

climate changes spatial planning

Communication

Time series transformation tool:
development and use in CCsP projects

J. Bessembinder

A. Bakker

R. Leander

A. Feijt

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Authors

J. Bessembinder
A. Bakker
R. Leander
A. Feijt

Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

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Summary

Summary

Parallel to the development of the KNMI'06 climate scenarios in 2006, a tool was developed to generate temperature and precipitation time series for the future. These time series are often needed for climate impact and adaptation models. The aim of this time series transformation tool is to alter a daily historical time series of precipitation or temperature in a way that corresponds to one of the four KNMI'06 climate change scenarios for a selected time horizon.

Until now no official report was issued, describing all aspects of the KNMI transformation tool, although an elaborate user guide is available on internet, and some popular-scientific publications are available. Within the COM28-project ("Climate data") this transformation tool was used regularly. As part of this project, a scientific background report was written, that gives a description of the tool together with an overview of the development of the program, the analyses performed by KNMI to determine the limitations and advantages of the program.

After the first publication in 2006 the transformation tool has been further developed and improved. This synthesis report gives an overview of the various versions of the temperature and precipitation transformation tool, the differences between the versions and a few examples of the analyses performed with the precipitation transformation tool (Chapter 2). The tool has been used in a considerable number of "Climate changes Spatial Planning" projects, some with assistance of KNMI. In Chapter 3 an overview is given of the projects that used the transformation tool, and the versions used in each project.

Chapter 4 describes the advantages and limitations of the current time series transformation tool, an example of the Delta-method, and it gives information on alternative methods for generating time series for the future (Direct method and Stochastic weather generator). The chapter indicates possible improvements and modifications in future versions of the transformation tool (e.g. more climate variables) and whether it is useful to develop (further) other methods to generate time series for the future. This is largely driven by user demands, which also are discussed shortly. Several ongoing or starting projects already include several of the desired and possible developments. A few examples are: "Theme 6: Climate projections" of the Knowledge for Climate programme, the project "Kritische Zone" of the National Model and Data Centre, and the activities for the next generation of the KNMI climate scenarios.

Summary in Dutch

Parallel aan de ontwikkeling van de KNMI'06 klimaatscenario's in 2006 is er een tool ontwikkeld om tijdreeksen voor temperatuur en neerslag voor de toekomst te genereren. Deze tijdreeksen zijn vaak nodig voor klimaatimpact en -adaptatiemodellen. Het doel van deze tijdreeks-transformatietool is het zodanig aanpassen van een historische tijdreeks voor neerslag of temperatuur (op dagbasis), dat de gegenereerde tijdreeks één van de vier KNMI'06 klimaatscenario's representeert en de geselecteerde tijdshorizon.

Tot voor kort was er geen officieel rapport met een beschrijving van alle aspecten van de KNMI tijdreeks-transformatie-tool beschikbaar, hoewel er wel een uitgebreide gebruikershandleiding op internet beschikbaar is en enkele populairwetenschappelijke publicaties. Binnen het COM28-project ("Klimaatdata") is de transformatietool regelmatig gebruikt. Als onderdeel van dit project is er een wetenschappelijk achtergrondrapport geschreven met een beschrijving van deze tool, een overzicht van de verschillende versies en de analyses die het KNMI heeft uitgevoerd om de beperkingen en de mogelijkheden van de transformatie tool te bepalen.

Na de publicatie van de eerste versie van de transformatie tool in 2006, is het programma verder ontwikkeld en verbeterd. Dit synthese rapport geeft een overzicht van de verschillende versies van de tijdreeks-transformatietool voor temperatuur en neerslag, de verschillen tussen de versies en enkele voorbeelden van uitgevoerde analyses met de neerslagtransformatie tool (Hoofdstuk 2). De tool is gebruikt in een aanzienlijk aantal "Klimaat voor Ruimte" projecten, sommige met assistentie van het KNMI. In Hoofdstuk 3 wordt een overzicht gegeven van die projecten en de versies die daarin zijn gebruikt.

Hoofdstuk 4 beschrijft de voordelen en beperkingen van de huidige tijdreeks-transformatietool, een voorbeeld van de Delta methode, en het geeft informatie over alternatieve methoden om tijdreeksen voor de toekomst te genereren (Directe methode en stochastische weergeneratoren). In dit hoofdstuk wordt ook aangegeven op welke punten de tool verbeterd of uitgebreid zou kunnen worden (bijv. voor meer klimaatvariabelen) en of het wenselijk is ook andere methoden voor het genereren van tijdreeksen (verder) te ontwikkelen. De gewenste punten voor verbetering en uitbreiding van de tool zijn sterk gelieerd aan gebruikerswensen, die ook kort worden besproken. In een aantal lopende en startende projecten zijn een aantal van de gewenste en mogelijke ontwikkelingen als verwerkt. Enkele voorbeelden daarvan zijn: "Thema 6: Klimaatprojecties" van het Kennis voor Klimaat programma, het project "Kritische Zone" van het Nationale Modellen en Data Centrum, en de activiteiten voor de volgende generatie KNMI klimaatscenario's.

1. Background and aim of COM28 and the time series transformation tool

1.1. Background and aim of the COM28 project

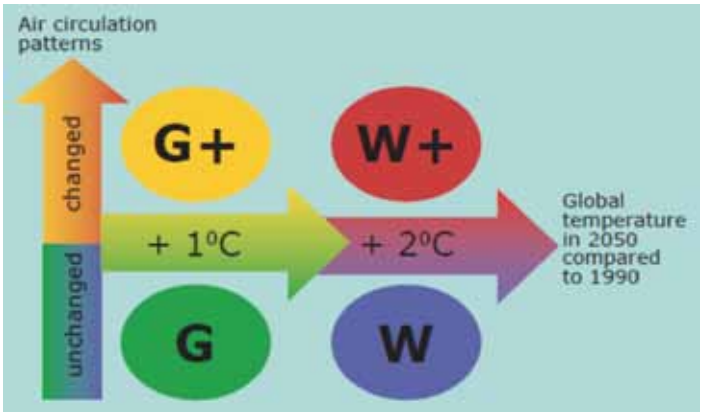
In 2007 it became clear that several projects within the "Climate Changes Spatial Planning" programme (CcSP) required tailor-made climatological time series (on daily basis) for climate impact and adaptation studies consistent with the KNMI'06 scenarios published in 2006. To overcome this problem the project COM28 "Climate Data" was formulated. The aim of this project was:

- To disclose climatological datasets of current and future climate for CcSP-projects;
- To improve the accessibility of climatological datasets and improve the user friendliness of internet tools to access and process climatological datasets[1].

