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SPECIAL ISSUE: HYDROLOGICAL DATA: OPPORTUNITIES AND BARRIERS

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Comparison of open access global climate services for hydrological data

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ABSTRACT
There is a high demand for openly accessible hydroclimatic data for climate change adaptation. Different data sources are available, however, discrepancy between the data can confuse users and should be evaluated and explained. This study, investigates how climate impact indicators (CIIs) developed for global users in the Copernicus Climate Change Service (C3S) are comparable to other openly available global data for water and climate. We found that, for temperature, datasets are comparable and climate impacts are thus considered robust. Important discrepancies arise in the precipitation indicators. Of the CIIs analysed in this study, the hydrological CIIs differ most so they should be used with care. These differences are probably caused by model uncertainty (hydrological model, HM; global climate model, GCM), ensemble size and model selection. A HM ensemble, as well as a GCM ensemble combined with improved model performance and selection criteria, should be used to ensure high-quality global water and climate services.

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1 Introduction

To facilitate adaptation and the development of a more climate-resilient society there is need for improved information on future climate change impacts (Hewitt *et al.* 2012). At the same time, the implementation of the Paris Agreement (UNFCCC 2015) on climate adaptation and several of the United Nations (UN) Sustainable Development Goals (UN 2015) demand easy access and readily available hydroclimate data and information for assessments, also in data-sparse regions worldwide. The use of climate information is, however, still strongly limited by the difficulty in accessing the information and the large uncertainty in future climate change projections (Dessai *et al.* 2009). At the same time, data and information on future climate change impacts often come from different inconsistent sources and it can be difficult to trace where the information comes from (Tall *et al.* 2018). For example, different climate models, emission scenarios and time ranges are used in different studies (Donnelly *et al.* 2018). As a result it is hard for both public and private climate change adaptation initiatives to find consistent dataset and information which addresses their needs.

Services with hydroclimatic information are often on a national or state/province scale, e.g. the Finnish Climate Guide and Cal-Adapt California (Sigel *et al.* 2016) and project-based on a European scale like the IMPACT2c web atlas (Jacob *et al.* 2018) and the SWICCA Copernicus proof of concept (Roudier *et al.* 2016, Donnelly *et al.* 2017). Most of the accessible global climate services are currently limited to climate data, e.g. KNMI climate explorer (van Oldenborgh 1999) and, more recently, soil moisture data (Acclimatize/PCA Global Drought Risk platform; Sheffield and Wood 2007, PCA 2019). Where the KNMI climate explorer is mainly focused at scientific users. A global climate service integrating both climate and hydrological data aimed at users outside the scientific community was still missing.

A new European initiative, Copernicus Climate Change Service (C3S[1]), was initiated to address persistent problems in scattered climate service development. The Sectoral Information Systems (SIS) aim at outreach and co-creation of climate services with users at global, regional and local scale worldwide.[2] The objective of this service is to give users the tools to adapt to increasingly frequent and intense climatic changes in several key sectors. This user-focused approach was identified as the key area of possible improvement and a major challenge for the development of climate services (Buontempo *et al.* 2014, Vaughan *et al.* 2016). The core of the SIS is to refine climate data into information and develop climate impact indicators (CIIs). CIIs are aggregated quantitative measures that show the key impacts of climate change on complex environmental phenomena in terms of trends and variability. CIIs are frequently used in climate impact assessments to assemble outcomes of climate and/or impact models into a quantity that is relevant for a specific business, system, or sector. CIIs contain condensed climate information which can be used for relatively quick and effective analysis, since their usage is much more efficient compared to going through a full climate modelling chain.

In this study, we present a number of new CIIs at global scale for hydrological climate-impact assessments. Developed in the

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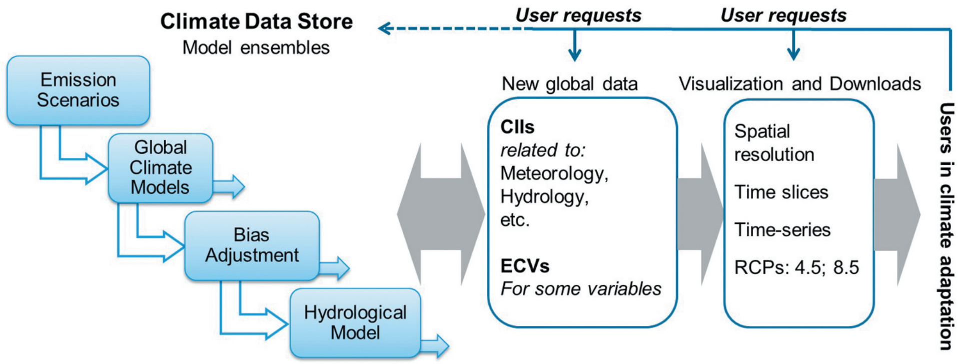

Figure 1. Production chain of climate impact indicators (CIIs) for global users of the Copernicus Climate Change Service (C3S).

C3S global users SIS.[3] These CIIs are used by global users, who are users operating globally (e.g. multinationals) as well more regional or local users of global data. The CIIs were produced using a traditional production chain (Fig. 1), starting with data already available in the C3S Climate Data Store (CDS,[4] Copernicus 2019a) (e.g. data from climate models), which were bias-adjusted and assessed through a hydrological model to retrieve information on climate impacts. User requests guided the production of CIIs and how they were presented in the web interface of the service. The new data produced were added to the C3S climate data store for easy access through its catalogue and possible further refinement through its toolbox. For hydrological impacts, a global catchment model was used (the world-wide HYPE; Arheimer *et al.* 2019).

Quality assurance of the data provided to users of the climate service is important. Many of the national, regional and global climate services are based on the results of Model intercomparison projects (MIPs) such as CMIP (Taylor *et al.* 2012) and Cordex (Jacob *et al.* 2014). The aim of these MIPs is to compare and improve models and to further develop the science. Outputs of models are stored and shared by and for scientists. The climate data were thus produced with another purpose than climate impact assessments. Data for scientists require a different quality control and assurance system than a climate service aimed at non-scientific users from the public and private sectors (van den Hurk *et al.* 2018). So to use these datasets for climate services there is a need for addition quality control. The question is how to perform this quality control and to define what is “good enough” for the users.

Moreover, we fully acknowledge that some of the CIIs produced already exist in other climate services at global scale and that the information presented in these other climate services can potentially be different from C3S. This discrepancy between different data providers may be confusing for the users and should thus be evaluated and explained to the extent possible. Therefore, there is a need to investigate to what extent this newly developed global climate service gives similar information as already existing systems or climate services of a similar magnitude and scope.

The aim of this study is to present an analysis of the hydrologically relevant CIIs produced for the C3S global service and compare these CIIs to other openly available data or climate service platforms. This could be from Earth observations in the reference period, from other models, grid-based or *in-situ* observations, or soft data such as expert opinions or global or regional atlases. Specifically, a comparison was made at a global level of a selection of CIIs using the model ensemble used in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the CMIP5 full ensemble for extremes and data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP, Warszawski *et al.* 2014), for which a climate service is also under development (ISIMIP 2019). We argue that this kind of assessment or evaluation should be performed as part of the protocol for additional quality measure to guide users and support the good quality of openly available data, while acknowledging challenges, limitations and further improvements when developing global scale CIIs.

Comparisons of climate services have mainly focused on regional climate services (e.g. van Vliet *et al.* 2015, Donnelly *et al.* 2017, 2018, Vaughan *et al.* 2019). van Vliet *et al.* (2015) and Donnelly *et al.* (2018) explicitly conducted studies comparing European hydroclimatic information services. In these studies Donnelly *et al.* (2018) focused on the difference between services for users on a local scale and van Vliet *et al.* (2015) and Donnelly *et al.* (2017) more specifically looked at model differences at a European scale. The focus of the comparison in this study, however, is to identify the differences between the data produced for the C3S climate service for global users and other global and openly available data sources and their implications for climate service development.

2 Methods and data

The data produced for global users of the C3S were subject to quality checks throughout the production chain. Additionally, the CIIs were compared to other freely accessible global climate and water data. This analysis covered both raw and bias corrected data. The datasets used for this comparison contain different ensembles of global climate

[3] https://climate.copernicus.eu/global-users-copernicus-climate-change-service, currently available at https://hypeweb.smhi.se/explore-water/climate-change-data/global-climate-change/.
[4] https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-ecv-cmip5-bias-corrected.

Table 1. GCM ensembles used by C3S and the datasets for comparison. The model ensembles have some overlap.

C3S ensemble	IPCC AR5 ensemble RCP8.5		CMIP5 ensemble of extremes	
ACCESS1-0	ACCESS1-0	GISS-E2-R p1	ACCESS1-0	GFDL-ESM2G
ACCESS1-3	ACCESS1-3	GISS-E2-R p2	ACCESS1-3	GFDL-ESM2M
bcc-csm1-1	bcc-csm1-1	GISS-E2-R p3	bcc-csm1-1	HadGEM2-CC
bcc-csm1-1-m	BNU-ESM	GISS-E2-R-CC	bcc-csm1-1-m	HadGEM2-ES
BNU-ESM	CanESM2	HadGEM2-AO	BNU-ESM	inmcm4
EC-EARTH	CCSM4	HadGEM2-CC	CanESM2	IPSL-CM5A-LR
CNRM-CM5	CESM1-BGC	HadGEM2-ES	CCSM4	IPSL-CM5A-MR
GFDL-CM3	CESM1-CAM5	inmcm4	CMCC-CESM	IPSL-CM5B-LR
GFDL-ESM2G	CMCC-CM	IPSL-CM5A-LR	CMCC-CM	MIROC5
GFDL-ESM2M	CMCC-CMS	IPSL-CM5A-MR	CMCC-CMS	MIROC-ESM
HadGEM2-ES	CNRM-CM5	IPSL-CM5B-LR	CNRM-CM5	MIROC-ESM-CHEM
HadGEM2-CC	CSIRO-Mk3-6-0	MIROC5	CSIRO-Mk3-6-0	MPI-ESM-LR
IPSL-CM5A-MR	EC-EARTH	MIROC-ESM	FGOALS-g2	MPI-ESM-MR
IPSL-CM5A-LR	FGOALS-g2	MIROC-ESM-CHEM	FGOALS-s2	MRI-CGCM3
IPSL-CM5B-LR	FIO-ESM	MPI-ESM-LR	GFDL-CM3	NorESM1-M
MPI-ESM-MR	GFDL-CM3	MPI-ESM-MR	**ISIMIP VIC ensemble**	
MPI-ESM-LR	GFDL-ESM2G	MRI-CGCM3	GFDL-ESM2M	
NorESM1-M	GFDL-ESM2M	NorESM1-M	HadGEM2-ES	
	GISS-E2-H p1	NorESM1-ME	IPSL-CM5A-LR	
	GISS-E2-H p2		MIROC-ESM-CHEM	
	GISS-E2-H p3		NorESM1-M	

models than the C3S data (see Section 2.1). The VIC (variable infiltration capacity) hydrological model forced with five GCMs from ISIMIP was used for the comparison of the hydrological data.

