Global and Planetary Change 191 (2020) 103199

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Research Article

Climate-induced trends in global riverine water discharge and suspended sediment dynamics in the 21st century

Nishani Moragoda*, Sagy Cohen

Department of Geography, University of Alabama, Box 870322, Tuscaloosa, AL 35487, USA

ARTICLE INFO

Keywords:
21st century climate change
River discharge
Sediment flux
Global-scale modeling

ABSTRACT

Anthropogenic climate change, particularly through increased greenhouse gas (GHG) emissions, is projected to impact 21st century precipitation distribution, altering fluvial processes such as riverine water discharge and sediment dynamics, worldwide. Changes in fluvial water and sediment discharges can have profound impacts on the functioning and connectivity of earth's natural systems. In this paper, we study the natural sensitivity of water discharge and suspended sediment fluxes in large global river systems to predicted climate change in the 21st century. A global-scale hydro-geomorphic model (WBMsed) was forced with precipitation and temperature projections generated by five General Circulation Models (GCMs), each driven by four Representative Concentration Pathways (RCPs). Anthropogenic drivers were excluded from the simulations in order to isolate the signal of 21st century climate change. The results, based on an ensemble of model outputs, revealed that global river discharge and sediment dynamics are highly sensitive to anthropogenic climate change in the 21st century. Increasing global warming will lead to more extreme changes and greater rates of changes (increasing or decreasing) in both variables. Despite substantial regional heterogeneity, a global net increase is projected for both natural river discharge and sediment flux toward the end of the 21st century under all climate change scenarios. These increases are larger with increasing levels of atmospheric warming. At the end of this century, projected climate changes under RCP 2.6, 4.5, 6.0 and 8.5 scenarios, will lead to 2%, 6%, 7.5% and 11% increases respectively in mean global river discharge relative to the 1950–2005 period, while mean global suspended sediment flux will show 11%, 15%, 14% and 16.4% increases under pristine conditions. In addition to magnitudes, inter-annual variability also increases with increasing warming. Changes in sediment flux closely follow the patterns predicted for discharge, and are mostly driven by climate warming-induced spatial and temporal variation in precipitation. However, the relationship between precipitation, discharge and sediment flux was found to be non-linear both in space and time, demonstrating the utility of explicit modeling of both hydrology and geomorphology.

1. Introduction

Human influence on the climate through anthropogenic greenhouse gas (GHG) emissions is leading to warming of the global climate system (IPCC, 2014). Climate warming has caused substantial changes in the hydrological cycle, altering the quantity and quality of available water resources in many regions worldwide (Bates et al., 2008). This has placed increased attention on the future of global rivers, especially how changes in climate will induce behavioral changes in fluvial systems (Bates et al., 2008; Syvitski et al., 2003; Walling, 2009). A comprehensive understanding of the response of fluvial systems to future changes in climate warrants detailed analysis of future riverine water discharge and sediment fluxes (Shrestha et al., 2016). Sediment transport by rivers plays an essential role in the functioning and connectivity of the earth's natural systems, by directly influencing ecohydrological, biogeochemical and geomorphological processes (Vörösmarty et al., 2003; Walling and Fang, 2003). It serves as an important sensitive indicator of changes in the Earth's processes (Fryirs, 2013; Walling, 2009), and is essential for studying nutrient cycles, contaminant pathways, biodiversity and habitat conditions in riverine, coastal and marine ecosystems (Mukundan et al., 2013; Syvitski and Milliman, 2007; Walling, 2009). Sediments are responsible for structuring landscape features such as deltas (Darby et al., 2015; Dunn et al., 2019) and controlling channel geometry and morphology (Pelletier, 2012; Vercruysse et al., 2017). In addition to the key role in natural planetary functions, sediment dynamics has important engineering and

---

* Corresponding author.
E-mail address: npmoragoda@crimson.ua.edu (N. Moragoda).

https://doi.org/10.1016/j.gloplacha.2020.103199
Received 4 September 2019; Received in revised form 17 April 2020; Accepted 21 April 2020

socio-economic implications on, e.g., dam sustainability, flood hazards, and water quality (Vercruysse et al., 2017). Although there is extensive literature with regard to estimation of sediment fluxes (e.g. Pelletier, 2012; Syvitski and Milliman, 2007; Syvitski et al., 2003; Walling and Fang, 2003), simulating global riverine sediment fluxes still remains challenging owing to the multiscale nature (Cohen et al., 2014; Pelletier, 2012; Vercruysse et al., 2017) and the non-linear relationship of the processes involved (Coulthard et al., 2012; Fryirs, 2013).

A major factor affecting changes in sediment transport and river discharge is climate (Aerts et al., 2006; Haddeland et al., 2014; Syvitski, 2003a; Syvitski, 2003b). Future changes in climate, particularly rises in temperature driven by increased GHG emissions, are projected to considerably alter 21st century precipitation intensity and distribution (IPCC, 2014; Lu et al., 2013; Oki and Kanae, 2006; Pendergrass et al., 2017). Research has shown that moderate changes in average climate conditions (i.e. changes of 1–2 °C, 10–20% precipitation) can lead to substantial changes in rivers including sediment yield (Knox, 1993; see Syvitski, 2003b). Not only average climate conditions, but also projected increases in extreme events due to climate change can have profound and complex impacts on hydrological responses of a catchment (Fryirs, 2013).

Human interferences on hydrological systems e.g., damming, soil erosion and conservation measures also have substantial influences on rivers (Walling, 2009; Wang et al., 2011; Syvitski et al., 2005). The increasing impacts of both human activities and climate change necessitate the need to identify and quantify the impacts from individual drivers on fluvial water and sediment discharges (Yang et al., 2015). Isolating the effects of changing climate as one of the primary drivers of changes in fluvial systems can facilitate more informed decision making with regard to human activities affecting hydrological systems. However it is difficult, in most cases, to disentangle the signal of climate from other human impacts (Lu et al., 2013; Walling, 2009).

A number of studies have been carried out to explore the recent trends in discharge and suspended sediment loads in global rivers at a range of scales (e.g. Cohen et al., 2014; Syvitski, 2002; Syvitski et al., 2003; Walling and Fang, 2003; Wang et al., 2011). Basin scale studies provide evidence of marked changes in the sediment loads and water discharge in recent years (Dai et al., 2009; López and Torregroza, 2017; Walling, 2009). In many instances, these changes are predicted based on the interactions between climate change and human impacts (Dai et al., 2009; Syvitski and Milliman, 2007; Syvitski et al., 2003; Walling and Fang, 2003; Wang et al., 2011). Although there is a wealth of literature related to the effects of GHG-induced global warming on future water discharge of rivers at a global scale (e.g. Milly et al., 2005; Nakaegawa et al., 2013; Nijssen et al., 2001; Sperna Weiland et al., 2012), assessments of sediment flux in response to climate change are mostly at the river catchment scale (Coulthard et al., 2012; Darby et al., 2015; Rodríguez-Blanco et al., 2016; Zhu et al., 2008). More recent studies such as Dunn et al. (2019) and Nienhuis et al. (2020) looked at changes in sediment delivery to river deltas worldwide and the different drivers responsible for these changes.

This paper is focused on providing a comprehensive and spatially explicit analysis of the natural sensitivity of global riverine water discharge and suspended sediment fluxes to future climate change trajectories. In order to achieve this objective, the study was conducted under conditions that mimic a pristine world without anthropogenic activities. This gives the opportunity to identify the direction and relative strength of the unmixed signal of GHG-induced climate change in the 21st century on global riverine fluxes, for different climate change scenarios. Existing anthropogenic activities (e.g. dams, land management practices) may hinder this signal and counter-balance the changes predicted based only on climate change.