1 See among others: www.klimaatatlas.nl, http://www.knmi.nl/klimatologie/daggegevens/download.html, http://www.knmi.nl/klimatologie/uurgegevens/ and http://www.knmi.nl/klimatologie/monv/reeksen/.

For climate impact studies data for the current climate (the reference) and for the possible future climates are needed. Data for the current climate are generally available from observations[2]. KNMI developed a "time series transformation tool" to modify historical time series consistently with the KNMI'06 climate scenarios published in 2006 (KNMI, 2006a and 2006b). This tool, often called the "transformation program", was used within COM28 to construct time series for several CcSP-projects.

Until recently no official report was available with a description of the KNMI transformation tool, although there is an elaborate user guidance in Dutch on internet and in some popular-scientific publications. As part of the COM28 project a technical report was written on this transformation tool. This synthesis report for COM28 summarizes the main points in this technical report and gives an overview of the use of the transformation tool within CcSP and related projects.



G	Moderate*	1°C temperature rise on earth in 2050 compared to 1990 no change in air circulation patterns in Western Europe
G+	Moderate +	1°C temperature rise on earth in 2050 compared to 1990 + milder and wetter winters due to more westerly winds + warmer and drier summers due to more easterly winds
W	Warm	2°C temperature rise on earth in 2050 compared to 1990 no change in air circulation patterns in Western Europe
W+	Warm +	2°C temperature rise on earth in 2050 compared to 1990 + milder and wetter winters due to more westerly winds + warmer and drier summers due to more easterly winds

Figure 1.1.
Schematic overview of the four KNMI'06 climate scenarios and the legenda.

1.2. Background and aim of the time series transformation tool

History

In May 2006 the KNMI'06 climate scenarios were published (KNMI, 2006a and 2006b; Figure 1.1). As part of the CcSP "tailoring" project[3], KNMI developed a transformation tool before the publication of the KNMI'06 scenarios. This first version 0.0 was developed to downscale climate information (Van den Hurk et al., 2006). Data generated with this version were used for the estimation of changes

2 For some impact studies the available observations are not sufficient to describe the current or reference climate. In the synthesis report on project CS7 methods are described to overcome this problem (Bessembinder et al., 2011b).
3 http://klimaatvoorruimte.klimaatonderzoeknederland.nl/nl/25222969-Klimaatscenario%27s.html, project CS7.

in extreme precipitation amounts and changes in climate indices (e.g. the number of warm and tropical days in summer and frost days in winter[4]). The transformation tool itself was put on the internet in May 2006 in order to give users the possibility to generate additional time series and data themselves.

In May 2006 version 0.0 of the tool was published, which produced time series for the winter months (December-February) and for the summer months (June-August). Soon after, professional users, especially water managers, asked for a tool that could produce "year-round" time series. This "year-round" tool also has been developed as part of the "tailoring-project". Since then, some adaptations were made to the program to improve the temporal consistency, to correct for small errors, etc.

Aim

The aim of the time series transformation tool is:

- To adjust a historical precipitation time series or a historical temperature time series on a daily basis in such a way that the newly generated time series for the future is consistent with one of the four KNMI'06 climate change scenarios and for the selected time horizon.

In more detail: the program applies the changes in averages and variability as prescribed by the selected KNMI'06 climate change scenario and the selected time horizon to a given historical time series for temperature or precipitation. Though the transformed time series correspond with a plausible **climate** in a statistical sense, they **do not give predictions of the weather** in the future on a specific day or in a specific year.

Requirements

Important requirements during the development of this transformation tool were:

- It should produce time series at daily basis, especially for temperature and precipitation;
- The time series produced should represent the climate change of the four KNMI'06 scenarios (it should provide time series that are consistent with these scenarios);
- It should be able to produce time series for various time horizons;
- It should be easy to use, promoting consistency in the methods used to generate time series for the future[5];
- It should be easy to adjust the program for the next generation of KNMI climate change scenarios, if they provide similar type of change coefficients.

1.3. Further reading

Chapter 2 gives a description of the development and various versions of the program. In chapter 3 an overview is given of the use of the transformation program in CcSP-projects and some other projects. Chapter 4 gives information on alternative methods for generating time series and conclusions and discussion points. It also describes how the transformation program could be further developed in the future.

4 http://www.knmi.nl/klimaatscenarios/knmi06/gegevens/.
5 For the KNMI climate change scenarios from 2000 also one or more methods were developed to produce time series for the future by others than KNMI. However, these were not that easily accessible.

2. Versions of the time series transformation tool

The time series transformation tool consists of two separate modules: one for precipitation and one for temperature. Since the first version published in May 2006, the modules have been further developed. Tables 2.1 and 2.2 summarize the development of and changes in the various versions of the transformation tool for precipitation and for temperature.

Table 2.1.
Overview of differences between the versions of the precipitation transformation tool.

