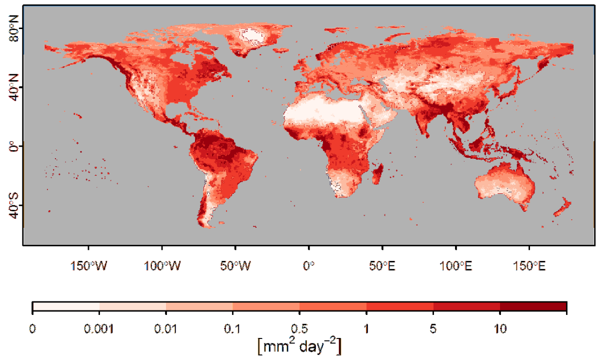
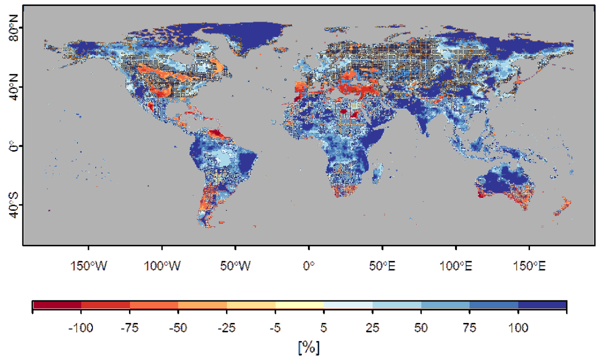
Technical Report No. 49

PROJECTED CHANGES IN FUTURE RUNOFF VARIABILITY - A MULTI MODEL ANALYSIS USING THE A2 EMISSION SCENARIO


Runoff variance (1971 - 2000)


Percentage change: from 1971 - 2000 to 2071 - 2100

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Introduction

Shifting precipitation and temperature patterns in a changing climate are expected to alter the terrestrial water balance, possibly impacting climate dynamics and water resources (Milly et al. 2005, Jung et al. 2010). In addition, both precipitation and temperature are expected to change their variability, possibly leading to more intense precipitation extremes (Min et al. 2011, Alexander et al. 2006) and changes in heat wave dynamics (Alexander et al. 2006, Schär et al. 2004). Several studies have suggested that these changes in atmospheric variability are likely to alter the recurrence rate of hydrological extremes such as floods (Dankers and Feyen 2009, Pall et al. 2011) and droughts (Feyen and Dankers 2009).

This study aims at assessing whether climate change is likely to alter the variability of the terrestrial water balance

$$\frac{dS}{dt} = P - E - Q\ ,$$

where S denotes the terrestrial water storage, P precipitation, E evapotranspiration and Q is total runoff. This study concentrates on the analysis of total runoff. Total runoff can be interpreted as an excess of water that is available to feed an increasing atmospheric water demand in warmer conditions and also as a renewable water resource.

To assess changes in global runoff variability, simulations of large-scale hydrological models (LSHM) from the 1971 – 2000 control period are compared to simulations in the 2071 – 2100 time interval. Simulations of the terrestrial water balance on continental and global scales exhibit a considerable uncertainty. Previous studies have indicated that the analysis of multi model ensembles of LSHMs can systematically increase model performance, while keeping track of the predictive uncertainty (Gudmundsson et al. 2011d, Gudmundsson et al. 2011b). This study is based on the analysis of a comprehensive multi model ensemble of LSHMs, which also allows to assess the significance of predicted changes in runoff variability.

Runoff simulations form a multi model ensemble

Global runoff simulations where obtained from a multi model ensemble consisting of eight large-scale hydrological models (LSHM) which were forced by three different global circulation models (GCM). The simulation setup is identical to the one described by Chen et al. (2011) and includes a bias correction of the GCMs precipitation and temperature (Piani et al. 2010). The effects of the bias correction were further evaluated by Hagemann et al. (2011). Table 1 lists the three GCMs used to force the LSHMs listed in Table 2. Both tables also provide the key references to the models. For most LSHMs (except Jules, see Table 2), model simulations forced with all three GCMs were available resulting in an ensemble of 23 members.