2. Methodology

2.1. Model description

Global riverine water discharge and suspended sediment fluxes were simulated using the spatially and temporally explicit global riverine sediment flux model WBMsed v2.0 (Cohen et al., 2014). WBMsed is an extension of the WBMplus global hydrology model (Wisser et al., 2010; see Cohen et al., 2013). A comprehensive description of the model infrastructure and input parameters can be found in Cohen et al. (2013 and 2014). WBMsed employs the BQART model (Syvitski and Milliman, 2007) as its governing equation for calculating long-term (> 30 years) average suspended sediment loads ($\bar{Q}_s$).

$$\overline{Q}_s = wB\overline{Q}^{0.31}A^{0.5}RT \text{ for } T \geq 2°C \tag{1a}$$

$$\overline{Q}_s = 2wB\overline{Q}^{0.31}A^{0.5}R \text{ for } T < 2°C \tag{1b}$$

where w is the coefficient of proportionality in units of kg/s which equals to 0.02, $\overline{Q}$ is the long-term average discharge (m^3/s) computed by the WBMplus model, A is the basin upstream contributing area (km^2), R is the difference in upstream relief (km), and T is the basin-averaged temperature of the upstream contributing area (°C). The term B accounts for glacial erosion processes (I), lithology (L), trapping of sediment due to reservoirs (T_E) and a human-influenced soil erosion factor (E_h; Syvitski and Milliman, 2007):

$$B = IL(1 - T_E)E_h \tag{2}$$

The Psi equation (Morehead et al., 2003) is used in WBMsed to calculate daily sediment load and is capable of capturing the intra- and inter-annual variability observed in natural river systems (Morehead et al., 2003; see Cohen et al., 2014):

$$\left(\frac{Q_{s[i]}}{\overline{Q}_s}\right) = \psi_{[i]}\left(\frac{Q_{[i]}}{\overline{Q}}\right)^{C_{(a)}} \tag{3}$$

where $Q_{s[i]}$ is daily sediment flux (kg/s), $Q_{[i]}$ is daily water discharge (m^3/s), $\psi_{[i]}$ is an exponential distribution as a function of $\overline{Q}$ where ψ is large for small rivers and ψ is small for large rivers, $C_{(a)}$ is a sediment rating parameter, that varies on a spatial and temporal scale as a function of R and $\overline{T}$ (Morehead et al., 2003; see Cohen et al., 2014). This gives the model the capability to reflect the temporal variability in water discharge-sediment flux relationship between different rivers (Cohen et al., 2014). Syvitski (2003a) states that climate influences on the sediment load variability in rivers are mainly explained by $Q_{[i]}/\overline{Q}$ ratio (as proxy to flood wave dynamics) and $C_{(a)}$ rating coefficient (as proxy to sediment transport efficiency). The water discharge module of the WBMsed model takes into account precipitation, evapotranspiration, infiltration, soil moisture, irrigation, reservoirs, diversions, and floodplain retention, and is based on the WBMplus model (Wisser et al., 2010; see Cohen et al., 2013). The WBMsed model is proven to be successful in predicting suspended sediment loads in global rivers and studying different mechanisms and drivers associated with these processes (e.g. Cohen et al., 2013, 2014; Dunn et al., 2019; Nienhuis et al., 2020; Syvitski et al., 2014, 2019; Taylor et al., 2015).

2.2. Climate models and scenarios

In order to investigate the response of future climate changes, daily precipitation and temperature projections generated by five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM- CHEM and NorESM1-M) which participated in the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; ISIMIP, 2019; Warszawski et al., 2014) were used as climate inputs to the WBMsed model. The ISI-MIP is a subset of five GCMs from the Coupled Model Inter-comparison Project Five (CMIP5), and provides outcomes for the IPCC's Fifth Assessment Report (ISIMIP, 2019). The ISI-MIP provides daily climate data for these GCMs that have been statistically downscaled to a 0.5° X 0.5° latitude-

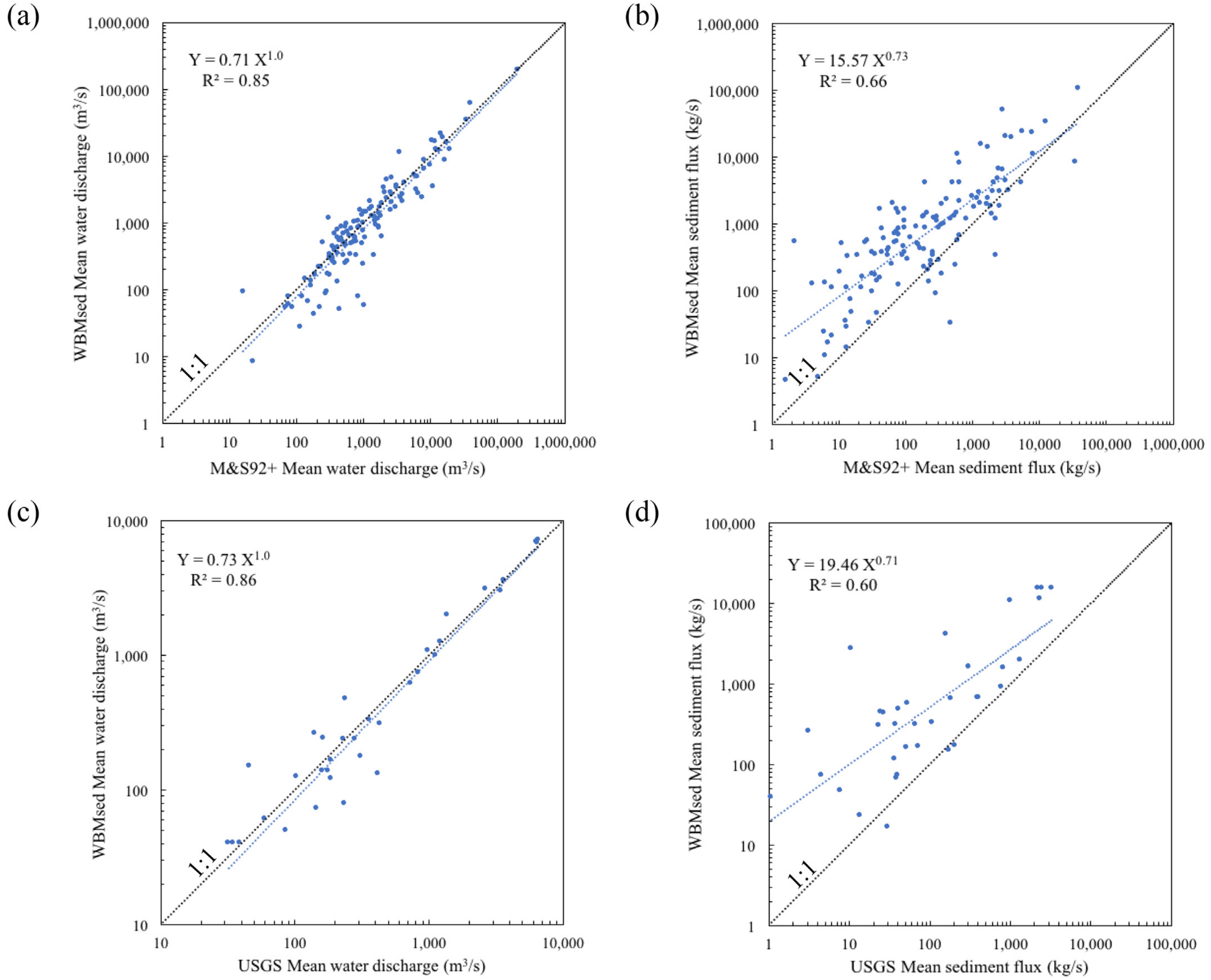

Fig. 1. Comparison of long-term averaged GCM based hindcast sediment loads for 133 global sites against M&S92+ observed water discharge (1a) and sediment loads (1b), and for 36 US sites against USGS observed water discharge (1c) and sediment loads (1d).

longitude grid using bilinear interpolation in space, and then bias-corrected by observational data on the grid using a trend preserving method. The ISI-MIP statistical downscaling and bias adjustment method is comprehensively described in Hempel et al. (2013), Frieler et al. (2017), and Lange (2019). 21st century riverine fluxes were simulated under the four Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0 and 8.5, that provide quantitative descriptions of concentrations of GHGs in the atmosphere over time, as well as their radiative forcing (Bjørnæs, 2013). RCPs are the latest generation of climate change scenarios, introduced by the IPCC as the base of the findings of its fifth assessment report (IPCC, 2014).

2.3. Simulation settings

In this global-scale analysis, the WBMsed model was used to simulate suspended sediment loads and river discharges through the 21st century under all the four RCP scenarios. Temperature and precipitation projections provided by the five ISI-MIP GCMs at 0.5° resolution, for both the hindcast (1950–2005) and future (2006–2099) periods were used to force the WBMsed model. Most, if not all the comparable studies done at a global scale have used this or more coarser resolution climate data (e.g. Arnell, 2003; Hirabayashi et al., 2008; Nakaegawa et al., 2013; Nohara et al., 2006; van Vliet et al., 2013). For each GCM and RCP, the hindcast climate data for the 1950–2005 period are the same, and the divergence into different future climate trajectories start at 2006. The analysis of future trends therefore started at the year 2006.