		Version					
		-1.0	0.0	1.0	1.1	1.2	2.0
		Mar. 2006	May 2006	Jan. 2007	July 2007	Apr. 2008	Feb. 2009
Period	Winter (DJF) + Summer (JJA)		X				
	Year-round	X		X	X	X	X
Changes per	Season		X				
	Calendar month			X	X	X[a]	X[a]
	10 days	X					
Wet day removal[b] based on	No wet day removal	X					
	Chronology		X	X			
	Statistical ranking per calendar month				X		
	Statistical rank per calendar month + beginning/end wet period					X	X
Transformation on the basis of changes in[c] ..	P_{mean}	X	X	X	X	X	X
	P_{99}		X	X	X	X	X
	Wet day frequency		X	X	X	X	X
Change of percentiles > P_{99}	Extrapolated		X	X			
	Same change as P_{99}				X	X	X
Determination of P_{99} in transformation	Calculated from observations per station		X	X			
	Determined on the basis of observations of 13 "pooled" stations				X	X	
	Fixed ratio for P_{99}/P_{mean} based on observations						X
Determination of coefficients *a* and *b* in transformation	Per station		X	X			X
	General (on the basis of 13 "pooled" stations)				X	X	

a Corrected values, compared to the earlier versions.
b Adding of wet days took place by selecting dry days by chronology, before version 1.1 by counting the dry days, from version 1.1. on by counting the wet days.
c P_{mean} = mean precipitation on wet days; P_{99} = the 99th percentile (1% of the values is higher).

Below a short chronological description is given of the major developments and changes in the transformation tool. A complete overview and a description of the transformation tool can be found in Bakker et al. (2011):

- Prior to the publication of the KNMI'06 climate scenarios in March 2006, preliminary data on climate change throughout the year were provided to RIZA and RIKZ[6] (**version -1.0**), in order to give them the possibility to do fast analyses on impacts of the new KNMI'06 scenarios for water safety and fresh water supply. For this purpose, changes in means per decade (about 10 days) year-round were supplied for precipitation (relative change), temperature (absolute change) and reference evapotranspiration (relative change);
- **Version 0.0** published in May 2006 on the website of the KNMI'06 climate scenarios (KNMI, 2006a; KNMI, 2006b) generated only time series for the winter (December-February) and for the summer (June-August) for precipitation and temperature. This version took into account changes in means and extremes, and for precipitation also changes in the number of wet days;
- Soon after the online publication of version 0.0, users asked for the development of a tool for "year-round" time series. For this first year-round **version 1.0** (January 2007, not published online) methods were developed to interpolate the changes for winter and summer and to disaggregate the values to monthly change factors[7] (Lenderink, 2006);
- The procedure as used in version 1.0 for precipitation appeared to result in extreme changes (sometimes more than 100%) for already extreme observed precipitation amounts. Since such changes are unrealistic and may hamper hydrological simulations, various options were considered to overcome this problem. It was decided to limit the relative change of extreme events (rarer than the 99th percentiles) to the relative change of the 99th percentiles (P_{99}; **version 1.1,** July 2007). In this version 1.1 also the procedure to adapt the wet day frequency was changed and the procedure to determine the coefficients for the precipitation transformation (on the basis of the "pooled" time series of 13 Dutch stations, to reduce the spatial variability in the 99th percentile of wet days per calendar month);
- In April 2008 a slightly adapted version of the transformation tool was published on the internet[8] (**version 1.2**). A minor correction of the monthly values for the temperature and precipitation transformation was applied. Also the procedure to change the number of wet days in the precipitation series was adapted (the procedure in versions 1.0 and 1.1 caused a serious decrease of the temporal correlation). This version is currently (October 2011) available on the internet;
- This **version 2.0** differs from version 1.2. in the way the 99th percentile of the daily precipitation per calendar month is estimated. For every calendar month, the ratio between the 99th percentile and the average precipitation on wet days (P_{99}/P_{mean}) is relatively stable throughout the Netherlands, although the total monthly precipitation can differ[9]. Therefore, in this version the 99th percentile was estimated by multiplying the average precipitation on wet days by a fixed ratio per calendar month. The coefficients in the precipitation transformation procedure were determined again iteratively per station;
- During the writing of the report of Bakker et al. (2011) a bug was detected in the way the 99th percentile was determined. This will be corrected in the future version 2.1.

6 Former governmental institutes for freshwater supply and water safety, now part of Deltares and the Waterdienst.
7 In 2008, it appeared that some of the derived monthly change factors were incorrect (slight deviation from the correct values). These were adjusted in version 1.2.
8 Data currently (October 2011) on http://www.knmi.nl/klimaatscenarios/knmi06/gegevens/index.html for temperature and precipitation are generated with this version (checked April 2011).
9 This new version was developed in a project for Flanders (KMI/KU Leuven/KNMI, 2009). The version for Flanders differs from the one for the Netherlands in the ratios P_{99}/P_{mean} used per calendar month.

Figure 2.1.
The 13 stations used to determine the coefficients in the transformation of precipitation.

Table 2.2.
Overview of differences between the versions of the temperature transformation tool.

		Version[a]			
		-1.0	0.0	1.0/1.1	1.2/2.0
		Mar. 2006	May 2006	Jan. 2007	Apr. 2008
Period	Winter (DJF) + Summer (JJA)		X		
	Year-round	X		X	X
Changes per	Season		X		
	Calendar month			X	X[b]
	10 days	X			
Transformation on the basis of changes in [c] ..	P_{10}		X	X	X
	P_{50}	X	X	X	X
	P_{90}		X	X	X

a Between version 1.0 and 1.1 no changes occurred in the temperature transformation. The same is true for versions 1.2 and 2.0 of the temperature transformation.
b Corrected values, compared to the earlier versions.
c P_{10} = 10th percentile (90% of the values is higher), similar for P_{50} and P_{90}.

3. Overview of projects in which the transformation tool is used

Since version 1.0 the transformation tool has been used in many projects within and beyond the CcSP programme. In the data delivery project in CcSP (COM28) it was used regularly to generate time series for the future. The broad use is probably stimulated by the following facts:

- The online supply of the tool makes it very easy (and fast) to generate time series for the future;
- At the moment it is still the only method available that can generate time series consistent with the KNMI'06 climate scenarios for the Netherlands;
- There was relatively a lot of support for users: guidance material on the internet, and a help desk at KNMI (option regularly used).

Table 3.1.
Overview of CcSP projects in which the transformation tool is used and in which KNMI was involved.