To assess changes in runoff variability, simulation results corresponding to the 1971 – 2000 control period where compared to projections in the 2071 – 2100 time interval. The three GCMs used to force the LSHM where run assuming the IPCCs A2 emission scenario (Nakicenovic et al. 2000). The analysis is based on monthly rates of total runoff (i.e. the sum of surface and subsurface runoff.). The ensemble of runoff simulations was build as a joint effort within Work Block 3 of the WATCH project (Chen et al. 2011).

Table 1: Global Circulation Models (GCM) used to force Global Hydrological Models (LSHM). Information's taken from Chen et al. (2011)

Model	Institution	Main references
ECHAM5	Max Planck Institute for Meteorology (MPI-M)	Roeckner et al. (2003) Jungclaus et al. (2006)
IPSL	Institute Pierre Simon Laplace	Hourdin et al. (2006) Fichefet and Maqueda (1997) Goosse and Fichefet (1999)
CNRM	Centre National de Recherches Météorologiques, Météo-France	Deque and Piedelievre (1995) Royer et al. (2002) Salas Melia (2002)

Table 2: Global Hydrological Models (LSHM) considered in this study

Model	Forcing	Main references
Htessel	ECHAM5, CNRM, IPSL	Balsamo et al. (2009)
Jules	ECHAM5, CNRM	Best et al. (2011) Clark et al. (2011)
LPJmL	ECHAM5, CNRM, IPSL	Fader et al. (2010) Bondeau et al. (2007)
MacPDM	ECHAM5, CNRM, IPSL	Arnell (1999) Arnell (2003) Gosling and Arnell (2011)
MATSIRO	ECHAM5, CNRM, IPSL	Takata, Emori and Watanabe (2003) Koirala et al. (2011a) Koirala et al. (2011b)
MPI-HM	ECHAM5, CNRM, IPSL	Hagemann and Dümenil (1998) Hagemann and Dümenil Gates (2003) Roeckner et al. (2003)
Orchidee	ECHAM5, CNRM, IPSL	d'Orgeval, Polcher and de Rosnay (2008)
WaterGAP	ECHAM5, CNRM, IPSL	Alcamo et al. (2003) Döll, Kaspar and Lehner (2003)

Characterizing runoff variability

Runoff variability is quantified for each grid cell individually, based on summary statistics derived from monthly runoff. The variability of runoff is characterized using the standard deviation of monthly runoff (σ_Q), which describes the average fluctuations around the mean. The magnitude of the standard deviation of any variable is closely related to the average magnitude and thus changes in σ_Q are expected to be closely related to changes in mean runoff (μ_Q). In this study, the coefficient of variation of monthly runoff,

$$cv_Q = \frac{\sigma_Q}{\mu_Q},$$

is therefore used as a measure of runoff variability. The coefficient of variation expresses the standard deviation of a variable as a fraction of the mean and $cv_Q > 1$ indicates that runoff fluctuations are, on average, larger than the mean runoff rate.

The coefficient of variation of monthly runoff captures the total runoff variability disregarding time scale and generating processes. Therefore the analysis also includes the coefficient of variation of the mean seasonal cycle of runoff

$$cv_{Q,Seas} = \frac{\sigma_{Q,Seas}}{\mu_Q}$$

and the coefficient of variation of the residual runoff

$$cv_{Q,\mathrm{Re}sid} = \frac{\sigma_{Q,\mathrm{Re}sid}}{\mu_Q},$$

where $\sigma_{Q,Seas}$ is the standard deviation of the mean seasonal cycle of runoff, defined as the long term mean of each month and $\sigma_{Q,Resid}$ is the standard deviation of runoff anomalies, which are obtained by removing the mean seasonal cycle from the monthly runoff series. Both the seasonal and the residual standard deviation are directly related to the standard deviation of monthly runoff as

$$\sigma_Q^2 = \sigma_{Q,Seas}^2 + \sigma_{Q,\mathrm{Re}sid}^2 .$$

This separation into a seasonal and a residual component allows for a more detailed interpretation of the projected changes in runoff variability. Changes in the coefficient of variation of the mean annual cycle ($cv_{Q,Seas}$) are for example related to changes in hydrological processes such as snow accumulation and melt as well as evapotranspiration, which influence both the timing as well as the magnitude of annual low and high flows statistics. The variability of runoff anomalies is in turn closely related to the intensity and number of rainfall-runoff events.