2.1 Data production

2.1.1 Climatological and hydrological data

The Copernicus Climate Change Service (C3S) has approved the quality assurance of a subset of 18 global climate models (GCM) from the Coupled Model Intercomparison Project (CMIP5, Taylor *et al.* 2012) to be included in the C3S Climate Data Store (CDS). These were used to calculate a set of CIIs related to climate and hydrological variables for global users of the C3S. This subset is a selected ensemble made for the first delivery of CDS. Table 1 lists the details of the climate model ensemble together with the ensembles of other datasets used in this study for comparison.

The C3S GCM ensemble was used in a state-of-the-art production chain, starting with CIIs calculated with raw output from the ensemble on global scale at a common 2.0° grid resolution, followed by bias adjustment and downscaling to 0.5°, and finally impact modelling with calculations of indicators related to hydrological variables (Fig. 1). This analysis uses two of the representative concentration pathways (RCP) 4.5 and 8.5, and a 30-year mean of annual values for the historical period of 1971–2000 and three future periods: 2011–2040 (early century), 2041–2070 (mid-century), and 2071–2100 (late century).

The C3S data were bias-adjusted with distributed-basted scaling. This method is a parametric quantile-mapping variant, which fits a statistical distribution to the cumulative distribution function and uses those fitted distributions to conduct the quantile-mapping. Here, a double-gamma distribution was used, i.e. separate gamma distributions for the bulk and the high tail (see Yang *et al.* 2010), for precipitation and a normal distribution for all the temperature variables. Temperature corrections were done conditional on the wet/dry state of the corresponding precipitation time series. The seasonal variations in the biases were represented by monthly parameter windows for precipitation and a smoothed seasonal cycle for the temperature distribution parameters. The smoothing was done using 12 harmonic components.

The CIIs were calculated from both raw and bias-adjusted GCM CMIP5 output using four Essential Climate Variables (ECVs): daily mean, maximum and minimum temperature and daily accumulated precipitation. The CIIs related to these four climate ECVs were calculated in two steps. First, the CIIs were calculated from the raw data (non-bias-adjusted) on the original resolution of each GCM. These were later interpolated to a common spatial grid of 2.0° for visualization and comparison purposes. Second, the four data from the ensemble of GCMs at a 0.5° × 0.5° spatial grid, using a global reference dataset developed, called HydroGFD2.0 (Berg *et al.* 2018).

The calculated water-related CIIs are based on hydrological impact modelling using, for the first time, the global catchment World-Wide-HYPE (WWHYPE Arheimer *et al.* 2019). WWHYPE is a hydrological model that calculates water volume and fluxes over large geographical areas, encompass many river basins, cross regional and international boundaries, and a number of different geophysical and climatic zones. Each river basin covers numerous coupled catchments and has thus a relatively high spatial resolution, although most basins are ungauged. The CIIs are provided for catchments (polygons) with an average resolution of 1000 km^2 globally. The bias-adjusted ECVs were used as forcing data for WWHYPE, and a complete run of the 18 GCMs for all time period was performed. To facilitate the data comparison, the water-related CIIs were gridded from polygons on a catchment scale to a 0.05° spatial scale. The small 0.05° scale ensures little to no data get lost on the catchment borders. Visual inspections of each CII ensured that the spatial patterns and magnitudes were not affected by this procedure.

2.2 Selection of indicators

The selection of the CIIs was based on user requests and interactions. Criteria for selection of indicators are based on (i) applicability for global assessment; (ii) clearly defined user needs; and (iii) quality of results and reliability. In total 21 CIIs which fulfil these criteria are now available on C3S (Copernicus 2019b). CIIs related to climate variables follow the definitions from the Expert Team for Climate Change Detection and Indices (ETCCDI, Klein Tank *et al.* 2009). The CIIs were calculated with CDO commands after they were validated against other computational routines. All CIIs and climate and hydrological modelling chain (production) included rigorous quality assurance checks which follow a quality assurance procedure developed specifically for C3S (Zahid *et al.* 2019 (sub)). Such quality checks involved checks before and after bias adjustment on the ensemble of CMIP5 used here, during the hydrological modelling and the calculation of the CIIs. These CIIs and bias-adjusted ECVs were used further for global users in the C3S (Copernicus 2019b) in a number of case studies for various sectors around the globe.

A subset of 14 of the 21 CIIs developed in C3S was selected for the comparison with other datasets. This selection was based on the availability of the CIIs in other openly accessible sources on a global scale and relevance for hydrological impact assessment (Table 2).

2.2.1 Confidence metrics

Two metrics were used to evaluate the confidence levels of the GCM ensemble for each CII used in this study: the agreement on sign of change and the inter-quantile range. The agreement on sign of change shows the number of models in an ensemble agreeing on a decrease, an increase or no change in the climate change signal of a particular CII. The more models agreeing on the sign of change, the more robust the sign of change is. The number of models agreeing on a decrease, increase or no change are classified into 4 confidence levels: Few (7–10 models agree on type of change); Some (11–14 models); Many (15 or more models); and Unclear (no dominant change type). Additionally, the inter-quantile range shows the difference between the 25% and 75% quantiles. This shows the model agreement on the amplitude of the projected change. A lower inter-quantile change would mean a higher confidence in the amplitude of change. In the results section, examples for these two metrics are given in maps for two CII, while for the rest the interpretation is merged with the description of results.

2.3 Data used for intercomparison

A qualitative comparison of the selected CIIs (Table 2) was made with other openly available climate services and datasets (Fig. 2), for the raw and bias-adjusted GCM (Table 1), and hydrological model outputs. All comparisons were done regarding the ensemble mean of each dataset. The CIIs derived from the raw GCM data at 2.0° spatial resolution and soil moisture data were compared to the IPCC AR5 Atlas ensemble (van Oldenborgh *et al.* 2013) CIIs and the CMIP5 ensemble for extremes (Sillmann *et al.* 2013), available at 2.5° resolution through the KNMI Climate Explorer (https://climexp.knmi.nl/). The CIIs derived from the bias-adjusted GCM data at 0.5° spatial resolution were compared to data from ISIMIP (Inter-Sectoral Impact Model Intercomparison Project (Warszawski *et al.* 2014), https://www.isimip.org/) and the hydrological indicators were compared with the VIC hydrological model (Liang *et al.* 1994) forced by the ISIMIP GCM ensemble. The ISIMIP data are not yet available through a climate service but are intended to become available through the ISIPedia project. The data were compared for RCP4.5 and RCP8.5 and the early, mid and end of century time periods. In this paper, we only present the comparisons from RCP8.5 as for this RCP the differences are most visible.

Difference maps were created for precipitation, temperature and consecutive dry days to make the differences between two compared ensemble-means more visible. The raw data were regridded from 2.0° and 2.5° to 0.5° to enable the subtraction. Difference maps were not created for the hydrological indicators due to the different nature of the datasets, catchment based and gridded.

2.3.1 CMIP5 ensemble available via the KNMI Climate Explorer

The IPCC AR5 Atlas model ensemble and the CMIP5 model ensemble for extremes were used to compare some of the global CIIs at the 2.0° resolution. These ensembles are at a 2.5° resolution and can be accessed and visualized via the

Table 2. Definitions of CIIs presented in this analysis, together with units for the analysis periods. Absolute change is defined as future period – reference period, while relative change as: 100 × (future period – reference period)/reference period).

Definition CII	Units
Mean temperature: calculated as the mean annual values of daily mean temperature averaged over a 30-year period.	°C for historical periods and °C (absolute change) for future periods
Mean precipitation: calculated as the mean annual values of daily accumulated precipitation averaged over a 30-year period.	mm/days for historical periods and % (relative change) for future periods
Consecutive dry days: calculated as the maximum number of consecutive dry days (daily precipitation < 1 mm) over a 30-year period	no. of days for historical periods and % (relative change) for future periods
Mean runoff: calculated as the mean value of daily water runoff over a 30-year period.	mm/year for historical periods and % (relative change) for future periods
Mean discharge: calculated as the mean values of daily water discharge over a 30-year period.	m^3/s for historical period and % (relative change) for future periods
Mean soil moisture: calculated as the mean annual soil moisture root zone as a fraction of field capacity over a 30-year period, as defined in WWHYPE.	No unit for historical period and % (relative change) for future periods
Mean aridity: calculated as the mean annual actual evapotranspiration as defined in WWHYPE divided by the mean annual precipitation over a 30-year period	No unit for historical period and % (relative change) for future periods

KNMI (Royal Netherlands Meteorological Institute) Climate Explorer (van Oldenborgh 1999). This is a climate service mainly aimed at scientists and professionals who have a general knowledge of climate data and data processing. This tool was used to generate maps with the same reference period and projection periods as in the C3S data presented here. It was not possible to retrieve the historical data from the Climate Explorer.