In order to evaluate the natural sensitivity of discharge and sediment flux to changes in future climate, the model simulations were conducted in the WBMsed ‘pristine’ mode which exclude all anthropogenic input parameters in its sediment and hydrological modules. In the sediment module, in pristine mode, the T_E and E_h parameters are set to a value of 1 (neutral). In the hydrological simulation, all anthropogenic drivers are excluded including irrigation, ground and surface water uptake, agriculture-affected evapotranspiration, dam operation, and water retention in man-made reservoirs. Therefore, the simulations do not necessarily represent modern fluxes of global rivers, but this allows us to isolate only the effect of climate change on the behavior of riverine fluxes.

Separate simulations were conducted for each GCM and each RCP scenario leading to 20 simulations (5 GCMs × 4 RCP scenarios). All simulations are at daily time step and 6 arc-min (~11 km) spatial resolution. Annual-averaged output was used in this study. The model's built-in spin up process was used to initialize the model runs with 10 simulation cycles, before it started producing outputs from 1950

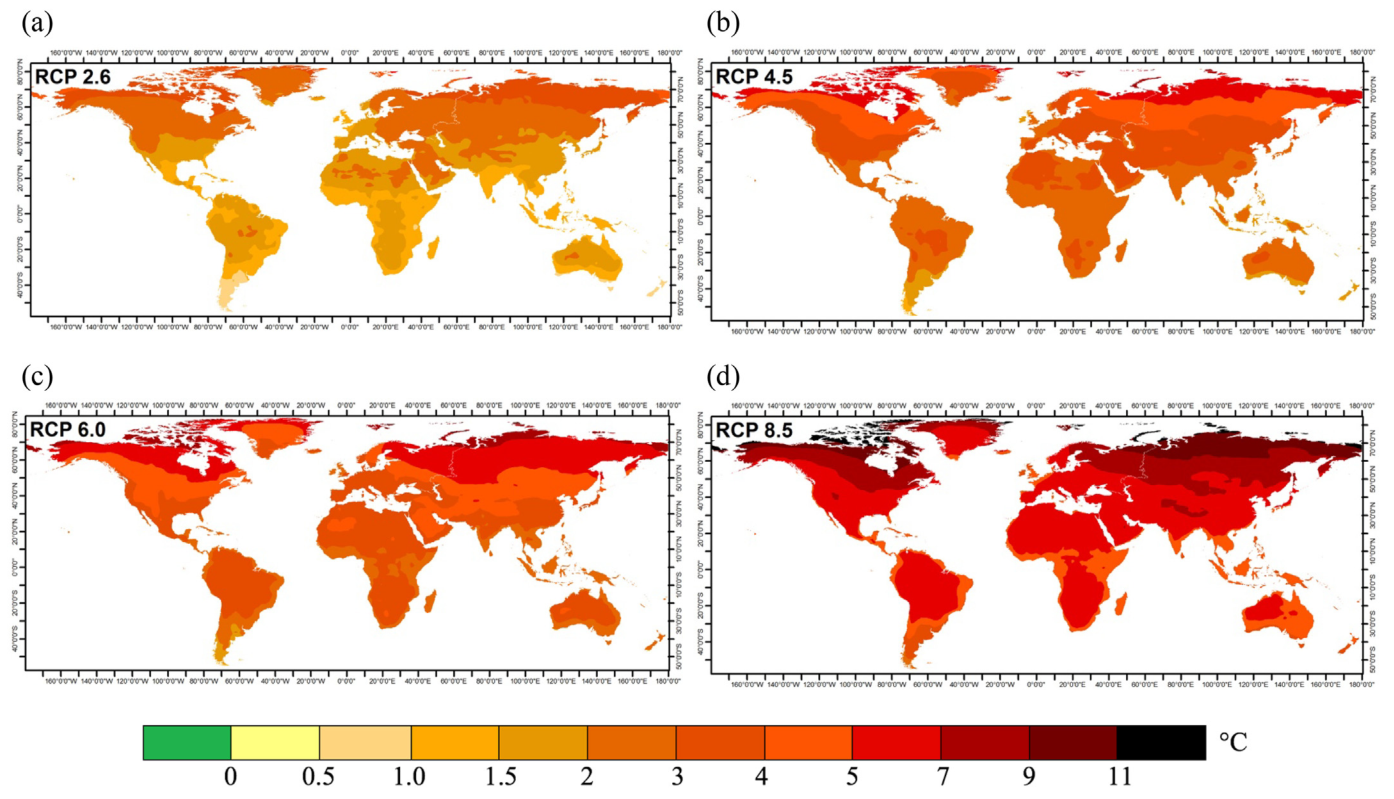

Fig. 2. Change in global averaged land surface temperature in the last decade of the 21st century (2090–2099) relative to the past (1950–2005) under all RCP scenarios based on the multi model ensemble projections.

onwards. The simulations were performed on the University of Alabama High Performance Computing Cluster.

2.4. Calculation of model ensembles

Ensembles of the simulation results were calculated for discharge, suspended sediment flux, and also for temperature and precipitation forcing data, by averaging all the five GCM-based runs, for each year from 1950 to 2099, for each of the four RCPs. A non-weighted mean from each GCM run was calculated, as a validation of individual GCM predictions against observed data showed little difference between GCM predictions. Also, weights derived from hindcast performances may not hold for the future periods and therefore can be misleading (Sperna Weiland et al., 2012). The result of the ensemble calculation was four datasets, one for each RCP. These were used as the basis of the analysis in this paper.

Given the limitations of the model predictive capabilities for small rivers (Cohen et al., 2014), grid cells with a contributing area $< 10{,}000\,\text{km}^2$ and average water discharge $< 30\,\text{m}^3/\text{s}$ were masked using a raster layer. The small grid cell size hinders visualization of the results in its native raster form. We therefore use a vectorized layer of the rivers for visualization purposes.

3. Results

3.1. Model validation

Cohen et al. (2013, 2014) evaluated the WBMsed model predictions of long-term averaged suspended sediment flux and water discharge (using observed climate inputs) and found a correlation of $R^2 = 0.66$ to observed sediment flux and $R^2 = 0.70$ to water discharge for 95 global sites. A stronger correlation was found to observed sediment flux for 11 USGS sites ($R^2 = 0.94$). In this study, the model's forecasting capability using GCM forcings was assessed based on the ensemble hindcast (1950–2005) predictions.

The long-term averaged water discharge and suspended sediment loads evaluated against 133 global sites listed in Milliman and Syvitski (1992) database (M&S92+) show that the ensemble of GCM based water discharge predictions correlate well ($R^2 = 0.85$) with observed data (Fig. 1a), while sediment loads have a more moderate correlation of $R^2 = 0.66$ (Fig. 1b). The validation of GCM based WBMsed hindcasts against 36 USGS sites across the continental United States obtained from the USGS National Water Information Systems (NWIS) website (U.S. Geological Survey, 2018), also resulted in a similar correlation of $R^2 = 0.86$ for water discharge (Fig. 1c) and $R^2 = 0.60$ for sediment loads (Fig. 1d). For both observational datasets, the time-averaged values do not represent the entire period of the model output (1950–2005). The reason for the weaker correlation in the USGS sites compared to Cohen et al. (2013), is due to the use of 'pristine' simulations in this study. Fig. 1b and 1d show that sediment flux is generally over-predicted by the model. This is due to the fact that most anthropogenic activities, especially dams, cause declines in sediment fluxes and these activities are not represented in this study. The bias in rivers with low sediment flux is (proportion wise) greater, as seen by the deviation from the 1:1 line. This is likely because the effect of sediment trapping is decreasing downstream of a dam and therefore, damming in smaller rivers will have the greatest relative effect. Overall, these results show that the ensemble of GCM based hindcast WBMsed simulations can compare well to the model's 'standard' observational dataset and can therefore be used with confidence for forecasting the future.

