Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

Climatological time series for the KfC project High-Quality Climate Projections (Theme 6 WP3)

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De Bilt, 2015 | Technical report; TR-348

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June 2, 2015

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Title	Climatological time series for the KfC project High-Quality Climate Projections (Theme 6 WP3)
Project	Knowledge for Climate (KfC), Theme 6: High-Quality Climate Projections, Work Package 3
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1. Introduction

After the publication of the KNMI'06 climate change scenarios for the Netherlands (Van den Hurk et al. 2006), it took several years before the impacts of these KNMI'06 scenarios were estimated. One of the reasons for this was the lack of climatological time series that could be used directly in models to simulate, for instance, hydrological, ecological and agricultural impacts. The data requirements vary with sector and case study and tailoring of the climatological data appears necessary. For instance, river management is typically interested in basin-scale extreme precipitation and agriculture in local extreme rainfall during certain periods of the growing season. Yet, there are also many similarities between the hydrological, agricultural and ecological data requirements: They need information, directly or indirectly, on rainfall (extremes and drought), temperature (mean, minimum and maximum), wind, humidity and radiation (directly or for the estimation of evapotranspiration), often on a daily time resolution.

Climate change itself is not of most interest to society, but the impacts in several sectors are. Therefore, in the Knowledge for Climate (KfC) project "High-Quality Climate Projections" (Theme 6) a Work Package (WP3) was included on "Scenario development for climate change impact". The central research question of this WP3 was: "How to couple climate projections to impact assessment models and how can uncertainty in the impact assessment be incorporated in such a way that it can effectively be used by the adaptation climate community?"

This report presents a set of time series that largely match the KNMI'14 climate change scenarios (KNMI 2014; van den Hurk et al. 2014), constructed to enable early impact assessments before the official publication of the KNMI'14 climate scenarios. In this way, the time between the publication of the climate scenarios and estimates of related impacts can be reduced and at the same time this may promote the coherence in data use between different sectors.

The data requirements were discussed with the partners in WP3 (climate variables, spatial and temporal resolution, area to be covered, etc.) and are discussed in chapter 2. After determining the requirements for the common dataset, methods were developed to generate the dataset. The future time series are obtained by *transformation* (chapter 3) of the reference time series. This is often referred to as *perturbation* or *delta* method. Some climate variables are derived with the help of the other transformed time series (e.g. potential evapotranspiration, relative humidity).

2. Reference time series

Two 30-year (1981-2010) reference datasets have been constructed to enable early impact assessments (Klerk et al. 2015, e.g.). The first dataset (Rhine-Meuse dataset) provides daily data for the entire Rhine and Meuse catchment and the entire surface of the Netherlands at a 0.25° x 0.25° regular grid similar to the E-OBS grid (see figure 2.1). Table 2.1 presents the variables that were derived.

Table 2.1: *Rhine-Meuse dataset: required variables, as discussed with the partners from WP3 in Theme 6, Knowledge for Climate research programme*

Variable	Symbol	Units	Source
daily mean temperature	Tg	[°C]	E-OBS v7.0
daily minimum temperature	Tn	[°C]	
daily maximum temperature	Tx	[°C]	
daily precipitation amount	P	[mm]	
daily mean sea level pressure	slp	[hPa]	
daily downward short wave surface radiation	Rs	[kJ m^{-2}]	ERA-Interim
daily Net long wave surface radiation	Rl	[kJ m^{-2}]	
daily maximum relative humidity	RHx	[%]	
daily minimum relative humidity	RHn	[%]	
daily mean wind speed at 10m	$w10$	[ms^{-1}]	
daily mean wind direction (from which blowing)	$wdir$	[degrees]	
daily mean atmospheric transmittance	kt	[-]	Rs
daily mean relative humidity	RH	[%]	RHn, RHx
daily reference crop evapotranspiration (according to Makkink)	ev_{mk}	[mm]	Rs, Tg
daily mean vapour pressure	e_a	[kPa]	RHn, RHx, Tx, Tn
early morning vapour pressure	e_a6h	[kPa]	RHx, Tn