The extreme indicators provided in the Climate Explorer are based on the ETCCDI using the CMIP5 ensemble for extremes. These are pre-calculated ETCCDI indicators provided by the Canadian Centre for Climate Modelling and Analysis (Karl *et al.* 1999). Figure 2 shows the CIIs calculated with the C3S data that are common with the IPCC AR5 subset indicators and other indicators calculated from the CMIP5 ensemble for extremes for the ETCCDI indicators.

2.3.2 ISIMP and VIC

The C3S bias-adjusted data on 0.5° scale and hydrological data were compared to data from the ISIMIP project which are freely available for download. ISIMIP is an ongoing sectoral model intercomparison project involving more than 100 modelling groups in different sectors. The newest simulation round of the initiative is ISIMIP2b (Frieler *et al.* 2017). However, the ISIMIP Fasttrack data (ISIMIP 2017) were used in this study. The ISIMIP Fasttrack simulation round contains 13 global hydrological models. The aim was to provide consistent projections for different sectors by collecting impact model runs based on the same climate forcing. This consistent database provides the opportunity to conduct rigorous cross sectoral and cross model analysis (Warszawski *et al.* 2014).

The ISIMIP Fast Track data (from now on ISIMIP data) provide a bias corrected dataset from an ensemble of climate models for the period of 1950–2099, with historical data up to 2004 on a 0.5° grid. A trend-preserving bias correction was used. This method preserves the long-term absolute trend of the simulated temperature and the relative trend for the precipitation, pressure, radiation and wind variables. The daily variability of the simulated data is modified so their monthly means match the observed daily variability (Hempel *et al.* 2013). The ISIMIP data are based on five models from the CMIP5 dataset (McSweeney and Jones 2016) (Table 1) of which four are also included in the CDS catalogue for CMIP5 model members.

The VIC hydrological model forced with ISIMIP bias-adjusted data was selected to be compare with WWHYPE. The VIC model (Liang *et al.* 1994) is a grid-based large-scale hydrological model that solves both the water balance and surface energy equations. VIC is initially developed as a land surface scheme to provide the boundary conditions for global circulation models. Currently, it also widely used as a hydrological model. The VIC model simulated sub-grid variability for vegetation, elevation, and soils by partitioning each grid cell into different land cover and elevation classes. The soil column is commonly divided into three soil layers. Evapotranspiration is estimated based on the Penman-Monteith equation and snow accumulation and ablation processes are solved on sub-daily time step using an energy balance approach (Wigmosta *et al.* 1994). The key differences between VIC and HYPE are discussed in van Vliet *et al.* (2015).

For the comparison we purposely selected VIC because of the relatively different modelling approaches of VIC and WWHYPE. Broadly speaking, the models are on different ends of the spectrum of possible choices for hydrological models. The result of the comparison clearly indicate the potential impact of the choice of the hydrological model on water-related climate services (van Vliet *et al.* 2015). Additionally, VIC is a relevant model for comparison because it was previously used in climate services (e.g. PCA 2019). In addition HYPE and VIC were used previously in a European hydroclimate service study (van Vliet *et al.* 2015) and both models will be the core of the Sectoral Information System for Water as part of the C3S (climate.copernicus.eu).

ISIMIP data for mean daily temperatures and precipitation were retrieved from the ISIMIP platform. These were then used to compute the temperature and precipitation-related CIIs for comparison with the C3S CIIs (Table 1, Fig. 2). Monthly datasets of VIC hydrological model forced with ISIMIP bias-adjusted data were retrieved and used to compute the indicator for the comparison of the mean annual discharge, mean annual runoff, soil moisture and aridity. The CIIs with the ISIMIP data and the C3S data were computed with the same CDO command sequence. This was done for the reference period of 1970–2000 and the impact periods of 2040–2069 and 2069–2099 with RCP8.5 for

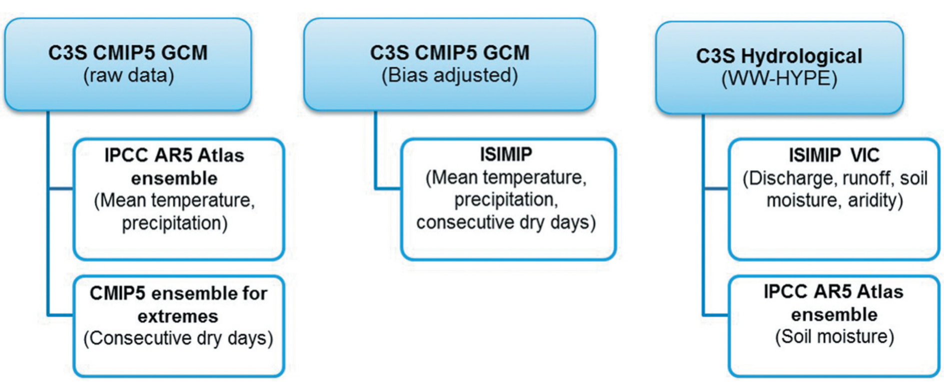

Figure 2. Climate impact indicators (CIIs) produced for global users of the C3S are compared to different other global datasets depending on availability; CIIs calculated from the C3S CMIP5 ensemble (interpolated to a common 2.0° grid) are compared to indicators from IPCC AR5 Atlas ensemble and CMIP5 ensemble for extremes; C3S CMIP5 ensemble of bias-adjusted GCMs at 0.5° grid are compared to indicators from ISIMIP data, and hydrological CIIs are compared to related ISIMIP VIC and IPCC AR5 Atlas data. All CIIs are calculated on an annual scale for a 30-year average.

the hydrological indicators and for RCP4.5 and 8.5 for the bias-adjusted indicators. The global assessment of the bias-adjusted and hydrological CIIs excludes Antarctica.

The C3S WWHYPE data for soil moisture were compared to the IPCC AR5 Atlas Ensemble as well as the ISIMIP-VIC data for soil moisture. The data sources use different indicators for soil moisture content. The soil moisture from IPCC AR5 Atlas and ISIMIP-VIC is measured in kg/m^2 moisture in the top 50 cm of the soil whereas WWHYPE gives soil moisture in the root zone as a fraction of field capacity.

3 Results

The results show the importance of different varieties and levels of quality assessments to compliment quality procedures followed in the production chain of data and climate services. First, quality checks on the raw CMIP5 ensembles showed inconsistencies between the models with respect to their realizations, availability of values in the entire time periods or having missing values. This indicated that some models were not quality assured enough to be used in hydrological impact modelling and had to be excluded. Second, similarities and discrepancies with other data sources were identified for the new CIIs from the C3S data. This information could be used in addition to judging of the robustness of the climate service.

3.1 Temperature and precipitation CIIs, not bias corrected

Absolute change of mean annual temperature for RCP8.5 for mid and late century was compared to related indicator from the IPCC AR5 Atlas ensemble (Fig. 3). The projected changes for the mean annual temperature are similar in both the C3S and the IPCC AR5 Atlas ensemble, with an expected increase of the global temperature of 2–3°C by mid-century and of 4–6°C by end-century for RCP8.5. Both ensembles suggest a higher increase in the Arctic and along the most northern latitudes, with the IPCC AR5 Atlas ensemble showing a slightly higher change. In tropical climates a slightly lower increase is projected compared to temperate climates. In both ensembles, the land surface temperature is expected to warm more than the oceans at a global average, while a higher increase is expected over mountain ridges than at sea level.

Relative change of mean annual precipitation in IPCC AR5 Atlas ensemble is similar to the related precipitation shown in the C3S for both mid and late century, with significantly higher changes for late century (Fig. 4). Precipitation is expected to increase most in East Africa, Canada, Northern Europe, Russia and Indonesia while the Mediterranean, Middle East, Central America, Chile, Southern Africa and Australia are seeing more of a decrease in precipitation. There are a few areas where differences between the IPCC AR5 Atlas and the C3S ensembles become more prominent. For example, for mid-century and RCP8.5 in the Sahara there is a high percentile increase (>50%) in the C3S ensemble and only a 20–30% increase in the IPCC AR5 Atlas data, difference can be more than 30%. Similarly, the Arctic has a higher peak of increase in the C3S data. The differences are concentrated in areas with low mean annual precipitation (e.g. Sahara and Middle East), these are areas where a small difference in absolute change can lead to a large difference in relative change. Additionally, these are also the areas where the C3S model