This validation procedure only evaluates the predicted long-term river discharges and sediment fluxes. Although a validation of the time series of river discharges and sediment fluxes using other standard statistical methods could provide more insight into model's forecasting ability, it is not suitable for this study. The main reason is the fact that GCM based simulations are conducted under the WBMsed pristine condition to exclude anthropogenic input parameters, and hence does not necessarily represent the real-world riverine fluxes. Majority of the

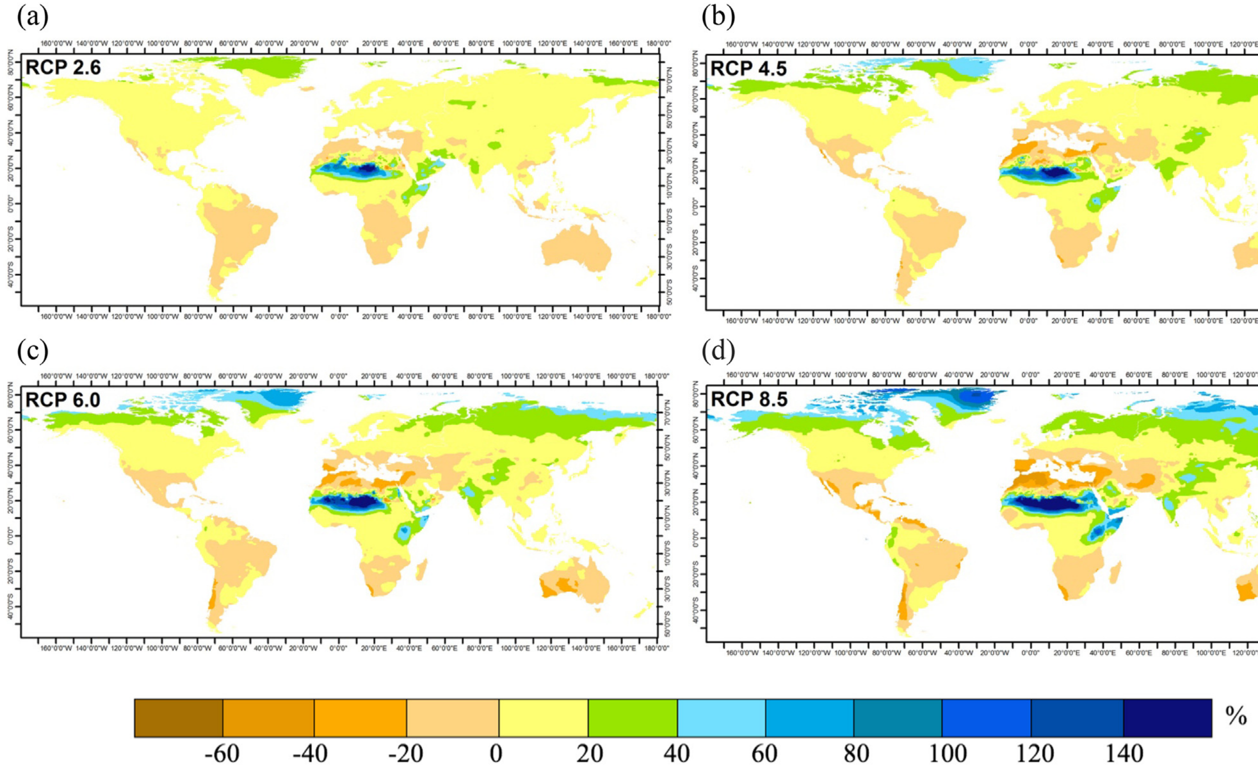

Fig. 3. Change in global averaged precipitation based on the multi model ensemble projections for the last decade of the 21st century (2090–2099) relative to the past (1950–2005) under all RCP scenarios.

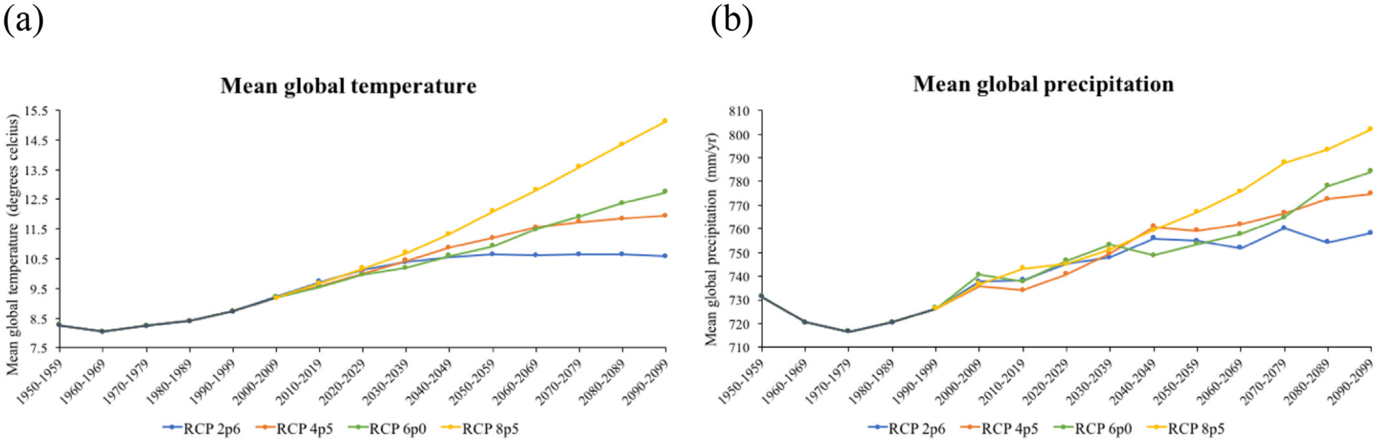

Fig. 4. Mean global land surface temperature (a) and mean global land surface precipitation (b) for each decade under each RCP scenario based on the multi model ensemble projections.

rivers in the US and outside are highly regulated by dam operations and other engineering and water use activities, and therefore have vastly controlled flows and sediment fluxes. In addition, freely available river discharge and suspended sediment flux records for the entire historical period is extremely rare outside the US and even in most US sites (Cohen et al., 2014).

3.2. Changes in global climate in the 21st century

Figs. 2 and 3 show the percentage changes in temperature and precipitation respectively, in the last decade of the 21st century (2090–2099) relative to the past (1950–2005), using an ensemble of all five ISI-MIP climate model projections used as climate forcing data. Global temperature shows a clear increase at the end of the 21st century in all the RCPs and increases are larger with increasing warming scenarios (Fig. 2). In all RCP scenarios, larger increases can be observed in the high latitudes of the Northern Hemisphere, in line with reported trends by the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2014).

Changes in precipitation is heterogeneous (IPCC, 2014) and does not necessarily follow the changes in temperature (Fig. 3). In different regions of the world, warming can lead to increases or decreases in precipitation. Larger increases in precipitation can be observed in high latitudes of the Northern Hemisphere, South Asia, Sahel region in Africa, and east Africa, with increasing RCP scenarios, as previously suggested (Bates et al., 2008; Haarsma et al., 2005; Sylla et al., 2016). Precipitation also increases in majority of Asia including the middle eastern region, and parts of North America. Larger decreases in