The second reference dataset (North sea dataset) has been constructed to model storm surges (Klerk et al. 2015). It provides 3-hourly instantaneous 'forecasts' from the ERA-Interim Reanalysis (Berrisford et al. 2011) (full resolution) for a region extending from 43.5° to 60° latitude and from -15° to 15° longitude. The dataset covers the entire North sea and includes the following variables (Table 2.2):

Table 2.2: *North sea dataset, as discussed with the partners from WP3 in Theme 6, Knowledge for Climate research programme*

Variable	Symbol	Units	Source
U-component (eastward direction) of daily mean wind at 10m	$u10$	[ms^{-1}]	ERA-Interim
V-component (northward direction) of daily mean wind at 10m	$v10$	[ms^{-1}]	
Sea level pressure	slp	[hPa]	

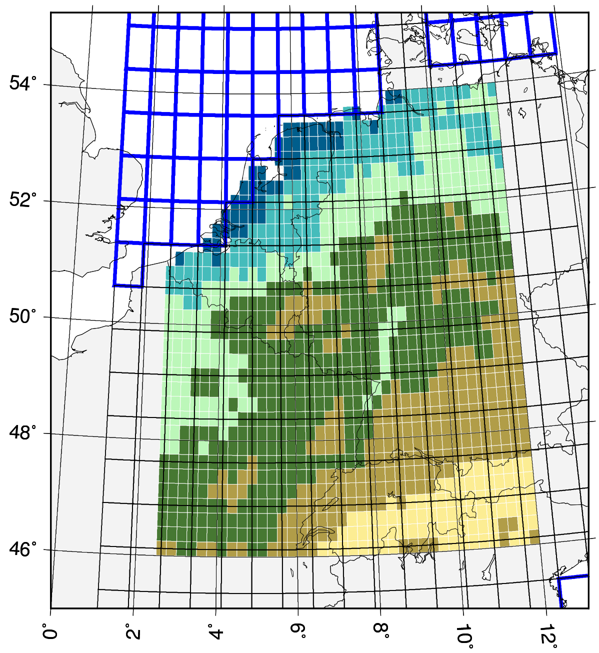

Figure 2.1: *Applied grid for land datasets (filled small boxes), where the colours refer to height with respect to mean sea level. The boxes with grey lines, other that the longitude/latitude lines show the ERA-Interim grid from which many data were derived. Blue bounded boxes refer to sea cells.*

2.1 E-OBS

Where possible daily time series were subtracted from the European daily high-resolution observational gridded dataset E-OBS version 7.0 (Haylock et al. 2008; Van den Besselaar et al. 2011) because of its high quality, rigorous documentation and general and easy availability. *Temperature* (Tg, Tn and Tx), *precipitation* (P) and *sea level pressure* (slp) have been obtained directly from this dataset.

2.2 ERA-Interim

E-OBS does not provide all necessary variables (see table 2.1) and neither it provides time series above sea at sub-daily temporal resolution necessary for assessments of storm surges (see table 2.2 Klerk et al. 2015). These data have been derived from the courser spatial, but finer temporal resolution ERA-Interim Reanalysis (Berrisford et al. 2011), if available. First daily values are estimated from the sub-daily 'forecasts' and 'analyses'. Second, these daily data are regridded to the E-OBS grid by a nearest neighbour interpolation from ERA-Interim land cells only.

Daily downward short wave (Rs) and net long wave radiation (Rl) have been obtained by summing two 12-hour accumulated 'forecasts'.

Daily minimum (RHn) and maximum (RHx) relative humidity have been obtained by selecting the minimum and maximum instantaneous 'forecasts' per day.