Project subject	CcSP project code	Reference/link[a]	Version transformation tool[b]
Ecosystems: ecohydrological effects in the Netherlands	A1	Witte et al., 2009	P: 1.2 T: 1.2/2.0 PET: 1.0
Ecosystems: impact on butterflies	A2	Cormont, 2011	T: 1.2/2.0 P: 1.2
Financial arrangements: water quality	A9	Loeve et al., 2006	P: 1.0
Financial arrangements: hydrology in water board area	A9	Immerzeel et al., 2007	River discharges: P/ PET: -1.0 + changes 4 seasons Hydrology NL: P: 1.0
Energy: overview changes climate variables related to oil industry	A11	Bessembinder & Keller, 2008	P: 1.1 T: 1.0/1.1
Agriculture: impact analyses Northern NL	A21	Wit et al., 2009	P: 1.2 T: 1.2/2.0
Fresh water supply: hydrological standard year	CS7	Bakker et al., 2009	P: 1.1 PET: 1.0
Water management water boards: time series for Quarles Ufford	CS7	http://www.knmi.nl/klimaatscenarios/maatwerk/water/index.html	Discharges: -1.0 P: 1.0[c] T: 1.0/1.1 PET: 0.0 + 4 seasons
Agriculture: time series for impact analyses crop yield in Europe	CS7	http://www.knmi.nl/klimaatscenarios/maatwerk/natuur/index.html	Delta method[d]
Spatial planning: spatial information on climate and climate change in maps	COM21	http://www.knmi.nl/klimaatscenarios/maatwerk/ro/	P: 1.1 T: 1.0/1.1 PET: 1.0
Spatial planning: spatial information on climate and climate change in maps	COM27	KNMI, 2009a	P: 1.2 T: 1.2/2.0 PET: 1.0

a Main reference. All documentation on the project can be found through http://kennisvoorklimaat.klimaatonderzoek-nederland.nl/publicaties/publicatiedatabank with the help of the project code.
b P=precipitation; T=temperature; PET=reference evapotranspiration.
c Probably used in this case study.
d The Delta method is used, however, not the current version of the transformation tool, since data were needed for Europe.

Tables 3.1 to 3.3. give an overview of projects in which the time series transformation tools are used. All projects in which KNMI was involved in some way are mentioned and some other projects of which we know they used the transformation tool (but more projects may have used the tool). The tables also indicate which versions were used (as far as known).

Table 3.2.
Overview of CcSP projects in which the transformation tool is used and in which KNMI was not involved directly (this means that the versions used are estimated).

Project subject	CcSP project code	Reference/link[a]	Version transformation tool[b]
Ecosystems: impact on habitat change species	A2	http://www.klimaatonderzoeknederland.nl/resultaten/klimaat-response-database	T: 1.0/1.1 or 1.2/2.0 P: 1.1 or 1.2
River discharges: extremes	A7	First estimates: Te Linde, 2007; De Wit et al., 2007; Van Deursen, 2006	P: -1.0 T: -1.0 PET: -1.0
Shipping: extreme river discharges	A8	First estimates river discharges: Te Linde, 2007; De Wit et al., 2007; Van Deursen, 2006	P: -1.0 PET: -1.0
Hydrology and water safety: impact on Zuidplaspolder	A14	De Moel et al., 2008 De Moel, 2008	P: 1.1 T: 1.0/1.1
Impacts climate change: Tilburg	A16	Schneider et al., 2007	P: 1.1 T: 1.1

a Main reference. All documentation on the project can be found through http://kennisvoorklimaat.klimaatonderzoek-nederland.nl/publicaties/publicatiedatabank with the help of the project code.
b P=precipitation; T=temperature; PET=reference evapotranspiration.

Table 3.3.
Some other projects in which the transformation tool is used[10].

Project subject	Stakeholder	Reference/link	Version transformation program[a]
Urban water management: change in hourly extreme precipitation	TU-Delft	Romero et al., 2011	P: 1.1 T: 1.1
Water management: change in extreme precipitation	DG-Water	Groen, 2007	P: 1.1
River discharges: first estimates	RIZA/RIKZ	Te Linde, 2007; De Wit et al., 2007; Van Deursen, 2006	P: -1.0 T: -1.0 PET: -1.0
Fresh water supply and water safety: time series for estimating river discharges and hydrological parameters	Waterdienst/ Delta model	Homan et al., 2011a and 2011b	P: 2.0 T: 1.2/2.0
Nature: climate scenarios and time series for Flanders	Instituut voor Bos- en Natuur Onder-zoek, Flanders	KMI/KU Leuven/KNMI, 2009	P: 2.0 (Flanders) T: 1.2/2.0
Energy: reduction in chance extreme cold winters and high temperatures in summer	GasTerra/ NAM	Wever, 2008	T: 1.0/1.1
Betuwe route: ice formation	Project organisa-tion Betuwe route	Groen & Jilderda, 2007	T: 1.0/1.1
Cooling water capacity: change in water temperatures	Waterdienst	M.J. Kallen, E.D. de Goede, P.M.A. Boderie	T: -1.0 P: -1.0 PET: -1.0
Schiphol: temperature extremes	Hotspot Schiphol	Wolters, 2011	T: 1.2/2.0

a Main reference. All documentation on the project can be found through http://kennisvoorklimaat.klimaatonderzoek-nederland.nl/publicaties/publicatiedatabank with the help of the project code.

Bakker et al. (2011) show all analyses performed with the various versions of the transformation tool. Below a few examples are shown. Figure 3.1 shows the effect of limiting the relative change for all daily amounts larger than the 99th percentile: compare the red and pink lines with maximisation with the green and blue lines without maximisation. The effect of other changes between the versions is, in general, smaller. Comparing the red line and the pink line shows the effect of calibrating the coefficients in the precipitation transformation on individual stations (pink) or on the "pooled" time series of 13 stations (red) distributed over the Netherlands.