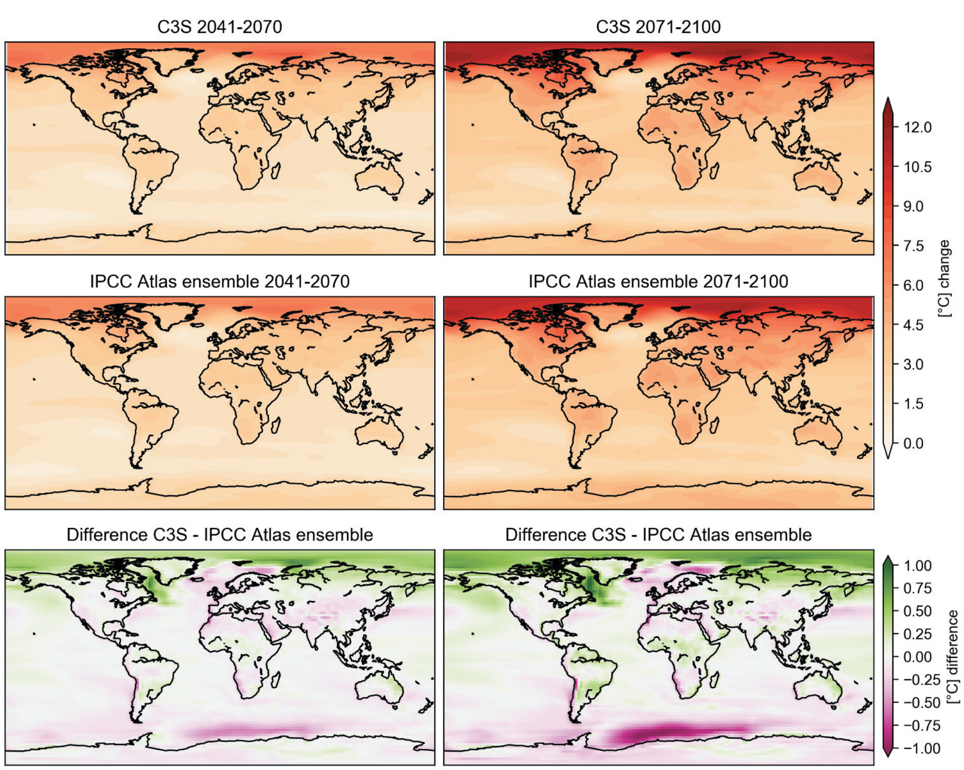

Figure 3. Absolute change in mean annual temperature (raw) for RCP8.5 for mid (2041–2070) and late century (2071–2100) with respect to the reference period (1971–2000): (top row) non-bias-adjusted C3S ensemble mean; (middle row) IPCC AR5 Atlas ensemble mean and (bottom row) difference between the C3S ensemble mean and IPCC AR5 Atlas ensemble mean.

ensemble shows a large inter-quantile range and *some* models agreeing on sign of change instead of *many* (Fig. 5) indicating a lower model certainty. The differences are likely caused by the different ensemble size and members; IPCC AR5 Atlas is a larger ensemble than the C3S.

The longest dry spell CII refers to the longest period of consecutive dry days over a 30-year period. The non-bias-adjusted C3S ensemble and the CMIP5 ensemble for extremes were compared (Fig. 6). The length of longest dry spells is expected to increase in large areas across the globe, especially for the Mediterranean, Indonesia, Eastern China and the Amazon. Decreases are expected in West, Central and East Africa as well as the North Pole, Mongolia and western China. Both the CMIP5 data and the C3S data show similar patterns for mid and late century. However, the magnitude of change is different in, for example, northern Africa where the C3S data show a higher increase (>50%) than the CMIP5 data (20–30%) for RCP8.5 in mid-century. Similarly, in northern South America, the C3S data an increase of 25–35% as opposed to 10–20% shown in the CMIP5 ensemble. For late century, the spatial gradient of the changes is similar but the magnitude of differences increases. Similar to Fig. 4, the differences in magnitude are could due to the different ensemble size and model members and can be related to a higher inter-quantile range.

3.2 Temperature and precipitation CIIs, bias corrected

The CIIs produced on a 0.5° grid from bias-adjusted C3S data are compared to the ISIMIP ensemble mean. The comparison in this section is bound to differences not only due to the different ensemble size and ensemble members of the two datasets but also due to the different bias adjustment methods and different reference datasets used.

For the future periods (Fig. 7) both datasets show similar global increases, with higher increases in the northern latitudes, and for late century. With an increasing temperature globally, there is no disagreement on sign of change within the C3S model ensemble. One visible difference between the datasets are local high values for the increase in temperature (mainly along the equator), e.g. in central Africa, where the C3S Global Impact CII show a spike in increasing temperatures at the border areas of Uganda, Rwanda and Congo Kinshasa. The difference is sometimes more than 2°C. Smaller but similar spikes are seen at the border of Kenya and Somalia, in Ecuador and Peru, on Papua-New-Guinea and the Indonesian island Sumatra. Additionally, the spatial pattern of change in Greenland for both future centuries is different between the two datasets, with C3S data having higher increases in the centre of Greenland. The observed differences occur where the ensemble value range of the C3S data is relatively high.

For the mean annual precipitation, the C3S and the ISIMIP data show the same patterns in the reference period and are comparable for the projections (Fig. 8). The two ensembles generally agree on sign of change, however, there are some differences in the absolute values (Fig. 8). ISIMIP data show a larger increase in precipitation in the Sahara region while the C3S data show a larger area with a high

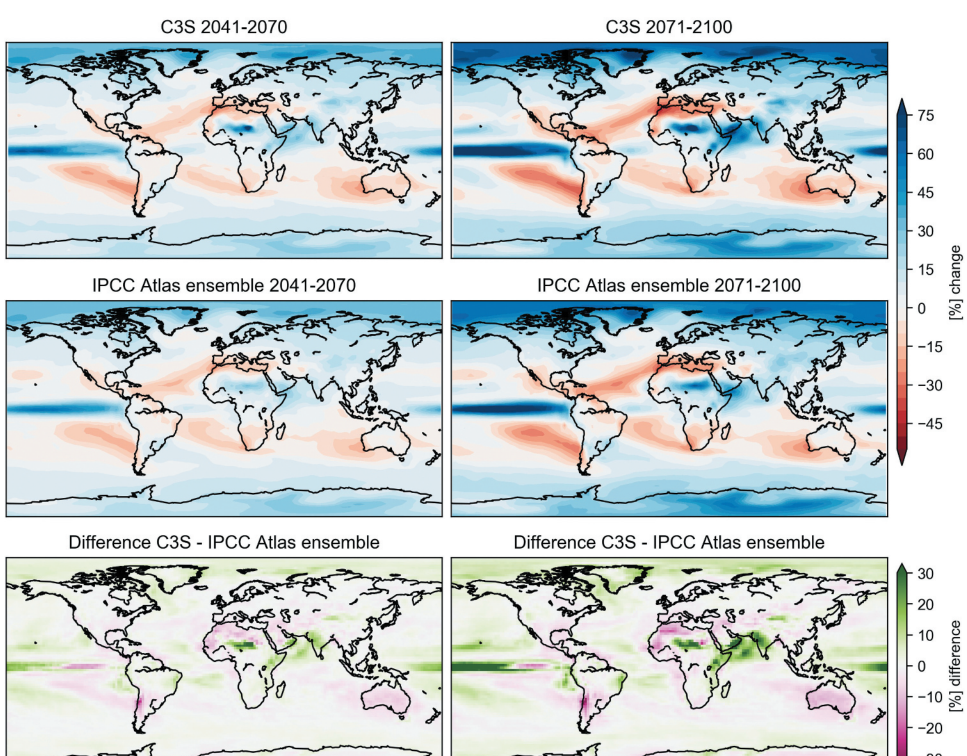

Figure 4. Relative change in mean annual precipitation (raw) for RCP8.5 for mid (2041–2070) and late century (2071–2100) with respect to the reference period (1971–2000): (top row) non-bias-adjusted C3S ensemble mean; (middle row) IPCC AR5 Atlas ensemble mean; and (bottom row) difference between the C3S ensemble mean and IPCC AR5 Atlas ensemble mean.

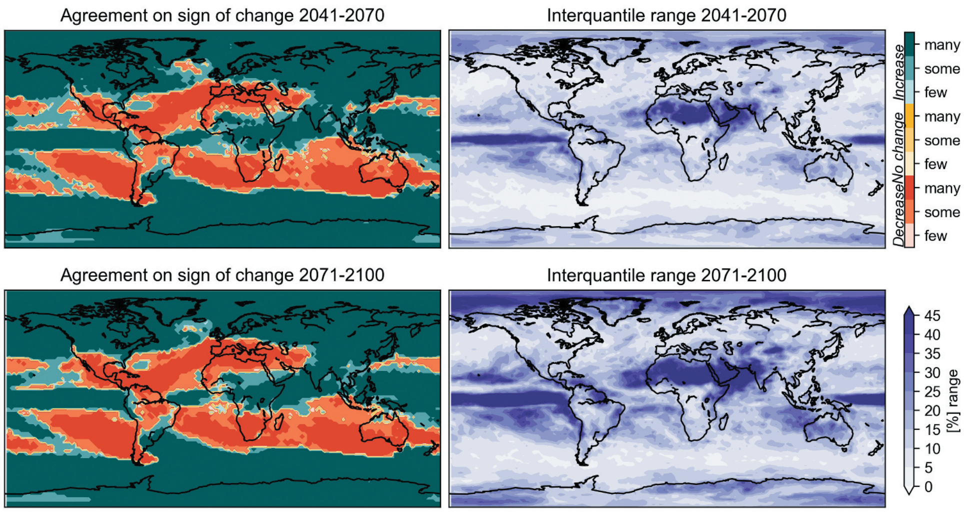

Figure 5. Confidence metrices for change in mean annual precipitation of the C3S data at the 2.0º resolution: agreement on sign of change (left) and inter-quantile range (right) for mid-century (2041–2070) and end of century (2071–2100).