Daily mean wind speed ($w10$) and wind direction from which blowing ($wdir$) have been derived from 6-hourly analyses of the U- and V-component of the 10m wind ($u10$ and $v10$, see table 2.1). For $wdir$, first, the daily mean $u10$ and $v10$ are estimated by equation 2.1.

$$X_{day} = \frac{X(0)/2 + X(6) + X(12) + X(18) + X(24)/2}{4} \tag{2.1}$$

where X is the particular variable of interest ($u10$ or $v10$) and the argument refers to the time of the particular day of interest in hours UT (0 = 0:00UT and 24 = 0:00UT next day). After obtaining daily mean $u10$ and $v10$, the direction is subsequently estimated from the two-argument arctangent of the two components (equation 2.2).

$$wdir = \mathrm{atan2}(-u10, -v10)\frac{360}{2\pi} = 270 - (\mathrm{atan2}(v10, u10)\frac{360}{2\pi}) \tag{2.2}$$

For the estimation of daily mean $w10$, first the 6-hourly values are calculated and subsequently the daily means are derived.

2.3 Remaining derived variables

Finally, the remaining variables necessary for the impact modelling or for the time series transformation are derived from the above mentioned data.

Atmospheric transmittance (kt)[1] is the quotient of Rs and the downward short wave radiation at the top of atmosphere (Angot radiation, R_A).

$$kt = \frac{Rs}{R_A} \tag{2.3}$$

Daily mean R_A [kJ m^{-2}] depends on day number J and latitude ϕ [rad] and can be estimated by the following equation (Allen et al. 1998)

[1] kt was originally preferred over Rs because it is more homogeneous in time. Yet, final results appear insensitive for the choice of variable and the official transformation program. Bakker (2015b) therefore applied a transformation of Rs.

$$R_A = 1000\frac{24 \cdot 60}{\pi}G_{sc}d_r[\omega_s \sin(\phi)\sin(\delta) + \sin(\omega_s)\cos(\phi)\cos(\delta)] \tag{2.4}$$

in which G_{sc} is the solar constant (0.0820 MJ m^{-2} min^{-1}), d_r the inverse relative distance Earth-Sun (equation 2.5), δ the solar declination [rad] (2.6) and ω_s the sunset hour angle [rad] (equation 2.7)

$$d_r = 1 + 0.033\cos(\frac{2\pi}{365}J) \tag{2.5}$$

$$\delta = 0.409\sin(\frac{2\pi}{365}J - 1.39) \tag{2.6}$$

$$\omega_s = \mathrm{acos}(-\tan(\phi)\tan(\delta)) \tag{2.7}$$

Vapour pressure Daily mean vapour pressure (e_a) and early morning vapour pressure (e_a6h) depend on temperature and relative humidity

$$e_a = \frac{e_s(Tn)\frac{RHx}{100} + e_s(Tx)\frac{RHn}{100}}{2} \tag{2.8}$$

$$e_a = e_s(Tn)\frac{RHx}{100} \tag{2.9}$$

where the saturation vapour pressure e_s depends on temperature (Allen et al. 1998)

$$e_s(T) = 0.6108\exp(\frac{17.27T}{T + 237.3}) \tag{2.10}$$

Reference crop evapotranspiration (ev_{mk}) The reference crop evapotranspiration is calculated by means of the Makkink equation (KNMI 2006)

$$ev_{mk} = R_s\frac{1000 \cdot 0.65 \cdot \delta_s(Tg)}{(\delta_s(Tg) + \gamma(Tg)) \cdot \rho \cdot \lambda(Tg)} \tag{2.11}$$

where ρ is the mass density of water (1000 kg m^{-3}), $\delta_s(Tg)$ the gradient (equation 2.13) of the saturation vapour pressure [hPa °C^{-1}] according to equation 2.12, $\gamma(Tg)$ the psychrometer-constant [hPa °C^{-1}] (equation 2.14) and $\lambda(Tg)$ the latent heat [J/kg] (equation 2.15).

$$e_s(Tg) = 6.107 \cdot 10^{7.5\frac{Tg}{237.3+Tg}} \tag{2.12}$$

$$\delta_s(Tg) = \frac{7.5 \cdot 237.3}{(237.3 + Tg)^2}\ln(10)e_s(Tg) \tag{2.13}$$

$$\gamma(Tg) = 0.646 + 0.0006Tg \tag{2.14}$$

$$\lambda Tg = 1000(2501 - 2.38Tg) \tag{2.15}$$

3. Future time series

Future time series are obtained by transformation of the reference data (often referred to as *perturbation* or *delta* method) or they are derived with the help of *transformed* time series of other climate variables (see table 3.1). Sea level pressure slp, net long wave radiation Rl and wind direction $wdir$ are not transformed because of a small (projected) change with respect to the natural variability and in the case of wind direction also because of the non-trivial interpretation of the changes[1].