10 And in which KNMI was involved or contacted.

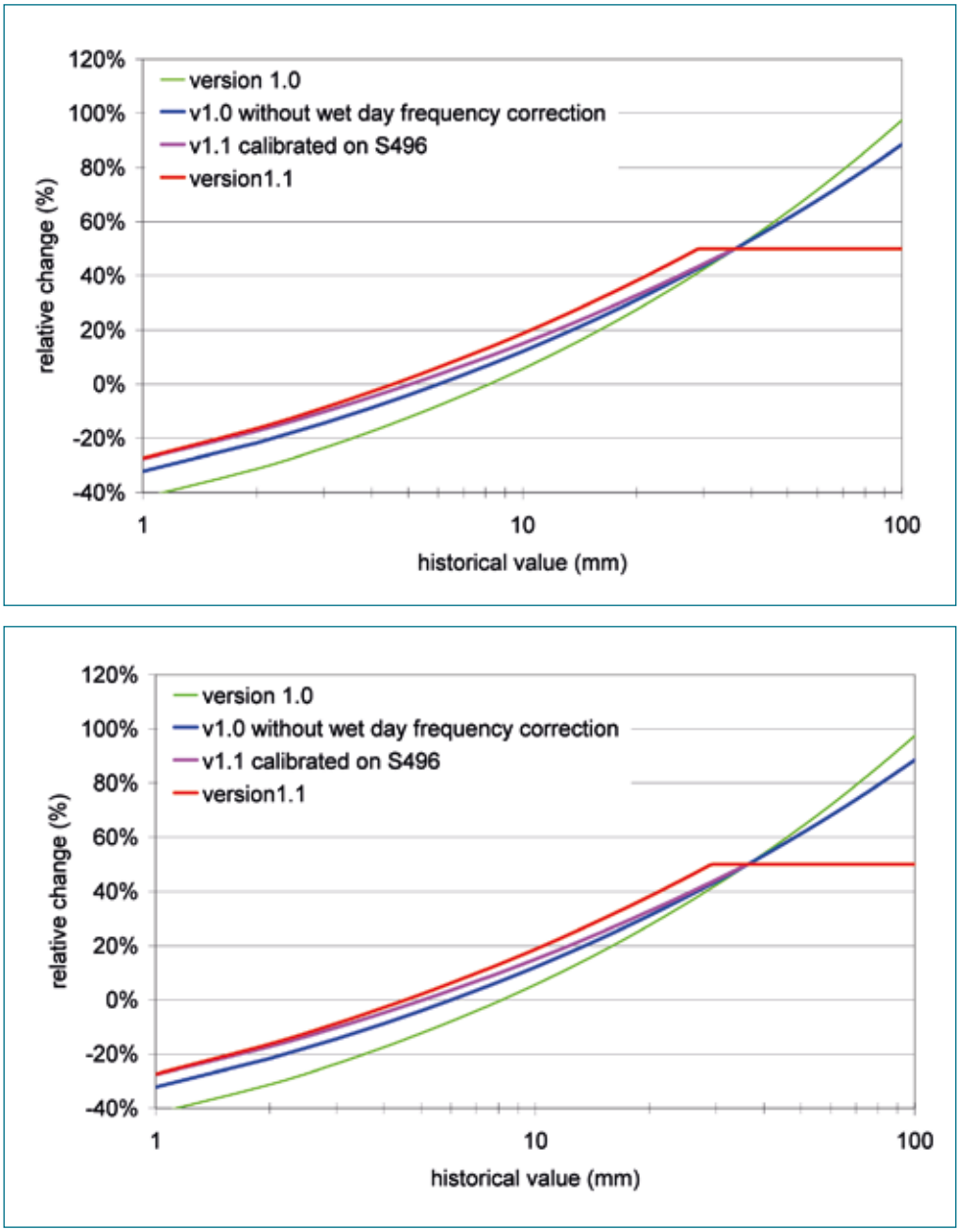


Figure 3.1.
Relative change of historical daily precipitation in the months of July (upper panel) and September (lower panel) (1976-2005) for station West-Terschelling (code S496) for KNMI'06 scenario W around 2100 in four different versions of the transformation tool. Pink = version 1.1 but with the coefficients calibrated for station S496 and not on the basis of all stations.

Figure 3.2 shows the autocorrelation between the daily precipitation amounts for four versions of the transformation tool, compared to the autocorrelation in the historical period. Version 1.0 and 1.1 did not try explicitly to maintain the autocorrelation structure, which clearly results in a decrease in autocorrelation (lower values compared to the historical time series).

