., Berg et al., 2012; KLIWA, 2012; Imbery et al., 2013). Additionally, further development is desired as, e.g., the generation of daily high-resolution data sets of solar radiation, wind speed, maximum and minimum temperature. An extension of the data base, e.g., including Poland and station data beyond the investigation area, would lead to a completely covered Oder river catchment and reduced extrapolation errors on the borders of the investigation area. In addition, a temporal extension of the data set is desirable and planned as soon as possible.

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