Quantifying changes in runoff variability

Let x_m be a summary statistic (e.g. the coefficient of variation of monthly runoff) derived from the model m for the control period and y_m the same summary statistic derived for the projection of future climate. The projected change is defined as $\Delta_m = y_m - x_m$ and the percentage change relative to the control period is

$$\Pi_m = \frac{\Delta_m}{x_m} .$$

Due to model uncertainty, both Δ_m and Π_m are expected to scatter among the different models, indicating predictive uncertainty. In this study the expected change is defined as the median absolute change (Δ) and the median percentage (Π) change. The differences in Δ_m impact the reliability of the prediction and can be used to assess its significance. In order to test whether the expected change Δ (and consequently also Π) is significantly different from zero, the Wilcoxon signed-rank test (Wilcoxon 1945) was employed, which is a nonparametric paired difference test. The Wilcoxon signed-rank test is analogue to a paired t-test, however it does not rely on the normality assumption and is thus more robust. The results will be presented as a map of the multi model median of the summary statistic derived for the control period (x) and a map of the median percentage change in the future. The map of the median percentage change also indicates significance. Significance is reported for $p < 0.01$.

Projected changes in runoff variability

Figure 1 shows global patterns of mean runoff and the standard deviation of monthly runoff. The patterns of projected change in monthly runoff confirm previously published results (Milly et al. 2005, Chen et al. 2011). The most pronounced feature is that runoff is expected to change in subtropical regions, especially the Mediterranean, the Golf of Mexico and Middle America. In northern latitudes and the tropics runoff is on the other hand expected to increase, indicating overall wetter conditions.

The global patterns of standard deviation of monthly runoff in the control period do overall follow the pattern of mean runoff. The projected changes in the standard deviation of monthly runoff share the same basic pattern as the changes in mean runoff. However, the projected changes are even more pronounced for the standard deviation. Especially noteworthy are the dramatic decrease in standard deviation found in the centre of the Eurasian and the North American continents as well as in northern Africa. In tropical regions, on the other, hand the standard deviation of runoff is projected to strongly increase.