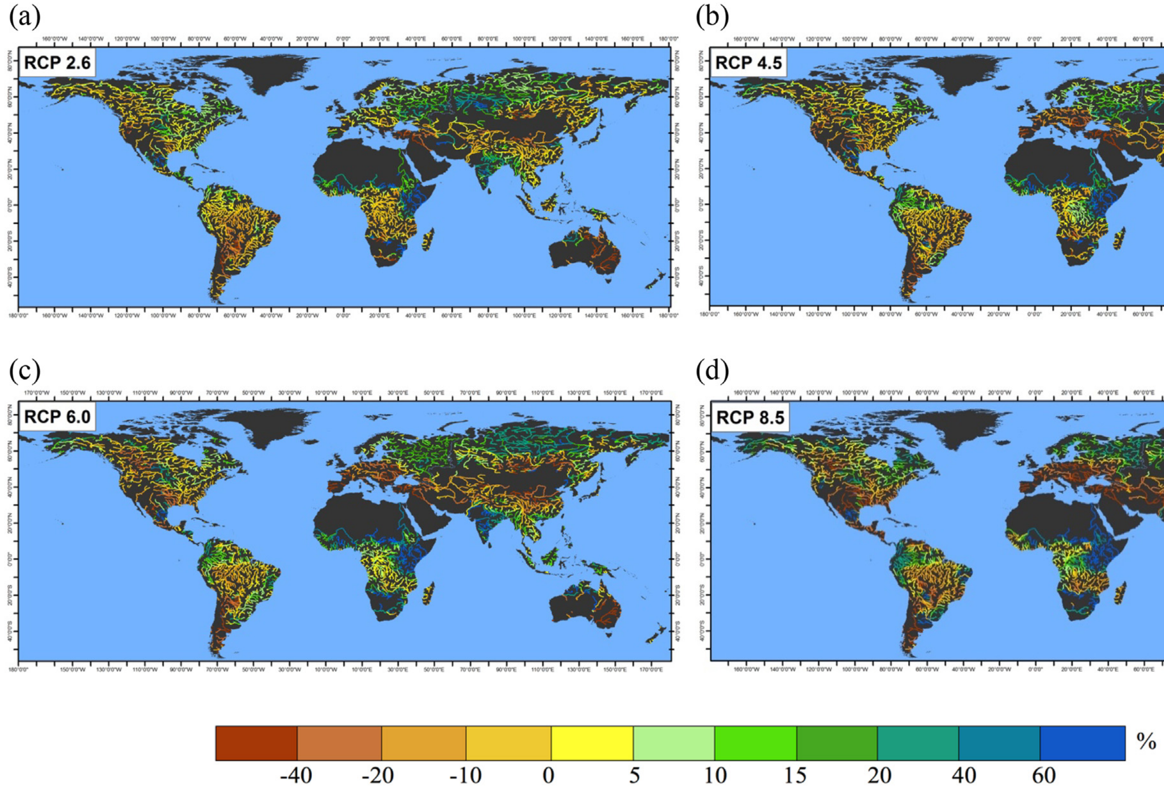

Fig. 5. Percentage difference in global pristine river discharge in the last decade of the 21st century (2090–2099) relative to the past (1950–2005) in all RCP scenarios based on the ensemble. Predictions are presented only for grid cells with a contributing area $> 10{,}000\ \text{km}^2$ and long-term average discharge $> 30\text{m}^3/\text{s}$.

precipitation with increasing RCPs are observed in northern Africa, Mediterranean regions, southern and western Europe, and some parts of Australia. In general, Central and South America, southern regions of North America, Australia, southern regions of Africa, and western regions of Asia will experience decreases in precipitation. These maps are largely consistent with the predicted climate changes in the IPCC (2014) climate change synthesis report and other climate change studies (Pendergrass et al., 2017; Trenberth, 2011).

Fig. 4 shows the decadal averages of mean global land surface temperature and precipitation throughout the study period (1950–2099). Toward the end of the century, both precipitation and temperature show an increase at a global scale with increasing warming represented by RCP scenarios. At the beginning of the century, changes in both variables are similar in all four RCPs; by the mid-21st century, the magnitude of the projected changes increasingly deviates for each RCP. Similar trends have also been reported in IPCC (2014).

3.3. 21st century changes in river discharge and sediment dynamics

Considerable changes in natural river discharge (Fig. 5) and suspended sediment loads (Fig. 6) are predicted for large global rivers in the last decade of the 21st century under projected changes in climate. River discharges are predicted to considerably increase in the Arctic, north and east Africa, Indian peninsula, Northern Europe, and some parts of North and South America, with increasing GHG-induced warming under pristine conditions (Fig. 5). Decreases in river discharges are projected for southern and western Europe, Mediterranean regions, central and west Asia, much of North America and South America. These changes are broadly consistent with other studies that have examined the global-scale response of river discharge to climate change (Hagemann et al., 2013; Nakaegawa et al., 2013; Schewe et al., 2013; Sperna Weiland et al., 2012; van Vliet et al., 2013).

Changes in sediment flux closely corresponds to the patterns in discharge (Fig. 6). However, larger increases in sediment flux are observed with relatively small increases in river discharge in many regions of the world such as Northern Europe and Southeast Asia. Since the relationship between discharge and sediment flux is nonlinear in space and time, both in the model and in reality (Vercruysse et al., 2017), the response of sediment flux to global climate change cannot be quantified based on discharge dynamics alone. Other parameters in the WBMsed model that drive the response of sediment flux such as relief, basin area, and lithology (Eqs. (1a), (1b) and (2)) also contribute to the predicted dynamics. Another source of variability in sediment flux predictions arises from the Psi equation that is used to generate short-term sediment flux (Eq. (3)). The Psi approach allows the relationship between discharge and sediment variability to change as a function of basin characteristics. This adds to the spatial variability in our results.

In most parts of the world, the changes in discharge and sediment flux are closely related to projected future changes in global distribution of precipitation (Hagemann et al., 2013; Syvitski et al., 2005; Zhu et al., 2008). For example, increases in riverine fluxes in the Arctic regions, East Africa and Indian Subcontinent correspond well with increases in precipitation in these regions with increasing levels of climate change. In the Nile river basin, although precipitation shows a decreasing trend toward the outlet, larger increases in precipitation are evident in the southern parts of the basin in all RCP scenarios (Fig. 3). The influence of basin wide precipitation patterns for discharge and sediment can be seen for the Nile in all RCP scenarios by the increases predicted for discharge and sediment flux toward the outlet (Figs. 5 and 6). Although the influence of precipitation is more pronounced, temperature also is a driver of changes in discharge and sediment flux. The impact of temperature on sediment flux is two-folds; the influence on evapotranspiration that affects runoff and discharge thereby sediment transport capacity, and the direct influence through Eqs. (1a) and (1b).

It is also evident that with increasing warming scenarios, larger and more extreme changes in both discharge and sediment flux can be expected under pristine conditions. Other studies such as Hirabayashi et al. (2008) found a similar trend for global river discharge whereas

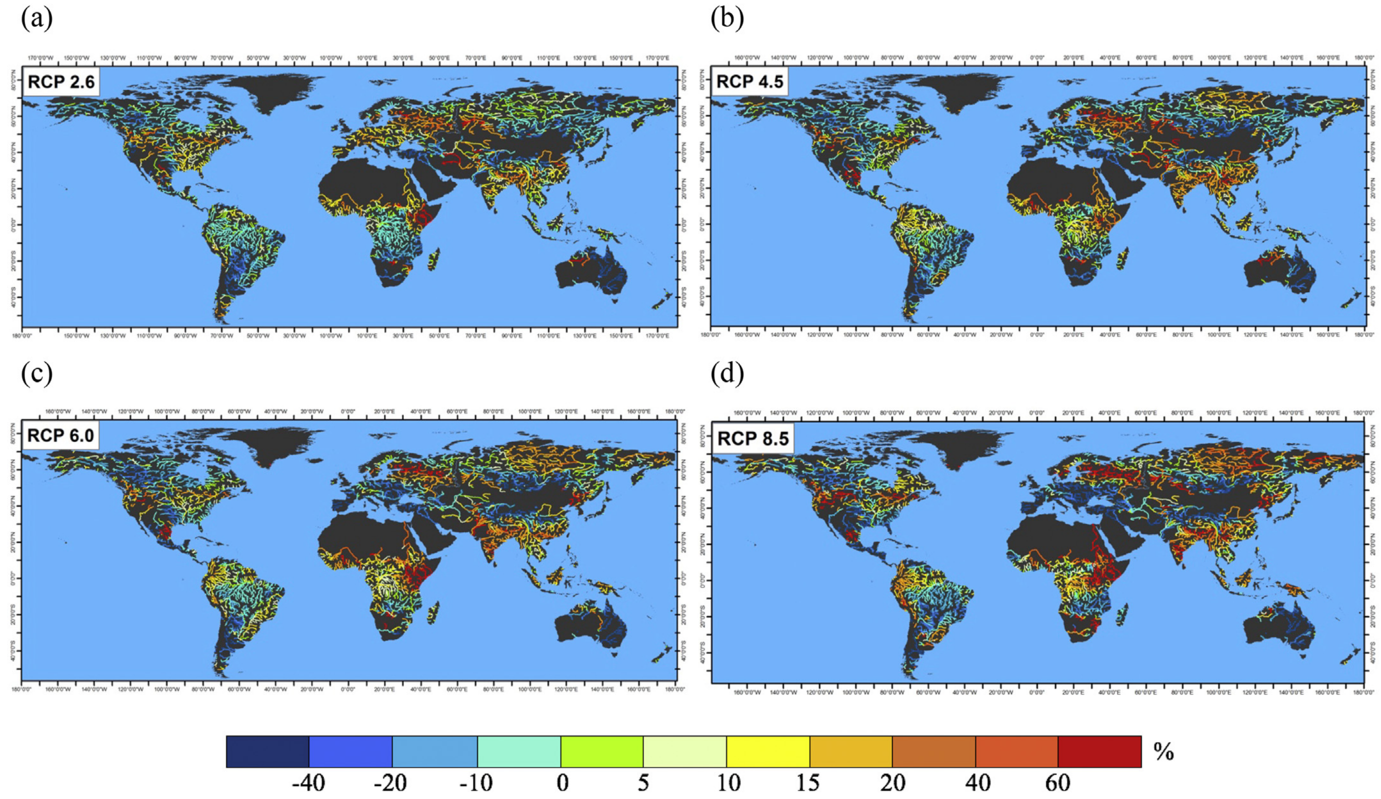

Fig. 6. Percentage difference in global pristine riverine suspended sediment flux in the last decade of the 21st century (2090–2099) relative to the past (1950–2005) in all RCP scenarios based on the ensemble. Predictions are presented only for grid cells with a contributing area > 10,000 km^2 and long-term average discharge > $30m^3/s$.