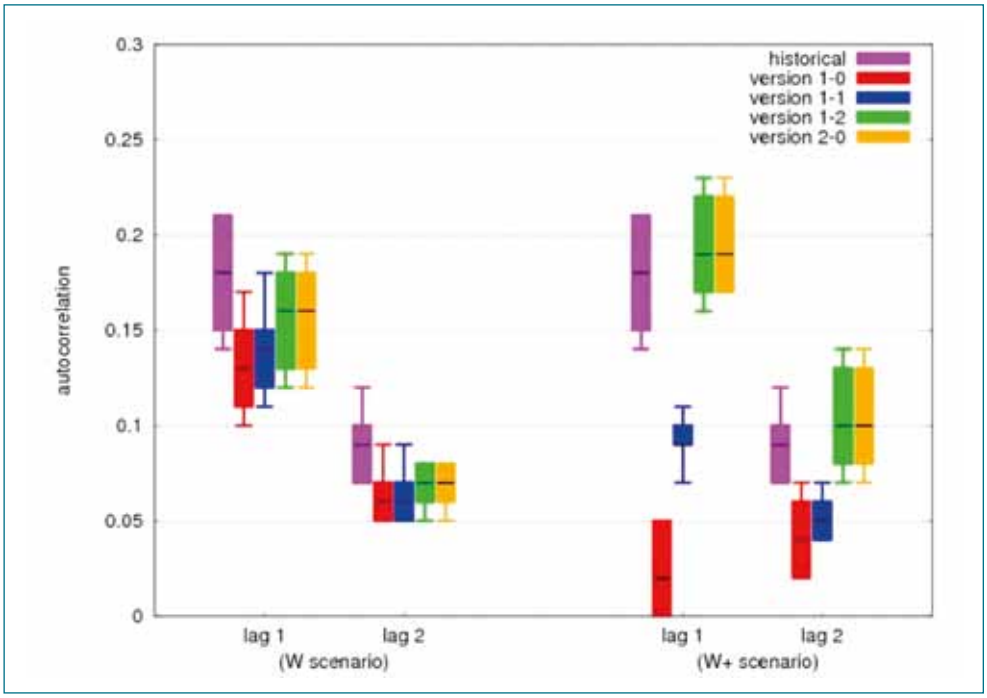


Figure 3.2.
Autocorrelation of the daily precipitation amount in summer (June-August), in the data for 13 Dutch stations for scenario W around 2100 and for scenario W+ around 2100, compared with the historical period 1976-2005. Shown is the correlation between two consecutive days (lag 1) and between days that are separated by one day (lag 2). The box plots represent the range in autocorrelation of 13 stations: the black horizontal line presents the median value, the vertical blocks present the 25th and 75th percentiles, and the thin vertical lines (whiskers) present the 10th and 90th percentiles.

For 2100, the W+ scenario gives a decrease in wet day frequency of almost 40% in summer (-31%,-40%,-45%, for June-July-August, respectively). Chronological wet-day removal (version 1.0) makes that a sequence of two successive wet days is hardly possible in the transformed series. This reduces the lag 1 autocorrelation to almost zero (lag 1, figure 3.2). The effect is less pronounced on the autocorrelation of days that are separated by one day (lag 2, figure 3.2). The autocorrelation structure in version 1.0 is unrealistic. Chronological wet day adjustment is, therefore, less suitable for time series transformation.

The wet-day adjustment in version 1.2 and higher is designed to change the autocorrelation structure as little as possible (no information is given in the KNMI'06 scenarios on the change of autocorrelation). The changes are indeed small compared to the historical period (Figure 3.2). In the W+ scenario, the autocorrelation slightly increases. This is caused by the fact that the number of isolated wet days is reduced after wet day correction.

4. Discussion and conclusions

In this chapter a description is given of the main advantages and limitations of the current transformation tool (Section 4.1). In Section 4.2 we shortly discuss alternative methods for generating time series for the future, and in the last paragraph we discuss the options for further development of methods to generate time series for the future in relation to user requirements and planned activities in various projects.

4.1. Advantages and limitations of the current transformation tool for the KNMI'06 climate scenarios

Advantages

- The current transformation tools are the only methods available at the moment that can generate time series for the future in the Netherlands that are consistent with the KNMI'06 climate scenarios. Consistent with those scenarios it takes care of the fact that the averages can change in a different way than the extremes;
- They can generate time series for all time horizons between 1990 and 2100;
- The generated time series can often be used directly in impact models that use daily values as input;
- The generated time series show spatial and temporal correlation between different variables, due to the fact that the historical time series on which they are based have spatial and temporal correlation (although by transformation the spatial correlation and the relation between variables may be reduced, since time series of each station are transformed individually);
- The transformation tool can be used to show what present-day extremes could look like in the future, as it directly modifies historical time series. For instance, it can be used to show how the return period of a year such as 2003 may change in the future. Especially for communication and for policy makers this type of "example years" or "example weather events" are very useful;
- The generated time series can be used to generate indices such as the number of frost days, the number of days with more than 10 mm precipitation;
- The tool generates time series very fast and is easily accessible through internet. Because of this, there is no need for other institutes or organisations to develop a method themselves to generate time series for the future in the Netherlands[11]. Therefore, it may promote consistency in the methods used for impact and adaptation studies to generate climatological time series;
- The time series transformation can be adapted easily to other regions or new scenarios. In case of new climate scenarios for the Netherlands with a similar tabular structure as KNMI'06, only the tabulated files with change coefficients[12] have to be updated or modified. In principle the transformation tool can also be used for other regions whenever the change coefficients used in the transformation tools can be provided for that particular region.

11 For some cases the current transformation tool is not the most appropriate method (e.g. when one wants to study the change in variability between years, when one is interested in very extreme daily rainfall events). The KNMI'06 scenarios do not give information on changes in variability between years or on very rare events. The transformation tool tries to adjust only those characteristics that are explicitly given in the scenarios.

12 And for version 2.0 of the precipitation transformation tool also the ratios between the precipitation amounts for the 99th percentile and the average precipitation on wet days have to be provided.

Limitations

- The time series for the various climate variables (temperature and precipitation) and stations are transformed independently in the current versions of the transformation tool. This reduces somewhat the spatial correlation of single (and multiple) variables and the consistency between climate variables. For the determination of the change coefficients in the KNMI'06 scenarios dependency between climate variables was taken into account (e.g. when precipitation and number of wet days decrease in the summer months, temperature increases more). This means that the climatological consistency is maintained;
- The length of the time series for the future depends on the length of the historical time series[13]. When long (synthetical) time series are available, also long time series can be generated with this method;
- Due to the way of removing wet days the most extreme daily precipitation in the time series for the future is sometimes lower than in the historical time series, although the climate scenario indicates that extremes will increase. (This is not necessarily an error in the transformation method, but is inherent to the rare nature of extremes, and occurs also in model simulations);
- The tool uses only the changes of a few points in the probability density function. For other points, especially those outside the range used, the changes can be overestimated or underestimated in the generated time series. This can e.g. be the case for historical days with precipitation amounts larger than the 99th percentile on wet days. However, change coefficients for these extremes were not provided in the KNMI'06 climate scenarios, since it was not possible to estimate these changes reliably;
- The transformation tool does not explicitly control the year-to-year variation. So, the year-to-year variation in the transformed time series largely depends on the historical time series, but may be slightly changed (mainly due to the adaptation of the number of wet days);
- The tool is developed only for transformation of average daily temperature and precipitation. Although the temperature transformation can be used also for minimum and maximum temperatures, it does not cater for changes in the diurnal cycle.