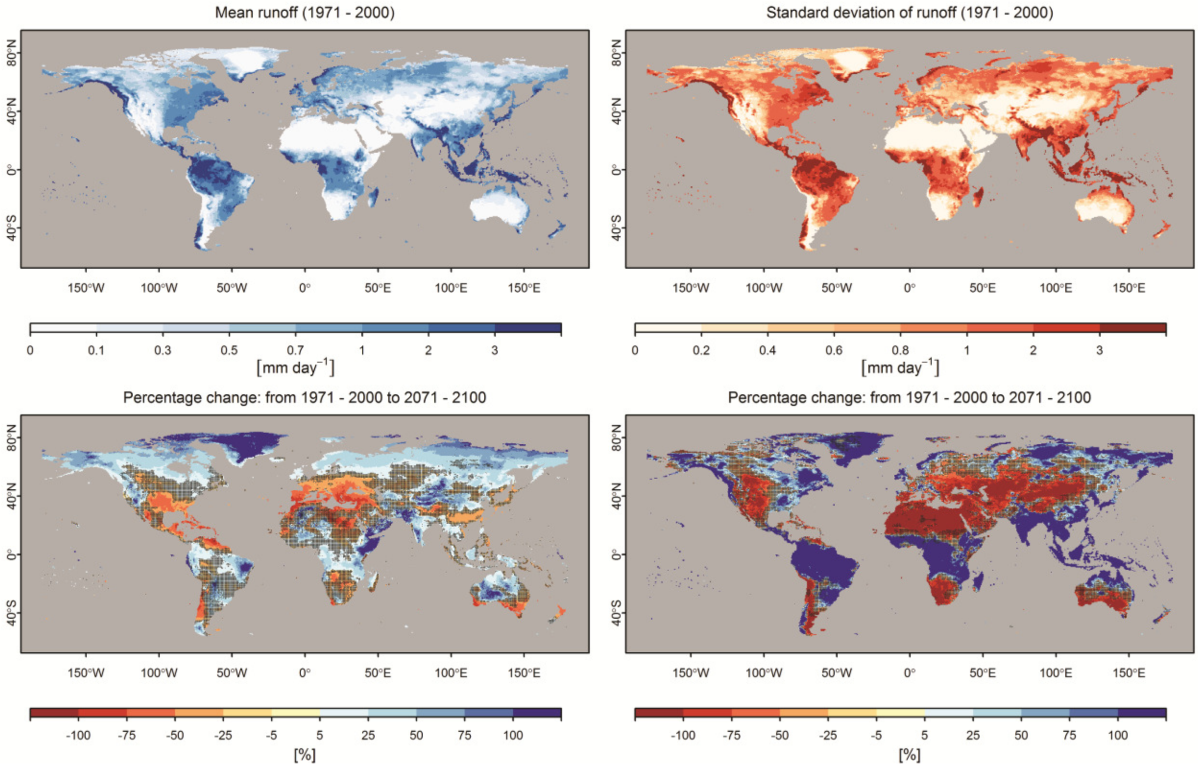

Figure 1: Projected changes in mean runoff and standard deviation of monthly runoff. The two top panels show the multi model median for the control period. The two bottom panels indicate the expected change in percent. Hatched areas indicate that the changes cannot be distinguished significantly from zero ($p < 0.01$, Wilcoxon signed-rank test).

Global patterns of the coefficient of variation of runoff (cv_Q) for the control period as well as the projected changes from the multi model ensemble, are shown in Figure 2A. Distinct global patterns are found in the control period. Runoff variability is highest in dry regions with little runoff and lowest in humid areas (Figure 2A, top panel). Values larger than one indicate that runoff fluctuations are, on average, larger than the monthly runoff rate. The A2 emission scenario triggers significant changes in runoff variability (Figure 2A, bottom panel), which is predicted to decrease for northern latitudes, and to increase in mid latitudes (northern and southern hemisphere). Most significant changes are in relative proximity to the coasts (e.g. Europe, Golf of Mexico), whereas changes in inland area (e.g. centre of Eurasia or North America) are less significant.

Changes in the coefficient of variation of the mean seasonal cycle of runoff ($cv_{Q,Seas}$, Figure 2B) are similar to the changes in cv_Q. This indicates that the projected changes in cv_Q are predominantly related to changes in the seasonal cycle. In Europe, previous studies have shown that the seasonal cycle is a major contributor to total runoff variance and that it is strongest in regions with snow (Gudmundsson et al. 2011c). This suggests that the decreasing runoff variability in the northern latitudes may be related to the decreasing influence of snow on the mean annual cycle in a warming climate. The increasing runoff variability in the mid latitudes may in turn be related to an amplification of the mean annual cycle of runoff due to increasing summer evapotranspiration rates. Interestingly, comparable patterns of changes in the seasonality of runoff in Europe have already been observed throughout the last decades (Stahl et al. 2010).

Changes in the coefficient of variation of residual runoff ($cv_{Q,Resid}$) also exhibit a pronounced north south pattern with decreasing variability in the north and increasing variability in mid latitudes (Figure 2C). The number of grid-cells with significant changes is smallest for $cv_{Q,Resid}$, indicating larger uncertainties. The location of the transition between increasing and decreasing variability differs in comparison to $cv_{Q,Seas}$ and is in general located further south.