Coulthard et al. (2012) found a similar trend for sediment flux at catchment scale. At a global scale, the number of river pixels that resulted in extreme increases (increases > 60%) in both natural discharge and sediment flux increase with increasing RCP scenarios, whereas, the number of river pixels that resulted in extreme decreases (decreases > 40%) in the two variables will also increase with increasing RCPs. However, in all RCP scenarios, the number of pixels that will experience extreme increases are greater than those of decreases for both the variables.

Although analyzing the sensitivity of sediment fluxes to extreme climate using short term model predictions may be tricky due to the model's tendency to over- and under-predict sediment fluxes during high and low discharge periods, respectively (Cohen et al., 2013), this analysis is based on relative changes in long-term (decadal) predictions. Therefore, these relative changes are solely driven by changes in climate represented by RCPs, hence, there is confidence in the investigated trends in extreme changes to discharge and sediment fluxes between scenarios.

The changes in pristine global mean river discharge and sediment flux in the last decade of the 21st century relative to the past (1950–2005) in large global rivers in response to the climate signal are presented in Table 1. Despite regional differences, at a global scale, discharge and sediment flux show a net increase at the end of the 21st century with all RCP scenarios. The increases are generally larger with increasing RCP. An overall increase in river discharge at a global scale in response to climate warming are also reported in other studies (e.g Hirabayashi et al., 2008; Sperna Weiland et al., 2012). The increase in sediment flux is greater than that of discharge in all RCP scenarios.

Table 1
Percentage difference in pristine global mean river discharge and sediment flux in the last decade of the 21st century relative to the past (1950–2005) in all RCP scenarios. Calculations are based only on grid cells with a contributing area > 10,000 km^2 and long-term average discharge > $30m^3/s$.

% difference in the last decade relative to the past	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Mean global discharge	2.0	6.1	7.5	11.0
Mean global sediment flux	11.0	15.2	14.0	16.4

Fig. 7 shows the decadal averages of total pristine river discharge and sediment delivery to global oceans from major river outlets throughout the simulation period. Temporal trends in fluvial fluxes to the oceans correspond well with global patterns in temperature and precipitation (Fig. 4), but with much more dramatic fluctuations. This demonstrates the complex relationship between precipitation and discharge at a global scale, and emphasizes the need to use numerical models, as precipitation alone cannot be used to quantify future trends in discharge or sediment flux.

A clear increase in natural discharge and sediment flux to global oceans is predicted toward the end of the 21st century with increasing RCP. In accordance with the trends in precipitation, RCP 4.5 and 6.0 moderate warming scenarios generate the largest discharge and sediment flux at a global scale in the mid-century under pristine conditions. However, interestingly, the hindcast simulations for discharge and sediment flux also shows high values in the 1950's, due to the effect of high precipitation projected by climate models (Fig. 4b). This trend in global precipitation with a sharp increase between 1950 and 1960 followed by a decline in 1970s has also been reported in observed global precipitation data (Dai et al., 1997; New et al., 2001).

3.4. Rate of change in river discharge and sediment flux in the 21st century

The rate of change in river discharge and sediment flux per decade over the 21st century caused by predicted climate change alone was calculated for large rivers in the world under pristine conditions (Fig. 8). Larger increasing rates in climate change-driven natural river

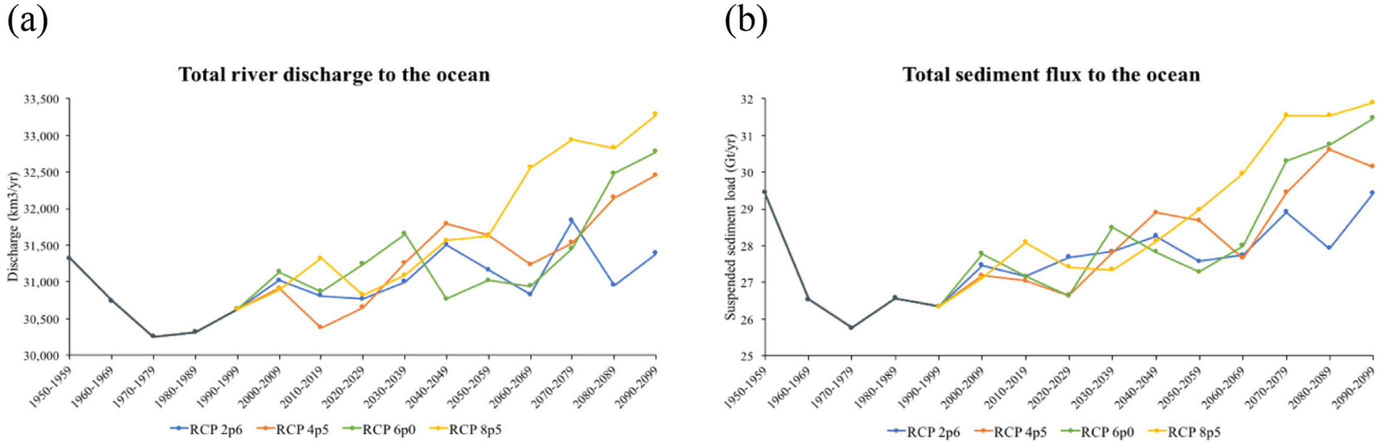

Fig. 7. Total global river discharge (a) and suspended sediment flux (b) to the ocean from major river outlets in the world (river outlets with > 10,000 km^2 drainage area and > 30 m^3/s long-term average discharge) for each decade based on the ensemble.

discharges can be observed in many regions of Africa, Indian Subcontinent, high latitudes in the Northern Hemisphere, some regions of North and South America with increasing warming scenarios. When fluvial sediment fluxes are considered, larger increasing rates can be observed in some parts of Africa, South and East Asia, high latitudes in the Northern Hemisphere, Northern Europe, most of North America, and some parts of South America. In contrast, larger decreasing rates in both discharge and sediment flux can be observed in Europe, Mediterranean regions, central Asia, some parts of North and South America and central regions of Africa due to 21st century climate change. At a global perspective, climate-induced rates of change in total global river discharge and total global sediment delivery to the oceans over the 21st century are increasing with increasing warming scenarios under pristine conditions (Table 2).

As global warming increases, the number of rivers that will experience high rates of climate-driven changes (increasing rates of > 5% per decade or decreasing rates of > 3% per decade) in natural discharge and sediment flux over the 21st century increases. This indicates that increasing GHG concentrations in the atmosphere will lead to more rapid and extreme changes in natural riverine fluxes in some regions. Other studies such as van Vliet et al. (2013) also reported a similar outcome for river discharge.

3.5. *Variability in future discharge and sediment flux*

Non-stationarity in global climate is predicted to increase in the future with increasing levels of climate change (IPCC, 2014; Krakauer and Fekete, 2014; Pendergrass et al., 2017). Changes in temporal dynamics of fluvial fluxes can considerably affect the hydrologic, geomorphic, and ecological functioning and regimes of a river system (Walling and Fang, 2003). It is therefore important to assess the signal of climate change on the temporal variability of future river discharges and sediment fluxes. To examine the changes in temporal variability, coefficient of variation (CV = SD/Mean) was employed (Arnell, 2003), rather than standard deviation (SD), as it gives the capability to compare between rivers with vastly different (orders of) magnitudes in fluxes. CV was calculated for the period between 2006 and 2099, using yearly outputs of discharge and sediment flux.