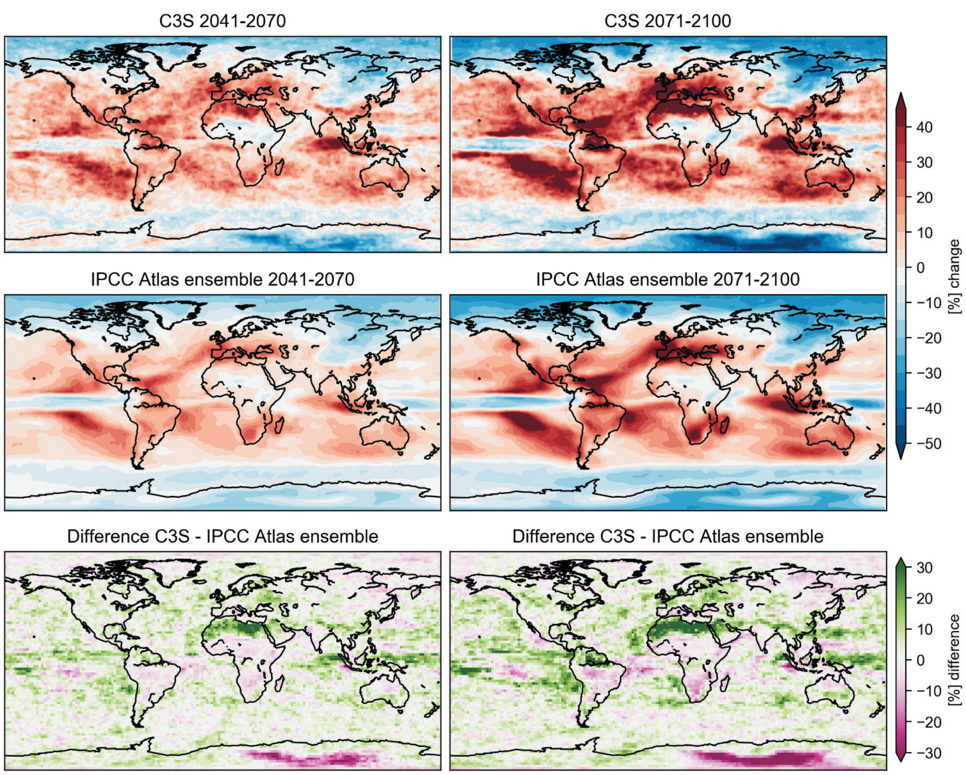

Figure 6. Relative change in consecutive dry days (raw) for RCP8.5 for mid (2041–2070) and late century (2071–2100) with respect to the reference period (1971–2000): (top row) non-bias-adjusted C3S ensemble mean; (middle row) CMIP5 full ensemble mean; and (bottom row) difference between the C3S ensemble mean and CMIP5 full ensemble mean.

increase in Yemen and Oman and East Africa, these are areas with very low precipitation which makes relative change a fickle indicator. A higher increase in the C3S data can be seen in western India, Myanmar and western China, with differences reaching over 30%. This is most prominent in the end of century projection for RCP8.5, where Myanmar has an increase of 40–50% in the C3S data and only 0–15% in the ISIMIP data. A difference in sign of change can be seen in part of Mexico and east Brazil where the C3S data show a slight increase in precipitation and the ISIMIP data give a decrease. The opposite is happening in eastern Australia where the C3S ensemble shows a decrease in precipitation while the ISIMIP data show a small area with a slight increase. The differences in sign of change between the two ensemble means can be linked to areas where *some* and not *many* models agree on the sign of change in the C3S model

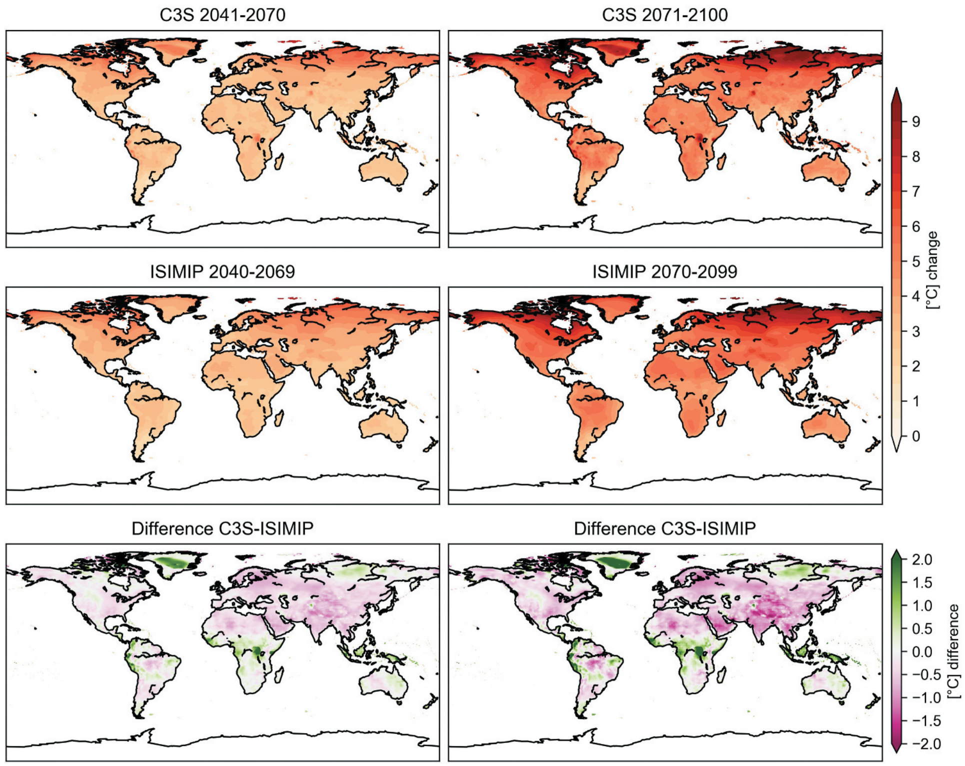

Figure 7. Absolute change in mean annual temperature (bias-adjusted) for RCP8.5 for mid (2041–2070) and late century (2071–2100) with respect to the reference period (1971–2000): (top row) C3S ensemble mean; (middle row) ISIMIP ensemble mean; and (bottom row) difference between C3S ensemble mean and ISIMIP ensemble mean.

ensemble (Fig. 9). The largest differences in Africa, the Middle East and Asia can be linked to the high inter-quantile range, however, not in all other areas with differences. Myanmar, for example, shows a low inter-quantile range in the C3S ensemble while the differences between the C3S data and ISIMIP data are clearly visible.

For the change in longest dry spell the patterns for the two datasets are very similar (Fig. 10). However, there are differences in both magnitudes and sign of change in some areas. The ISIMIP data show larger percentages of change in the USA and Ukraine. C3S data show an increase in the longest dry spell while the ISIMIP data show a decrease in, for example, Colombia and Papua New Guinea, this is where the difference between the two datasets is largest. The opposite happens in central east India and some parts of southern Greenland. Additionally, the ISIMIP data show a spike of decrease in the Sahara and a spike of decrease in Congo-Kinshasa which is not visible in the C3S data. For RCP8.5, late century, a large area of extreme increase can be seen in the north of South America, while this extreme increase covers less area in the ISIMIP data, this can be seen very clearly in the difference maps (Fig. 10, bottom row). The north of South America, South-East Asia and northern Africa are also the regions where the C3S model ensemble has the highest inter-quantile range. The agreement on sign of change is mainly "some" around the globe, indicating that there is a variety between sign of projected by the models in the ensemble.

3.3 Hydrological CIIs, bias corrected

In the comparison of the future change in discharge for C3S combined with WWHYPE and VIC forced by ISIMIP data there are some noticeable differences (Fig. 11). WWHYPE results expect discharge to consistently increase in Most of Africa, northern Europe, Canada, India and eastern Argentina. Larger areas in Europe, South America and Australia are expected to be affected by a large decrease in water discharge. Discharge changes become extreme towards late century with some areas having twice as much river flows and sometimes reductions of more than 50%. For ISIMP VIC, however, discharge decrease covers larger areas such as eastern China, Iran and Australia for both future periods. The most striking differences can be found in Sub-Saharan Africa where the ISIMIP VIC data show large areas with a decrease in discharge while the WWHYPE data only show an increase. Similarly, the ISIMIP data show areas with a decrease in discharge where the C3S data show an increase, e.g. around the United States-Canada border, in Brazil and northern Europe.

For parts of Africa, the middle east, Australia and the US the differences in the change in runoff are not surprising. These are areas with low annual precipitation and discharge where a small absolute change propagates into a large relative change in precipitation and discharge. In these areas it is difficult to predict runoff and changes in runoff.

For the historical periods WWHYPE shows lower runoff rates on a global scale than the VIC model. This is likely to be due to the differences the GCM ensembles used to force the two models and due to differences between the models themselves (hydrological vs land surface model). Changes and patterns in mean annual runoff are similar to the ones described in mean annual discharge (Fig. 12). The differences between the WWHYPE data and the VIC data are also similar to the observed differences in the discharge. With more increase in