The results demonstrate that climate change does not only alter overall water availability, but also impacts the variability of total runoff. The detected patterns of changes in runoff variability are further investigated using a time scale dependent analysis, to support a process based interpretation (Gudmundsson et al. 2011a)

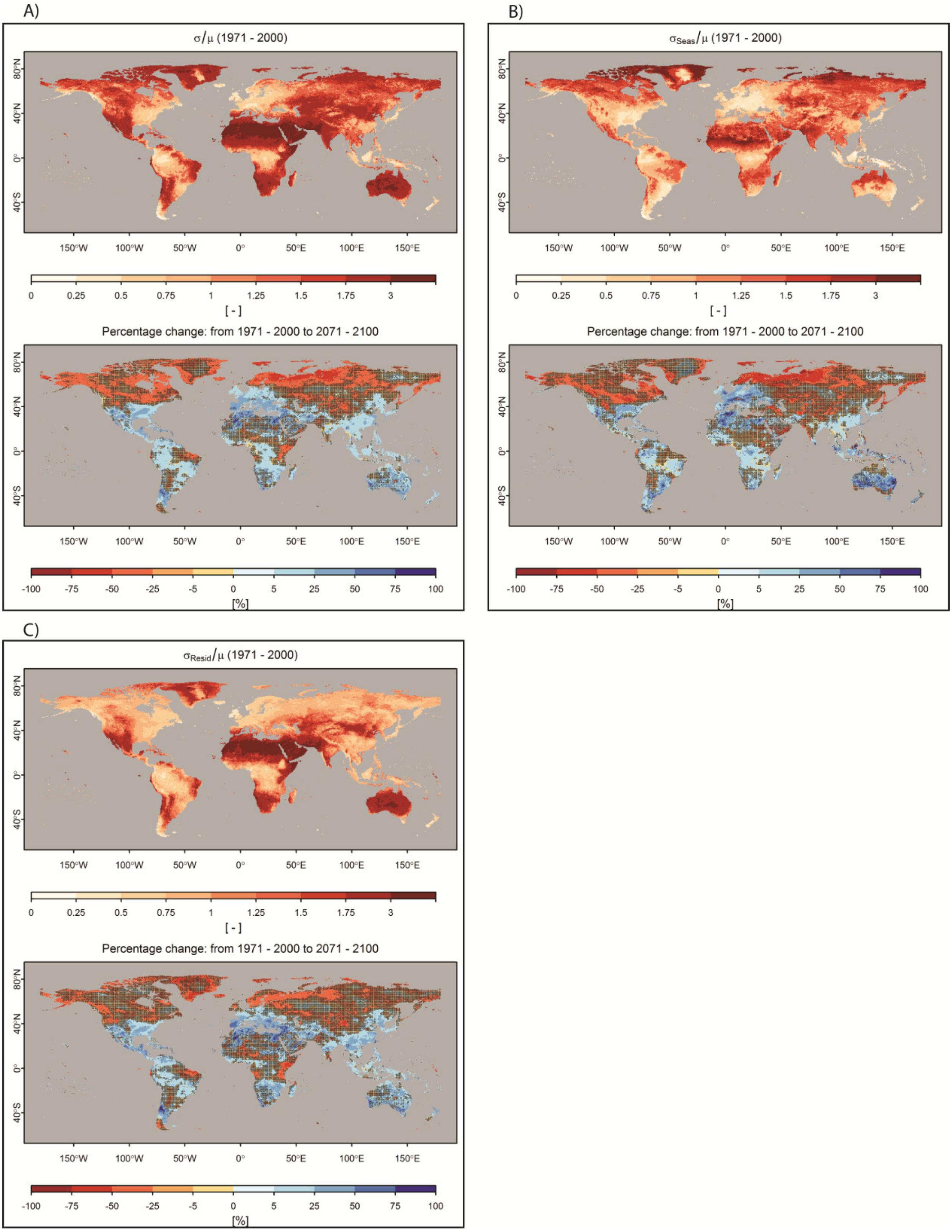

Figure 2: Projected changes in the coefficient of variation of monthly runoff (A), mean seasonal cycle of runoff (B) and monthly runoff anomalies (C). Top panels: the current conditions. Bottom panels: projected changes in percentage. Hatched areas indicate that the changes are not significant ($p < 0.01$, Wilcoxon signed-rank test)

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