Table 3.1: *Future variables derived for impact modelling*

Variable	method
Tg	linear quantile scaling
Tn	linear quantile scaling
Tx	linear quantile scaling
P	wet-day correction + power-law transformation
kt	linear transformation
RHx	linear transformation
RHn	linear transformation
$w10$	power-law transformation
Rs	f(kt)
RH	f(RHn,RHx)
ev_{mk}	f(Rs,Tg)
e_a	f(RHn,RHx,Tx,Tn)
e_a6h	f(RHx,Tn)
$wdir$	NO TRANSFORMATION
slp	NO TRANSFORMATION
Rl	NO TRANSFORMATION

3.1 General transformation framework

The reference time series are transformed by applying a certain change (or "delta") to daily values. For every grid cell 12 sets (one set per calendar month) of change factors were derived from an ensemble of eight samples per climate scenario, resampled from eight climate model simulations.

[1] In case of biased climate model output, projected relative or absolute changes in frequencies of different wind directions can *never* be 'applied' to observed frequencies in an internally consistent way. This is also the case, but to a lesser extent, for other variables (see discussion on wet and dry days in Bakker 2015a, section 2.6).

The applied resampling method is a preliminary version of the resampling that was used for the KNMI'14 climate change scenarios for the Netherlands (Van den Hurk et al. 2014). The climate model output is available at a rotated grid of about 0.25° x 0.25°. The change factors have been translated to the regular grid (figure 2.1) by a nearest neighbour interpolation.

Note that, the transformations are performed for each grid cell and for twelve calendar months independently, but that the equations in the following do not specifically refer to the calendar month and grid cell.

Note that none of the presented transformation procedures exactly matches the final transformation tool (Bakker 2015b, see also "Toelichting transformatieprogramma" on www.klimaatscenarios.nl/toekomstig_weer/transformatie/index.html.). The main reasons for this are that

- ***the presented datasets cover a much larger area than the KNMI'14 climate change scenarios***
- ***the change factors vary with grid cell rather than using universal deltas for the entire area of interest like in KNMI'14***
- ***there were reasons to include higher quantiles in KNMI'14***

Indirectly derived variables

For some variables *deltas* are not available. In this case, future time series are derived with the help of *transformed* time series of other climate variables by applying equations 2.3 to 2.15.

3.2 Precipitation

Future precipitation (P^f) time series are obtained by a two-step transformation of the reference precipitation (P) such that the wet-day frequency F and the 55th and 95th percentile (P_{55} and P_{95}) of the original wet-day amounts are perturbed by the relative changes ΔF, ΔP_{55} and ΔP_{95}.

$$\begin{aligned} F^f &= (1+\Delta F)F \\ P_{55}^f &= (1+\Delta P_{55})P_{55} \\ P_{95}^f &= (1+\Delta P_{95})P_{95} \end{aligned} \tag{3.1}$$

First the wet-day frequency F is adjusted and second a power-law transformation is applied to transform the wet-day amounts. Wet days are defined as days with 0.1 mm or more precipitation.

Note that the applied percentiles are slightly different from the statistics used for the official transformation program (Bakker 2015b). P_{55} is on average close to the wet-day mean, but its use makes the estimation of the coefficients much more efficient. P_{95} is used rather than P_{99} because the monthly P_{99} cannot be robustly estimated for individual grid cells.

wet-day frequency In the case that the wet-day frequency decreases ($\Delta F < 0$), the following wet-day adjustment is applied

$$P^* = \max(P - c, 0) \tag{3.2}$$

where P^* is the wet-day adjusted precipitation and c is the correction constant that is chosen such that $-\Delta F$ of the wet days are 'dried' or 'set to zero'.