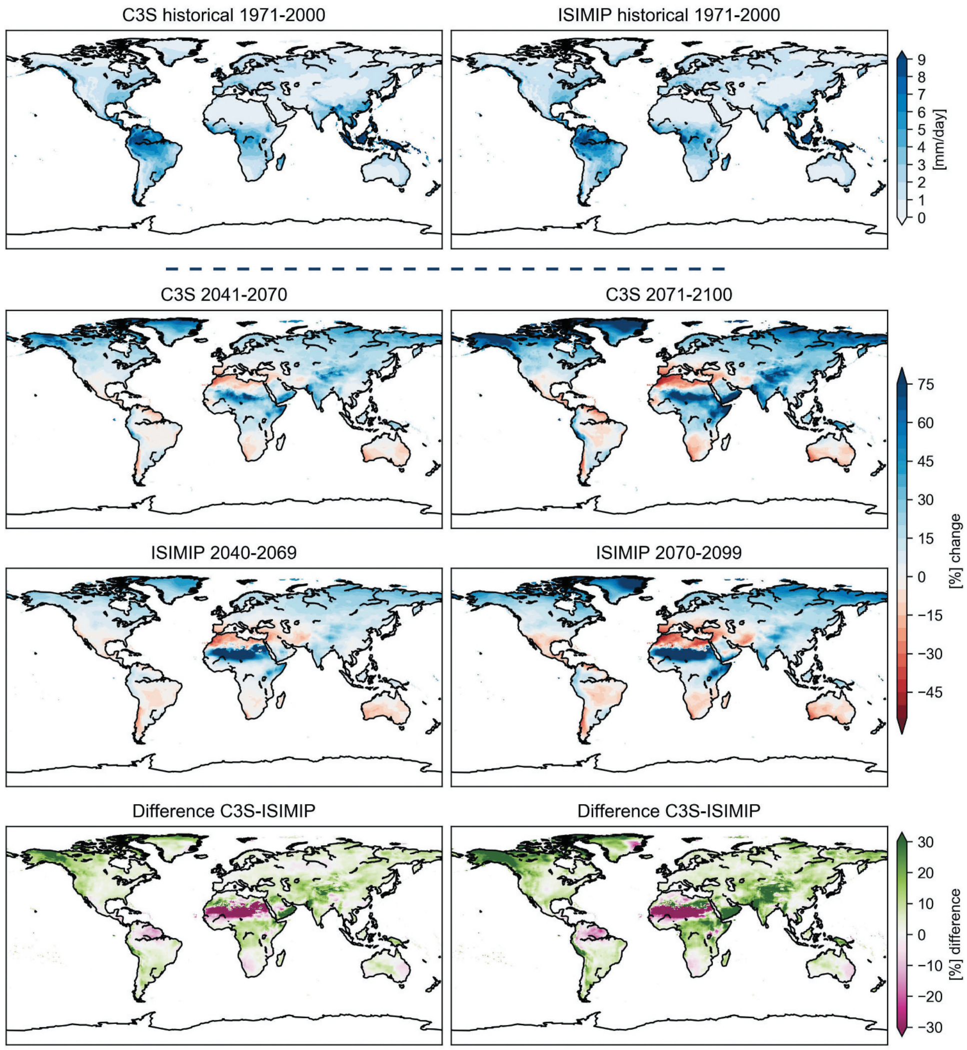

Figure 8. Historical mean annual precipitation (top row) and relative change in mean annual precipitation (bias-adjusted) for RCP8.5 for mid (2041–2070) and late century (2071–2100) with respect to the reference period (1971–2000): (second row) C3S ensemble mean; (third row) ISIMIP ensemble mean and (bottom row) difference between C3S ensemble mean and ISIMIP ensemble mean.

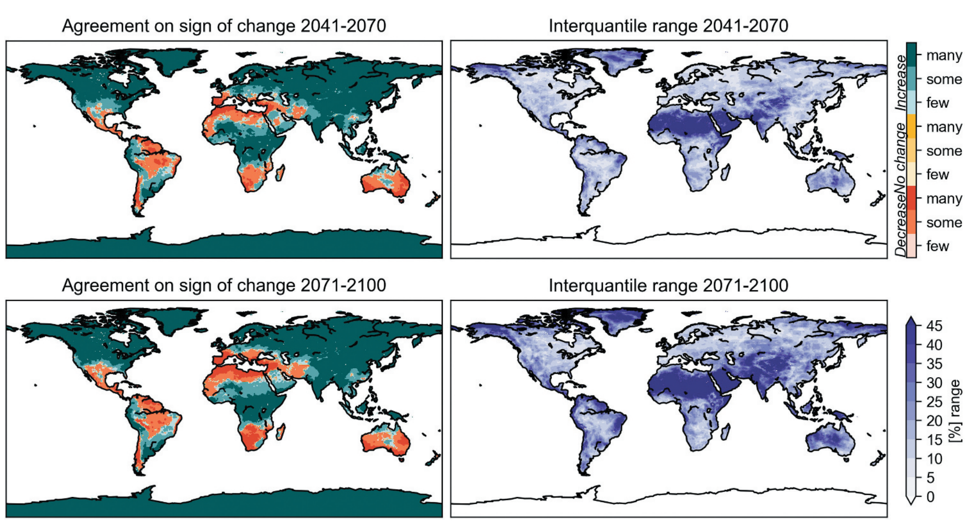

Figure 9. Confidence metrices for change in mean annual precipitation of the C3S data at the 0.5° resolution: agreement on sign of change (left) and inter-quantile range (right) for mid-century (2041–2070) and end of century (2071–2100).

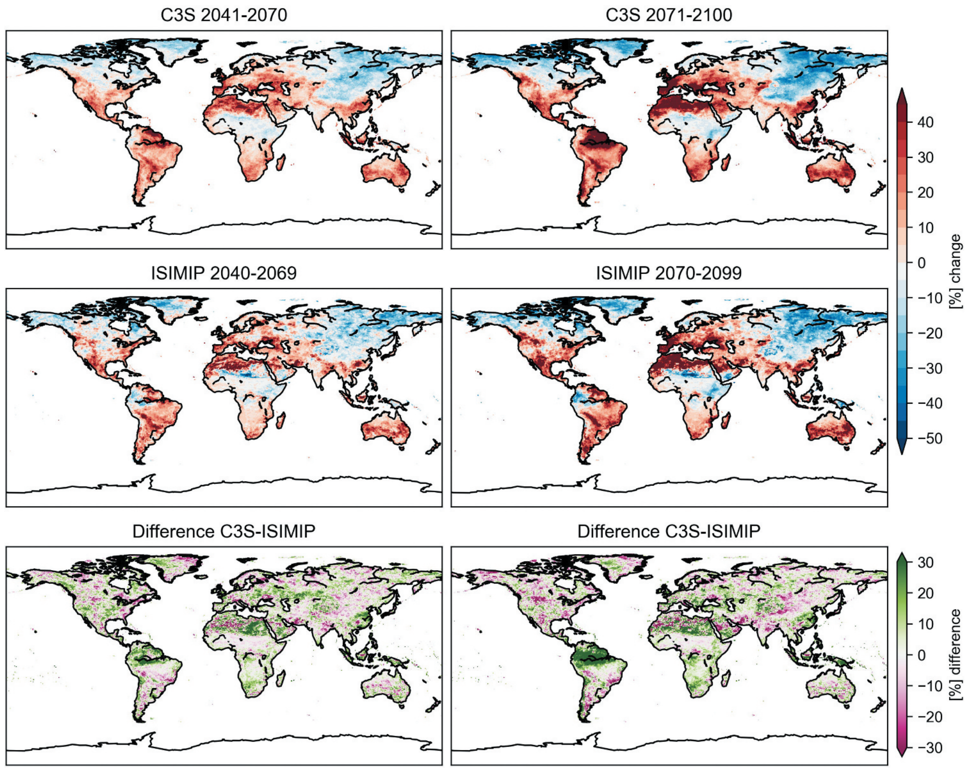

Figure 10. Relative change in longest dry spell (bias-adjusted) for RCP8.5 for mid (2041–2070) and late century (2071–2100) with respect to the reference period (1971–2000): (top row) C3S ensemble mean; (middle row) ISIMIP ensemble mean; and (bottom row) difference between C3S ensemble mean and ISIMIP ensemble mean.

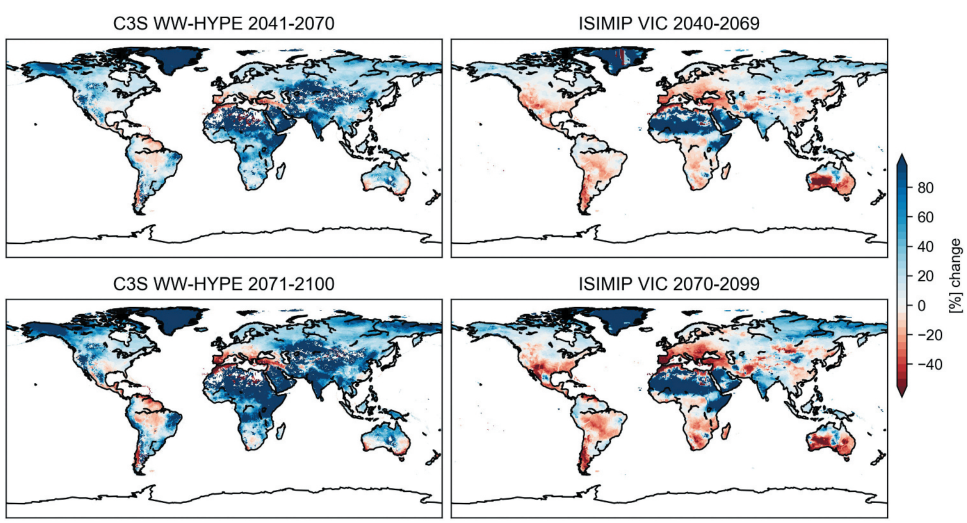

Figure 11. Change in mean annual discharge for RCP8.5: mid (2041–2070) and late century (2071–2100) with respect to the reference period (1971–2000): (left column) C3S WWHYPE and (right column) ISIMIP VIC ensemble.

runoff in the WWHYPE data and more projected decrease in the VIC data.