The results show that inter-annual variability in both natural river discharge and sediment flux increases with increased GHG-induced warming (Fig. 9), in agreement with other studies (e.g. Arnell, 2003). This increase in inter-annual variability can be explained by the predicted increases in temporal variability of precipitation and temperature patterns in the 21st century (IPCC, 2014; Pendergrass et al., 2017), as they are the primary drivers of change in river discharge and sediment fluxes in this study. The patterns in inter-annual variability in discharge coincide with that of sediment flux, however the magnitude of the variability differ between the two variables. Climate change-induced inter-annual variability in both variables are larger in Australia, southern and eastern Africa, central parts of North America, central and eastern parts of South America, middle eastern Asia, and some parts of Europe, under pristine conditions (Fig. 9a). In contrast, less inter-annual variability in natural river discharge and sediment flux can be expected in south east Asia, high latitudes of Northern Hemisphere, eastern parts of North America, northern Europe, central Africa and central South America (Nijssen et al., 2001) in response to the climate

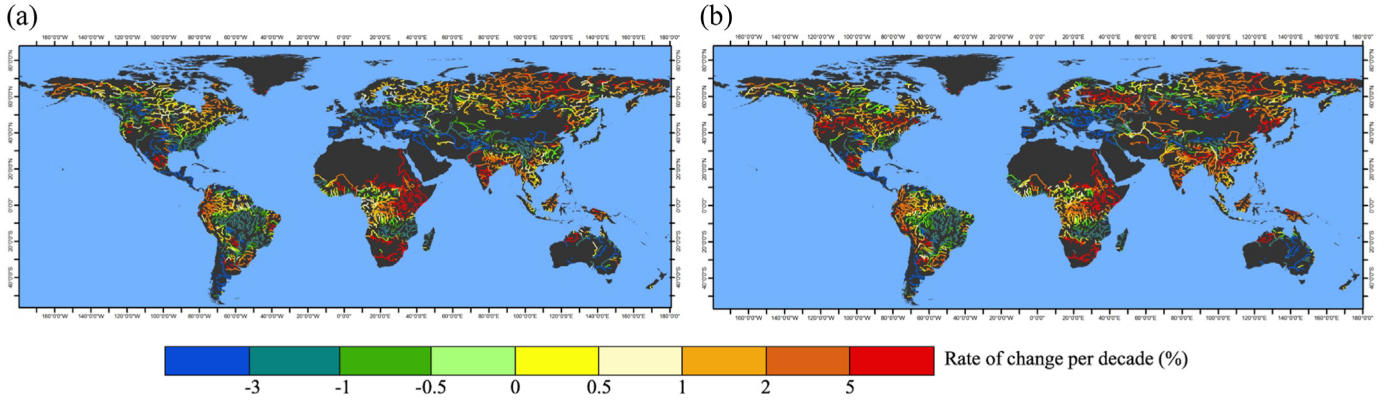

Fig. 8. The rate of change in pristine river discharge (a) and sediment flux (b) per decade in the 21st century for RCP 8.5. Predictions are presented only for grid cells with a contributing area > 10,000 km^2 and long-term average discharge > 30m^3/s.

Table 2

Rate of change per decade in total global river discharge and sediment delivery to the ocean in the 21st century due to climate change under pristine conditions.

The rate of change per decade in the 21st century (%)	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Total global river discharge to the ocean	0.25	0.60	0.7	0.87
Total global sediment delivery to the ocean	1.2	1.4	2.0	2.1

signal alone. In order to assess how the temporal variability varies between RCP scenarios, the ratio between the CV of a given RCP scenario and RCP 2.6 was calculated (Fig. 9b). The number of grid cells that will experience increases in climate change-induced inter-annual variability relative to RCP 2.6 increases with global warming, in both discharge and sediment flux under pristine conditions (Table 3).

Changes in climate-induced 21st-century natural discharge and sediment delivery to global oceans at river outlets and their temporal variability between each 1° latitudinal region bin, are shown in Fig. 10. Global river discharge (Fig. 10a) to the oceans is highest around the equator, but sediment delivery (Fig. 10b) is highest in 23° N latitude closely followed by 34° S. Inter-annual variability in both discharge and sediment flux increases with increasing warming scenarios in most of the latitudinal regions under pristine conditions (Fig. 10c and 10d). Inter-annual variability in natural water discharge to the oceans in response to predicted climate change is larger in the tropical regions of both Northern and Southern Hemispheres while the mid-latitudes of the Southern region also show a large variability (Fig. 10c). Inter-annual variability in natural sediment delivery to global oceans is largest in the mid-latitudes in both hemispheres as well as around the equator (Fig. 10d). Larger variabilities are also predicted for many latitudinal regions of the tropics in natural sediment flux.

It is interesting to note that variability in discharge does not always mean variability in sediment flux when averaged across latitudinal regions. This also demonstrates the complex and nonlinear relationship between discharge and sediment flux in rivers. Also intriguing is that inter-annual variability in discharge and sediment flux does not show a link to the changes in inter-annual variability in precipitation in latitudinal regions (not shown here). Although precipitation patterns mainly drive the changes in discharge and sediment flux, their nonlinear linkages mean that precipitation characteristics (e.g. seasonality, fluctuation) rather than their mean yearly values may be most influential on future changes in the variability of fluvial fluxes (Coulthard et al., 2012).

4. Discussion

Due to the different structures and parameters used in GCMs, projected future changes in temperature and precipitation have large spatial and temporal uncertainties even for the same radiative forcing levels (Cai et al., 2009; Knutti and Sedláček, 2013). Therefore, studies that investigate climate change responses of fluvial systems show varying degrees and directions of changes over the 21st century (Arnell, 2003; Haddeland et al., 2014; Hagemann et al., 2013; Schewe et al., 2013; van Vliet et al., 2013). Our analysis also shows a considerable spread in individual GCM-based simulation results, mainly due to different precipitation distribution patterns projected by GCMs (Fig. 11). These discrepancies between studies are also partly due to the number of GCMs used to generate predictions. Some studies have used only one GCM (Nakaegawa et al., 2013), while some studies were done using as much as 19 (Nohara et al., 2006). Therefore, the use of multi-model ensemble has been advised in many studies (Haddeland et al., 2014; IPCC, 2014; Milly et al., 2005; Nijssen et al., 2001). However, there are instances where one or two GCMs dominate the direction of change due to their high magnitudes. Also, by averaging the results of multiple GCM-based riverine flux simulations to create the ensembles, extremes are reduced and changes become less pronounced (Materia et al., 2010). Here we used five GCMs to obtain future temperature and precipitation projections which were used as input to the WBMsed global-scale hydro-geomorphic model, and the predicted changes in discharge and sediment flux were averaged for all GCMs to generate ensembles. Future riverine flux projections generated by these ensembles were generally consistent with most previous studies. However, direct comparisons are difficult to be made with most previous studies in part due to the differences in climate change scenarios used and different variables simulated in those studies.

While the use of GCM projections of future climate are a major

Table 3

Percentage of grid cells with ratio in CV between a given RCP scenario and RCP 2.6 for natural river discharge and sediment flux. Calculations are based only on grid cells with a contributing area > 10,000 km^2 and long-term average discharge > 30m^3/s.

	Ratio in CV between a given RCP and RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Water discharge	< 1.0[a]	43.2	32.8	21.8
	> 1.0[b]	56.8	67.1	78.2
Suspended sediment flux	< 1.0[a]	49.6	46.0	30.6
	> 1.0[b]	50.4	54.0	69.4

[a] Indicate low inter-annual variability relative to RCP 2.6.

[b] Indicate high inter-annual variability relative to RCP 2.6.

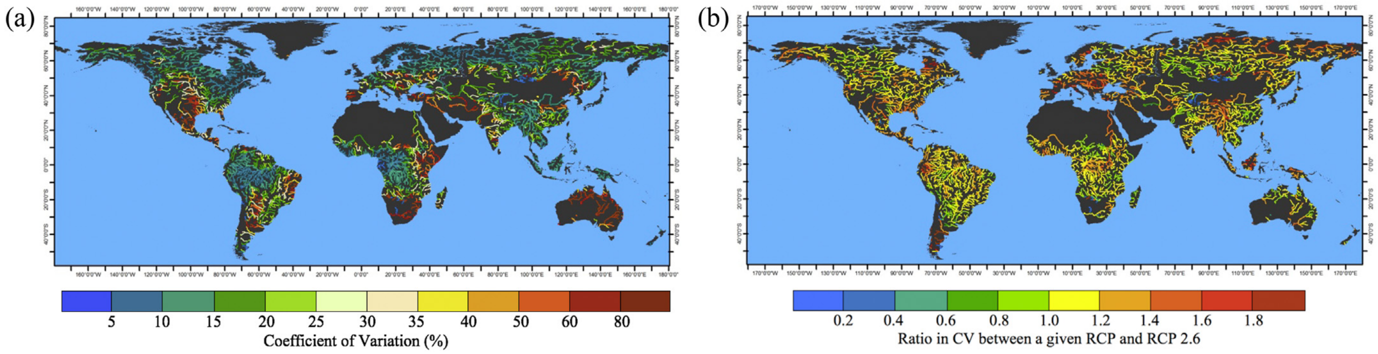

Fig. 9. Inter-annual variability in pristine river discharge during the 21st century for RCP 8.5 (a) and the change in CV in river discharge in RCP 8.5 relative to RCP 2.6 (b). Predictions are presented only for grid cells with a contributing area > 10,000 km^2 and long-term average discharge > 30m^3/s. Inter-annual variability in sediment flux coincide with these patterns predicted for discharge.