Occasionally, for some grid cells in some calendar months, a positive ΔF is projected, but this is usually smaller than 5%. The transformation does not account for these projected increases in the wet-day frequency.

wet-day amounts The second step applies a power-law to P^* such that the 55th and 95th percentile (P_{55} and P_{95}) of the original wet-day amounts P are perturbed by ΔP_{55} and ΔP_{95}

$$P^f = a(P^*)^b \tag{3.3}$$

Note that this equation is applied to all percentiles, which is different from the procedure followed by the Transformation Program KNMI14 (Bakker 2015b).

The constants a and b are obtained as follows

$$b = \frac{\log(P_{95}^f / P_{55}^f)}{\log(P_{95}^* / P_{55}^*)} \tag{3.4}$$

$$a = \frac{P_{95}^f}{(P_{95}^*)^b} = \frac{P_{55}^f}{(P_{55}^*)^b} \tag{3.5}$$

3.3 Temperature

Future mean, minimum and maximum temperature (Tg^f, Tn^f and Tx^f) are derived by transformation of reference temperature (Tg, Tn and Tx) such that the 5th, 50th and 95th percentile (T_{05}, T_{50} and T_{95}) are perturbed by the absolute changes ΔT_{05}, ΔT_{50} and ΔT_{95}

$$\begin{aligned} T_{05}^f &= T_{05} + \Delta T_{05} \\ T_{50}^f &= T_{50} + \Delta T_{50} \\ T_{95}^f &= T_{95} + \Delta T_{95} \end{aligned} \tag{3.6}$$

where T refers to Tg, Tn or Tx

This is done by a linear transformation after which the mutual consistencies between Tg, Tn and Tx are checked and corrected for.

$$T^f = \begin{cases} T^f_{50} + a1(T - T_{50}), & \text{if } T \geq T_{50} \\ T^f_{50} + a2(T - T_{50}), & \text{if } T < T_{50} \end{cases} \tag{3.7}$$

where the $a1$ and $a2$ coefficients are estimated for every grid cell, calendar month and variable independently

$$a1 = \frac{T^f_{95} - T^f_{50}}{T_{95} - T_{50}} \tag{3.8}$$

$$a2 = \frac{T^f_{05} - T^f_{50}}{T_{05} - T_{50}} \tag{3.9}$$

3.4 Relative humidity and atmospheric transmittance

Daily minimum and maximum relative humidity and atmospheric transmittance are transformed such that the averages RHn_{av}, RHx_{av} and kt_{av} are perturbed by the relative changes ΔRHn_{av}, ΔRHx_{av} and Δkt_{av}

$$X^f_{av} = (1 + \Delta X_{av})X_{av} \tag{3.10}$$

where X refers to RHn, RHx or kt

This is done by a simple linear scaling that prevents the values to exceed a certain upper threshold X_{max}

$$X^f = \min(\alpha \cdot X, X_{max}) \tag{3.11}$$

where the coefficient α is iteratively estimated and X_{max} is set 100% for RHn and RHx and 0.7 for kt. A maximum value of 0.7 for kt is caused by a typo in the program and it would have been better if this value was set to 0.75 (Allen et al. 1998). Clear-sky radiation is therefore slightly underestimated.

3.5 Wind speed

For future wind speed $w10^f$ the same power-law transformation as used for wet-day precipitation amounts (see equations 3.3, 3.4 and 3.5) is applied to perturb the 50th and 95th percentile ($w10_{50}$ and $w10_{95}$) of the reference wind speed $w10$ by the relative changes $\Delta w10_{50}$ and $\Delta w10_{95}$

$$\begin{aligned} w10^f_{50} &= (1 + \Delta w10_{50})w10_{50} \\ w10^f_{95} &= (1 + \Delta w10_{95})w10_{95} \end{aligned} \tag{3.12}$$

North sea dataset

The North sea dataset provides 3-hourly data for the U- and V-component of the wind. Before transforming, this is aggregated to daily wind speed by applying the procedure as described in section 2.2. After transformation, for each day the relative change is determined and applied to the 3-hourly u- and v-components of the particular day.

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