The C3S WWHYPE actual aridity CII was compared to ISIMIP VIC (Fig. 13). The aridity CII is calculated as the fraction of precipitation that evaporates or transpires (ET/P) a higher value relates to higher aridity. The ISIMIP VIC data generally show a higher relative increase in aridity. This is most clearly seen on the European continent where, for example for Scandinavia in mid-century, ISIMIP VIC gives increases in the aridity of more than 30% while the C3S WWHYPE data show an increase of 5–10%. Similar differences can be seen in North America and in parts of Asia. Another difference can be seen in Australia. Here the WWHYPE data show some areas with an increasing aridity, where the VIC data show a decreasing aridity. For Australia, this can partly be explained by the differences in the projected change in precipitation of GCM ensembles. The differences cannot be linked to the agreement on sign of change and the inter-quantile range confidence metrics. Therefore, they are probably related to the use of different hydrological models. High uncertainty for the Sahara region and part of the Middle East is due to the very low values for precipitation and thus a very high aridity. The results in this area look different

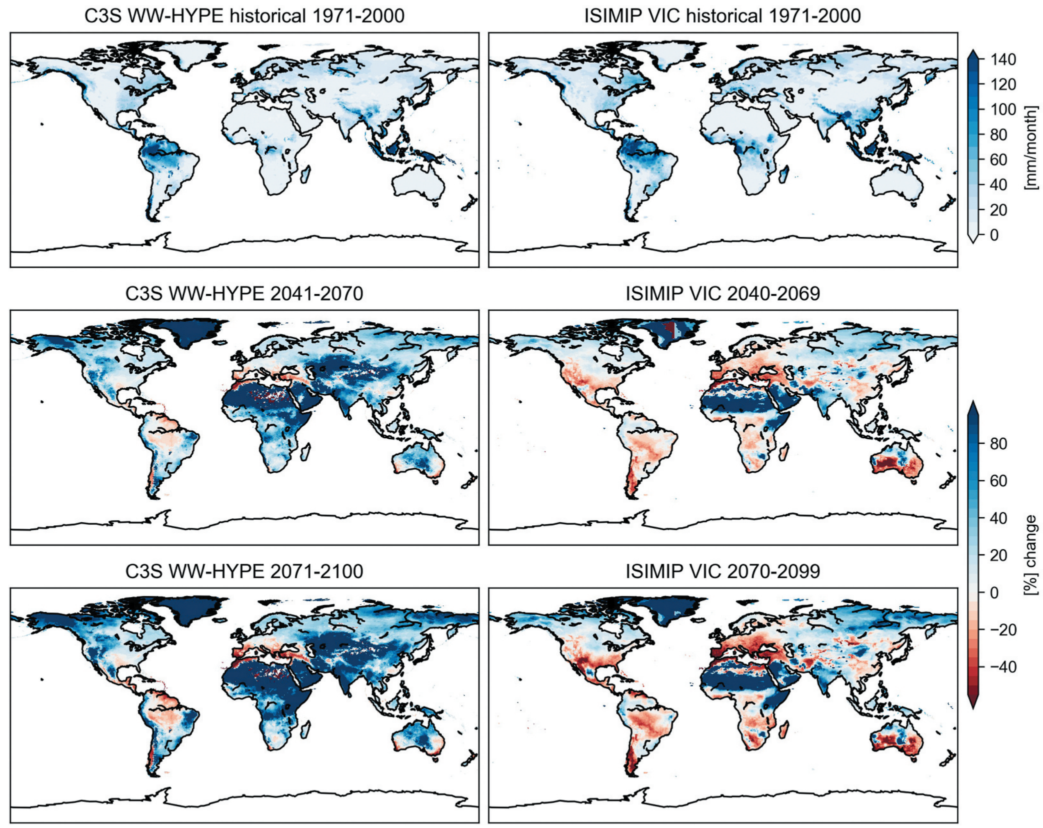

Figure 12. Mean annual runoff of 30-year average for historical period (1971–2000) and RCP8.5 for mid (2041–2070) and late century (2071–2100): (left column) C3S WWHYPE and (right column) ISIMIP VIC ensemble, presented as absolute values for the historical period and relative changes for future periods.

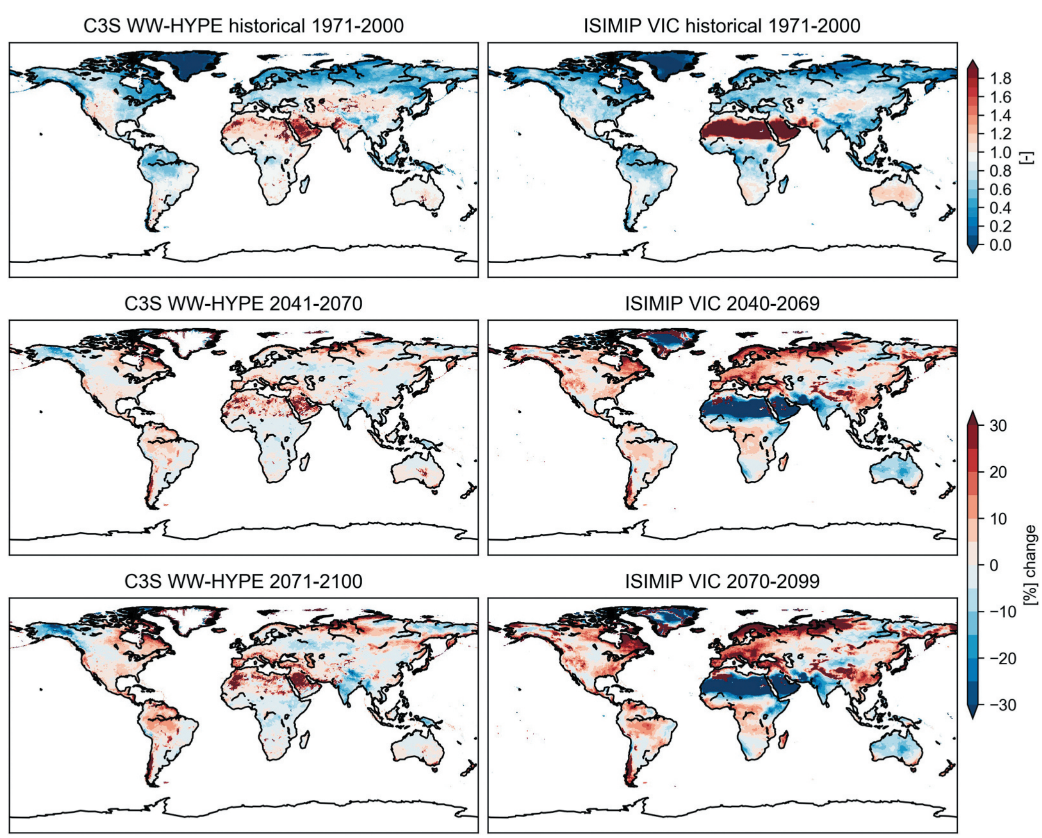

Figure 13. Mean annual aridity (ET/P) of 30-year average for historical period (1971–2000) and for RCP8.5 for mid (2041–2070) and late century (2071–2100): (left column) C3S WWHYPE and (right column) ISIMIP VIC ensemble, presented as absolute values for the historical period and relative changes for future periods.

between the datasets because the aridity CII was limited to a maximum value of 10 in the WWHYPE output and not limited in the VIC output.

The C3S WWHYPE soil moisture was compared to the respective indicator calculated from the ISIMIP VIC setup and the one available in the IPCC AR5 Atlas ensemble for both mid and late century (Fig. 14). There are significant differences between the C3S WWHYPE and the other two; the IPCC AR5 Atlas and the ISIMIP VIC, show similar patterns of changes and magnitude for both future periods, with the exception of Greenland and small coastal areas in North America and the Arctic. There is mostly a higher decrease in C3S WWHYPE (e.g. Spain) but there are also differences in sign of change (Fig. 14). This can be linked to the difference in soil moisture indicator and specifically in the different processes used for simulating soil moisture. WWHYPE uses % moisture content in the root zone where VIC and IPCC AR5 use kg/m^2 moisture content in the first 50 cm.

In Australia (for RCP8.5 end of century), the C3S data show predominantly decreasing soil moisture values (down to −50%) with one area of increase in the centre, while the IPCC AR5 Atlas data and ISIMIP data vary between 0 and −10%. In the Mediterranean and western Mongolia, the decrease is more extreme in the C3S. In North America, the area around the western USA–Mexico border and the area that includes Alaska and northwest Canada show increases in soil moisture in the C3S data, while the IPCC AR5 Atlas data show a decrease. At this location, high ensemble value ranges of the C3S GCM ensemble were observed leading to high uncertainties. For the Sahara region, northeast Africa and Kazakhstan and Mongolia, C3S WWHYPE shows a significant increase in soil moisture for both future periods, which is not observed in the other two datasets. Note that areas with a high ensemble value range in the C3S data are generally also identified as areas with a high uncertainty in the IPCC AR5 Atlas data. In addition, the differences in dry areas are magnified by the use of percentile change, where a small absolute change results in a large percentile change.

4 Discussion

Global water and climate information is needed to facilitate climate adaptation decisions of both global organizations and regional users without access to local information. Some of the main challenges of such an information service are uncertainties and data quality, while at the same time such services can bridge the gap between user needs and data availability. Consistency with other services can increase trust in the service. A proper comparison with other available information services increases the awareness of the inconsistencies of different climate services. This is especially important when climate services include indicators derived from modelling chains such as hydrological models (HMs) driven by climate model output. This modelling chain introduces an additional layer of uncertainty to the information service. One of the aims of this paper is to highlight the difficulty of dealing with uncertainties in climate impact data.

Uncertainties in climate modelling and the large spread between the models has been addressed in previous studies (e.g. Knutti and Sedláček 2013). However, it is also important to acknowledge that uncertainties and model spread vary per CII. Uncertainties in climate models are higher for precipitation than for temperature (Kumar *et al.* 2014). This study also showed a larger spread in the model ensemble for precipitation CIIs compared to temperature CIIs. An additional source of uncertainty is introduced in the hydrological CIIs such as runoff and evapotranspiration (ET) related CIIs (Hagemann *et al.* 2013). Different ways of simulating the same processes can increase the uncertainties of the current hydrological impact assessments (Haddeland *et al.* 2011). For example, in this study, HYPE and VIC have different approaches in modelling ET and snow melt. The different simulation methods for ET could explain the large differences found in for the aridity CII (ET/P) for the two hydrological models. van Vliet *et al.* (2015) also showed large differences between VIC and HYPE in future changes in ET for Europe.