Some of the above limitations are more related to the limitations of the KNMI'06 scenarios (e.g. no information on change of diurnal cycle of temperature), than to the limitations of the transformation procedure itself.

4.2. Alternative methods to generate time series for the future

Most climate impact studies or climate adaptation studies need time series as input for their models, or indices derived from these time series. The transformation tool as described in Bakker et al. (2011), has been used frequently in the Netherlands. However, there are also other methods for generating time series for the future, each with its own advantages and limitations. These can roughly be subdivided into three groups:

- Delta method: changes (or "deltas") are applied to historical time series. The time series transformation tool is an example of this method;
- Direct method: output of climate models is used and if necessary bias-corrected;
- Stochastic weather generator: generate time series by means of statistical relations and properties.

Within each group various alternatives are possible some of which are used by other countries (e.g. perturbation tool: KMI/KU Leuven/KNMI, 2009; weather generator UK: Jones et al., 2009). As

13 For the Delta model (Homan et al, 2011b) the transformation tool was combined with the KNMI "rainfall generator" which recombines daily precipitation and temperature data to generate very long synthetic time series.

indicated before, the KNMI transformation tool is an example of the Delta method. In the simplest version of the Delta method, also denoted as the classical Delta approach, only an average change is applied: the average change is applied to every daily value in an historical time series for e.g. temperature or precipitation. The (non-linear) KNMI transformation program takes into account that extremes may change differently than average values. Besides, in the precipitation transformation a change in the number of wet days is included.

Table 4.1 gives an overview of the three groups of methods and their main advantages and limitations. From a daily perspective, each method will generate somewhat different time series, although they may represent the same changes in climate variables as given in e.g. the KNMI'06 scenarios. The KNMI'06 scenarios give information about a limited number of climate characteristics. The time series may differ in characteristics that are not given by these scenarios, but that may be important for impact analyses. This means that the methods to generate future time series themselves can be an extra source of uncertainty.

Table 4.1.
Future climate: methods tot generate meteorological time series.

	Delta method	Direct method	Stochastic weather generator
Basic material	Historical time series	Output climate model	Statistical pro-perties/ relations between variables
Processing	Apply climate change signal to time series (transformation)	Correct for biases[a] in climate model output	Adapt generator to climate change signal
Suitable[b] for KNMI'06 climate scenarios	Yes	No	Yes
Correlation (between variables, spatial and temporal)	Yes, limited by transformation and change values	Yes, limited by model biases and ways to correct for those	Yes, depends on method[c]
Different sequence of weather events than in observed time series?	No, hardly[d]	Yes	Yes
Possibility to generate information on "example" years (e.g. "2003")?	Yes	No[d]	Yes
Long time series possible (much more than 100 year for the same climate)?	No[e]	Yes	Yes[f]
Can be made available easily to a broad group of users?	Yes	No	Yes
Time needed to generate time series for the future	Little time	Much	Little time

	Delta method	Direct method	Stochastic weather generator
Currently available for the Netherlands for the KNMI'06 scenarios?	Yes	No	No
Used in, among others[g]	• COM21/COM27 (provinces): climate effect atlases and climate sketchbook • CS7 (RIZA/ Waterdienst): hydrological standard year • Delta model: time series for hydrological modelling • GasTerra/NAM: Reduction in the change of extremely cold winters and hot days in summer	• CS7 (Alterra): Time series for impact on crop production in Europe • CS7/A7 (RIZA/ Waterdienst): long synthetic time series for extreme river discharges • RheinBlick2050 project (D, F, CH, NL)	• UKCP09: time series for the climate scenarios of the UK • No examples available from CcSP projects

a Bias = a systematic deviation of climate model output compared to observations. To determine the bias of climate model output, a climate model run for the current climate is used.
b Suitable = can be adjusted such that time series consistent with the KNMI'06 scenarios can be generated.
c Some parametric models use the spatial correlation to fit the model. However, these models often have difficulties simulating adequately drought in a large region.
d At present no, but work on this is in progress.
e Only possible if long synthetic time series are generated, e.g. with the KNMI "rainfall generator", as is done for the Delta model. (Homan et al., 2011b).
f However, several weather generators show difficulties reproducing extreme events with return periods of 10 years or more.
g See also the synthesis report of project CS7 of the "Climate changes Spatial Planning" programme (Bessembinder et al., 2011b).

4.3. Directions and recommendations for the further development

In this section we recommend potential improvements and extensions of the transformation tool and whether it is useful to develop other methods to generate time series for the future. Desired points for improvement and extension are closely linked to user requirements, which are discussed first.

User requirements

In April 2011 a report on user requirements related to the next generation KNMI climate scenarios is published (Bessembinder et al., 2011a). This report indicates that users have interest in especially the following aspects related to generation of time series for the future:

- Transformation tools for other climate variables than precipitation and temperature, especially for reference evapotranspiration, (global) radiation, wind and humidity;
- Correlation between climate variables and neighbouring stations. Spatial correlation is asked for e.g. for determining the combined effect of low river discharges and drought in the Netherlands. It is not clear which temporal correlation is needed, probably not directly at the daily level, but more at the weekly of monthly level for most users;

- Inclusion of possible changes in year-to-year and intra-annual variation[14] in the transformation procedure;
- Methods to generate time series for larger areas than the Netherlands. This means that spatial variation in climate change can be included in the method to generate time series for the future.

Possible points of improvement or extension of the current transformation program

- Exploring alternative methods to remove wet days and their effect on spatial and temporal consistency. In Bakker et al. (2011) one can see that the method for removing and adding wet days has a clear influence;
- Exploring the possibilities to transform other climate variables conditional on (the changes in) precipitation. In the preliminary methods described in Annex 2 of Bakker et al. (2011) this was already done for global radiation and humidity;
- Combining different methods for generating time series for the future: e.g. a stochastic weather generator could be used to generate time series for other climate variables or for generating the temperature on days that were made dry;
- Applying the estimation of percentiles in a consistent way (see Chapter 2 "version 2.1"). The temperature transformation may contain the same error as detected in the determination of the 99th percentile in the precipitation transformation tool version 2.0 and before;
- Developing a multi-site version of the transformation tool that can include spatial differences in climate change and that preserves the spatial dependence[15].

Use of alternative methods to generate time series for the future

As indicated in Section 4.2. there are three main groups of methods to generate climatological time series for the future. For each of the three main groups many variants exist (especially for precipitation).

In climate impact and adaptation research it is often important to determine the vulnerability of a system and the robustness of adaptation measures. This means that uncertainties about our future climate and the system under study have to be taken into account. The method to generate time series for the future also introduces uncertainties. Therefore, it would be interesting to have more than one method available for generating time series for the future. However, few users are aware of the uncertainty related to methods to generate time series and, therefore, it is hardly ever requested explicitly. First explorations of the effect of various methods for generating time series show a potentially large effect for extreme river discharges (Bakker, 2010), but effects on crop growth are probably less pronounced, since they are the cumulative result of a longer period (> 100 days).

The possibilities of stochastic weather generators for generating time series for the future are hardly investigated in the Netherlands. It might be interesting to do this, since stochastic weather generators have some interesting advantages (option to create long time series, often fast in generating time series, option to adapt year-to-year variation, etc.; see Section 4.2). The main challenge seems to be the difficulty to build a multi-site stochastic weather generator with realistic spatial correlation.

14 The options to fulfil this requirement also depend on which information will be provided in the next generation of KNMI climate scenarios.

15 It is not clear whether the spatial dependence can be preserved completely, but probably it can be done in a better way that in the current versions of the tool (e.g. in case of drying wet days, also dryer these wet days from neighbouring stations).

At KNMI we have considerable experience with bias correction of climate model output. When it is possible to generate climate model output consistent with one of the KNMI climate scenarios, the direct method is also an option to generate time series for the future. This would make it easier to generate time series for a wider area than the Netherlands, consistent with the next generation of climate scenarios for the Netherlands.

Activities in other projects related to generation of future time series

In several other projects activities are planned or have almost finished that are related to generation of time series for the future. Below an overview is given:

- Transformation of hourly precipitation (project HSHL05/HSRR04 of the Knowledge for Climate-programme; will be finished in June 2011): a pilot version of a transformation tool for hourly precipitation, consistent with the daily transformation is ready. The requirement that there should be consistency at the daily level is highly restrictive. Besides, the knowledge about possible future changes of hourly precipitation is very limited. Therefore, the status of the hourly precipitation tool is experimental;
- A comparison of "Delta methods" and "Direct methods" (CS7 of the CcSP-programme; will be finished in June 2011): in the last pilot project together with Alterra, time series with both a transformation tool and based on bias-corrected climate model output are developed. The effect on the estimation of crop production will be compared;
- Regional distribution of climate change and generation of time series for other climate variables (NMDC "Kritische Zone" for the National Model and Data Centre; until the beginning of 2012): in this project it is investigated how the procedures for generating time series for other climate variables (Annex 2 Bakker et al., 2011) can be adapted;
- Development of methods and datasets for generation of time series for the next generation of KNMI-scenarios (within the "Theme 6" consortium of KfC and within the "KNMInext-project"): For the next generation KNMI climate scenarios probably again the transformation tool will be used to generate time series for the future, although the program may be adapted (see above). At the same time it is investigated whether climate model runs can be generated that are consistent with the new KNMI scenarios. This would open up the option to generate also time series for the future by using the direct method. It is also investigated whether time series for the future can be generated that fit the requirements of various sectors at the same time. This could improve the efficiency of generating time series for the future and promote standardization in the use of climate data within impact and adaptation research.

Several of the desired and possible developments are already included in the projects mentioned above.

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Links

- Website transformation program (in Dutch, version 1.2): http://climexp.knmi.nl/Scenarios_monthly;
- Climate explorer (linked to the transformation tool, for downloading time series, visualisation tool, statistical processing, etc.): http://climexp.knmi.nl (EN);
- KNMI website on climate scenarios: http://www.knmi.nl/climatescenarios (EN); http://www.knmi.nl/klimaatscenarios (NL);
- KNMI website: Examples of "Tailoring" projects (in Dutch; in several the transformation tool is used): http://www.knmi.nl/klimaatscenarios/maatwerk;
- Knowledge for Climate, Theme 6 "High quality climate projections": http://knowledgeforclimate.climateresearchnetherlands.nl/highqualityclimateprojections;
- For more information on the projects in which the transformation tool is used: http://klimaatvoorruimte.klimaatonderzoeknederland.nl/projecten.

Climate changes Spatial Planning

Climate change is one of the major environmental issues of this century. The Netherlands are expected to face climate change impacts on all land- and water related sectors. Therefore water management and spatial planning have to take climate change into account. The research programme 'Climate changes Spatial Planning', that ran from 2004 to 2011, aimed to create applied knowledge to support society to take the right decisions and measures to reduce the adverse impacts of climate change. It focused on enhancing joint learning between scientists and practitioners in the fields of spatial planning, nature, agriculture, and water- and flood risk management. Under the programme five themes were developed: climate scenarios; mitigation; adaptation; integration and communication. Of all scientific research projects synthesis reports were produced. This report is part of the communication series.

Communication

Adequate dissemination of knowledge can take place only if there is a closely-knit network between researchers and end users. Climate changes Spatial Planning created this knowledge network and monitored conditions to ensure it functions properly. Knowledge was made available to a wider audience and translated so that it can be used to better support national policy-making. Specific products included a website, conferences, workshops, brainstorming sessions, visits by foreign experts and a front office.

Programme Office Climate changes Spatial Planning

p/a VU University Amsterdam, FALW
De Boelelaan 1085
1081 HV Amsterdam
The Netherlands
T +31 20 598 7318
office@klimaatvoorruimte.nl

p/a Alterra, Wageningen UR
P.O. Box 47
6700 AA Wageningen
The Netherlands
T +31 317 48 6540
info@klimaatvoorruimte.nl

www.climatechangesspatialplanning.nl