Several hydrological impact studies have compared the uncertainties and/or model spread originating from differences in either HM or GCMs (e.g. Hagemann *et al.* 2013, Schewe *et al.* 2014, Gosling and Arnell 2016, Pechlivanidis *et al.* 2017, Vetter *et al.* 2017). Hagemann *et al.* (2013) found that the spread of GCMs was higher than the spread of global HMs for runoff. For ET the spread for HMs was larger. Other studies agree that the highest contribution to the uncertainty of river flow generally comes from the GCMs (Pechlivanidis *et al.* 2017, Vetter *et al.* 2017), especially in regions where the rivers are predominantly fed by precipitation (Hattermann *et al.* 2018). HM uncertainty, on the other hand, can be dominant in regions where hydrological processes like glacier melt and ET are mainly controlling river flow (Hattermann *et al.* 2018) as well as in dry regions (Schewe *et al.* 2014). Our results also show that there are large differences between VIC and WWHYPE in snowmelt dominant regions, such as Russia, as well as in dry regions where the effects of ET are more dominant, like southern Africa and Australia, there was a significant difference between VIC and WWHYPE

Areas such as southern Africa, India and southern Australia show important differences between the WWHYPE and VIC ISIMIP results. In some areas the ensemble mean *reduction* in annual precipitation resulted in an ensemble mean *increase* in annual runoff in WWHYPE (e.g. Africa), which is counterintuitive. This can partly be related to the non-linear relation between annual precipitation and annual runoff. On a higher temporal resolution, short high intensity precipitation events generate more runoff than long low intensity precipitation. This means that, even with a lower mean annual precipitation, the mean annual runoff can increase if there are more extreme rainfall events. The WWHYPE model seems to show this effect in some parts of the world. Including CIIs for extreme precipitation events can provide important additional information in a future climate service. The results are further influenced by outlier climate models. Some climate models which showed higher rainfall resulted in a very high relative increases in runoff. This contributed to an increased ensemble average, even though there are fewer climate models showing an increase in precipitation compared to the number of models showing a reduction. The agreement on the sign of change in the WWHYPE model runs is relatively low in areas like

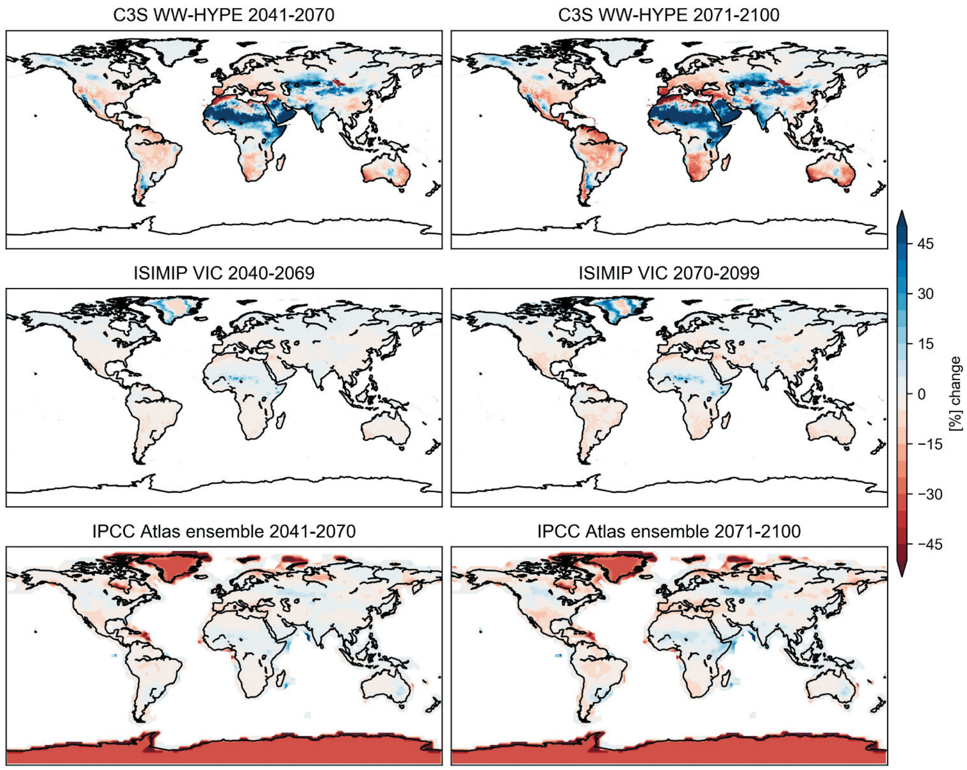

Figure 14. Mean annual soil moisture of 30-year average presented as relative changes for RCP8.5 for mid and late century for: (top row) C3S WWHYPE, (middle row) IPCC ISIMIP VIC and (bottom row) AR5 Atlas.

southern Africa and central Australia. Using the median instead of the average would limit the impact of outliers (see Supplementary material). The medians of the VIC and WWHYPE model runs with the same GCM ensemble show more similar results in both Australia and South America, indicating that these differences are partly caused by the differences in the GCM ensemble (see Supplementary material). In this subset the differences due to the bias adjustment methods and hydrological model structure remain. Another reason is the relatively poor performance of the WWHYPE model in arid regions (e.g. central USA) and regions with limited data (e.g. the Middle East, Africa and Asia) as seen in the WWHYPE model performance map (SMHI 2019).

If we compare our result with regional hydrological assessment, we find mixed results which can be related to the water balance and model performance mentioned in the previous paragraph. The decrease in runoff shown in this study for southern Europe, eastern Australia and the northern part of south America are consistent with changes found by Hagemann *et al.* (2013). These are areas with a high WWHYPE model performance. Hagemann *et al.* (2013) also found decreases in large parts of the Middle East, South Africa and the USA, similar to the ISIMIP VIC results. These findings are not in line with the results of WWHYPE and are areas where WWHYPE has a low model performance or a lack of data (SMHI 2019). Pechlivanidis *et al.* (2017) found consistent results for low (Q10) and high (Q90) flows for both VIC and HYPE for the Ganges, Lena and Rhine river basins. Result of this study showed that WWHYPE and global VIC are similar for the Rhine and parts of the Lena but not for the Ganges. The Ganges is located in an area of poor model performance of WWHYPE and large outliers in precipitation which can explain the differences.

When we compare our findings to local climate services, we find see more similar results for temperature and precipitation indicators and larger differences for hydrological indicators. Of the national climate services for Spain (AEMET 2018), The Netherlands (KNMI 2014), The United States (University of Idaho 2012), Australia (Clarke *et al.* 2011), Kenya (CAS 2018) and Bangladesh (CAS 2016), only the Spanish climate service showed visible differences in magnitude of change for temperature and precipitation compared to the C3S service.

Several studies have called for the use of multiple impacts models in climate services (Haddeland *et al.* 2011, van Vliet *et al.* 2015, Donnelly *et al.* 2017), however, there are also limits to the use of multi-model ensembles. For example, Zaherpour *et al.* (2018) showed that their model ensemble did not perform better than the best individual model and cautioned against summarizing results in a multi-model mean. Gosling *et al.* (2017, p. 591) also indicated that: "*it remains possible that all models may miss (or not represent well enough) certain key processes, for instance the response of glaciers to global warming and in turn on runoff – thus even a 'complete' ensemble may not sample the true spread*". When using a limited set of climate models, careful selection of GCMs is necessary (Gosling and Arnell 2016). A standardized model selection process in addition to striving for a large model ensemble can help in reducing uncertainty (Hattermann *et al.* 2018). In addition, there is room for improvement of individual GCMs and HMs (Schewe *et al*. 2014, Krysanova and Hattermann 2017, Zaherpour *et al*. 2018) and the measurement networks to detect historical climate trends (Asrar *et al*. 2012, Vaughan *et al*. 2016).

From both a modelling and a user perspective, there is often a preference for regional impact models for climate services. In many cases, however, regional climate services are not available and sometimes global data are needed. Ensemble medians of regional and global HM are similar but the ensemble spread tends to be higher in global models (Gosling *et al*. 2017, Hattermann *et al*. 2017). When impacts for a specific basin are of interest, regional models that are calibrated and validated for local conditions are often more suitable than GHM (Hattermann *et al*. 2017). A global climate service can be useful for multinationals operating globally and when regional climate services are not available. The information from global climate services, however, can be misleading for local adaptation (Ekström *et al*. 2016, Donnelly *et al*. 2018) because it is often difficult to assess the performance of global models at local scale.

To get from the model intercomparison studies, with abundant data, to a comprehensive climate service is no easy task and has yet to be accomplished. There is often a struggle between the clear message needed by the users and the scientific aim to present the full range of future uncertainty. The C3S demonstrator project for global users assessed in this paper made an attempt at this, although only using one hydrological model. Agreement on sign of change and inter-quantile range of the models were used as uncertainty indications. In addition to the C3S global climate service development, the ISIpedia project (ISIMIP 2019) is working on a climate service including 4 GCMs and multiple regional and global impact models. In the development of these climate services, quality, but also consistency is important.

5 Conclusion

One of the main challenges in developing long-term climate services is the balance between giving a clear message and easy data access to the users while presenting the uncertainty range of the different models. Especially, when a model chain of climate and impact (hydrological) model is used the uncertainty ranges can be very high. For the key indicators assessed in the study it can be concluded that for temperature-related CIIs the uncertainty range is relatively low and the results of the Copernicus climate service is very similar to other services and datasets. These datasets can thus be considered as robust and give good opportunities for developing decision support. However, for hydrological data represented by indicators related to changes in the water cycle such as precipitation, evaporation, runoff and aridity, the discrepancies between data sources are much larger. These datasets should then be used with caution as they show less confidence.

While there are clear similarities between datasets for some regions, such as the drying Mediterranean climate and a wetter northern part of the Northern Hemisphere, there are also regions where different datasets show opposite signs of change. These differences are partly due to the fact that different climate models are used and partly due to different hydrological models. To develop more robust climate services for key hydrological indicators it is needed to develop multi-model systems using both multiple climate and multiple hydrological models. While multi-model systems have been developed in project such as ISIMIP (Frieler *et al.* 2017) and WATERMIP (Haddeland *et al.* 2011) and (Hagemann *et al.* 2013) these modelling systems have not been used in developing climate services yet, although the ISIpedia project is under construction.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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