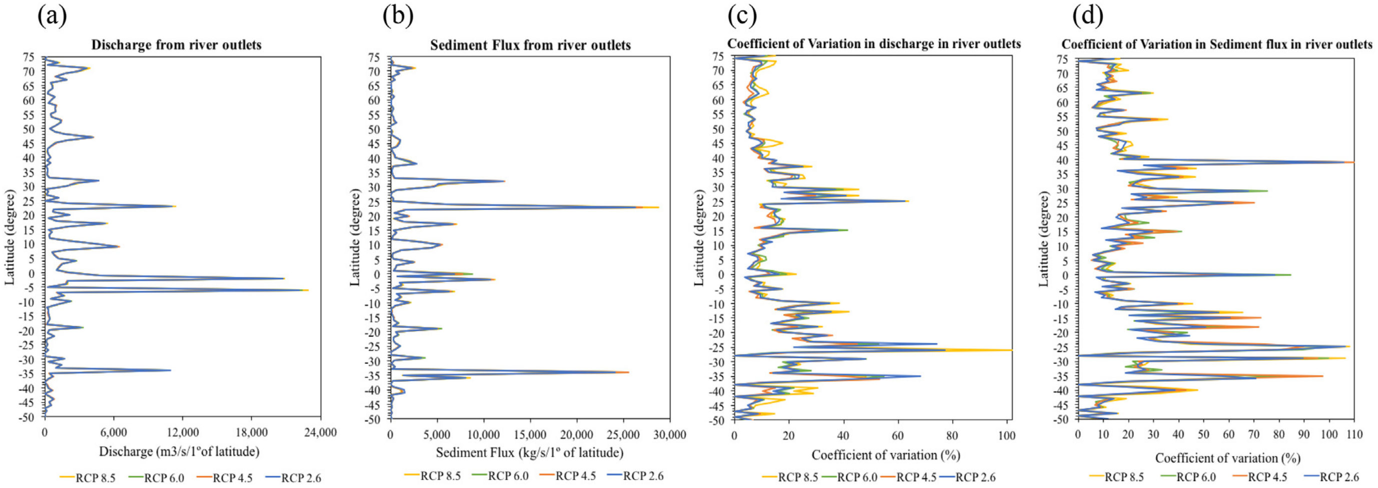

Fig. 10. Change in long-term average global pristine river discharge to oceans (a), sediment delivery to oceans from river outlets (b), inter-annual variability in discharge (c), and inter-annual variability in sediment delivery (d) between latitudinal regions for the period between 2010 and 2099. Values averaged across 1 degree of latitude, only for river outlets with a contributing area $>$ 10,000 km^2 and long-term average discharge > 30m^3/s.

source of uncertainty (Teng et al., 2012), there are other sources of uncertainties associated with this study. The range of changes in future climate conditions that can be captured by ISI-MIP climate models may have limitations, and thereby introduce some uncertainty to the study (Hattermann et al., 2018). McSweeney and Jones (2016) showed that the fraction of the full range of future climate across different regions and seasons that can be captured by the ISI-MIP subset, relative to the CMIP5 full ensemble of 36 GCMs, varies between 0.5 and 0.9 for temperature and between 0.3 and 0.8 for precipitation. However, this subset of five GCMs is widely used in climate change impact assessment

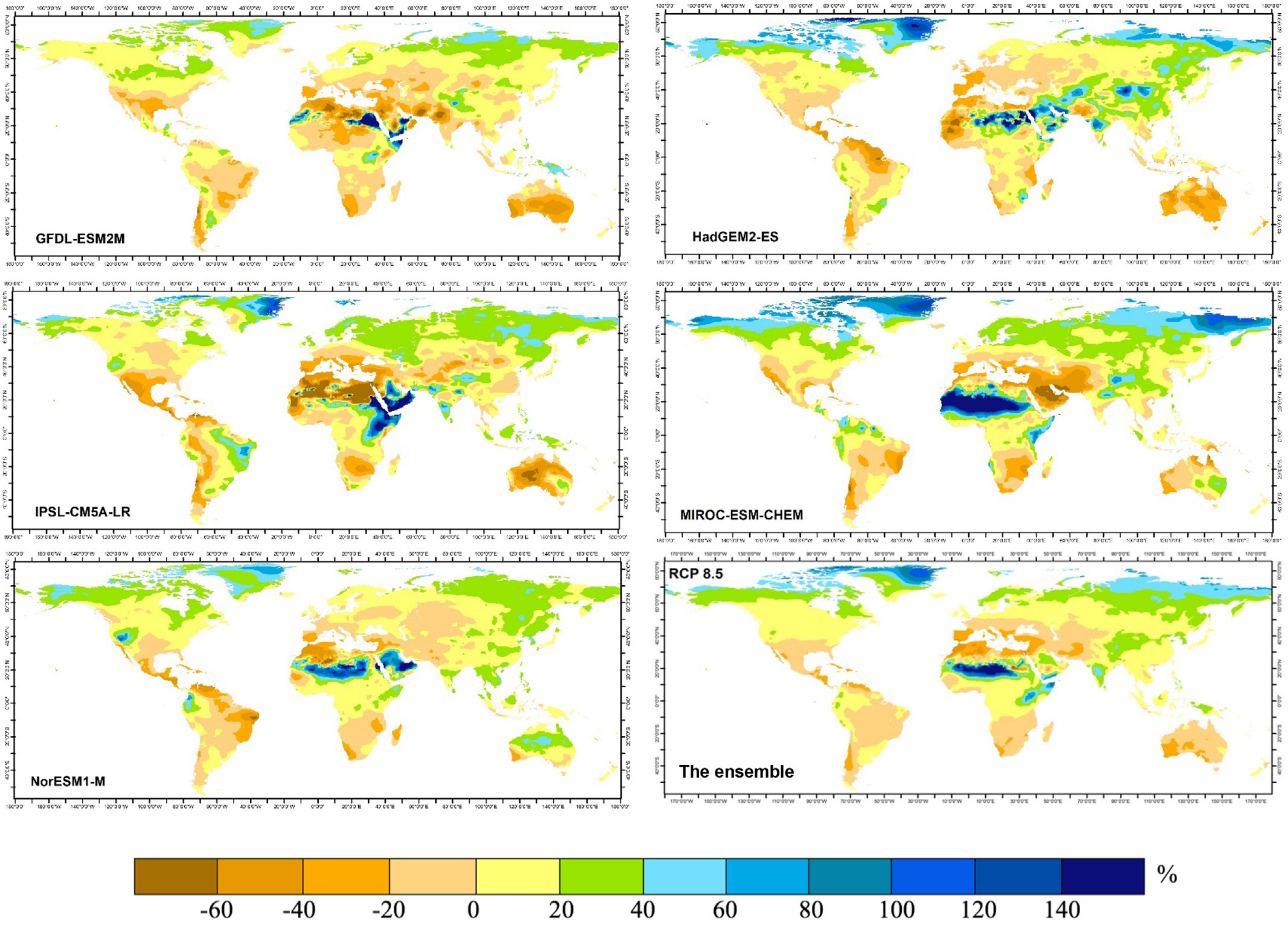

Fig. 11. The spread of individual GCMs for global averaged precipitation projections for the last decade relative to the first decade of the 21st century under RCP 8.5 scenario.

studies and accounts for climate impacts in different sectors (such as water, biomes, agriculture, health, and infrastructure; ISIMIP, 2019). Another source of uncertainty comes from the future GHG concentration scenarios, as they mimic a wide range of possible changes in future GHG concentrations based on a number of assumptions (Bjørnæs, 2013). In addition, the WBMsed model accuracy and simulation settings also introduce biases to this analysis as quantified in the validation procedure.

Precipitation and temperature are the main driving forces of discharge and sediment flux in most hydrologic models when assessing the influence of climate (Syvitski et al., 2005). Cohen et al. (2014) showed that while spatial and temporal variation in precipitation may have a major effect on discharge and thus sediment dynamics, other factors such as relief and lithology may augment this effect. Areas with high relief and soft lithology, that are more prone to erosion, can increase the sediment loads of rivers (Ludwig and Probst, 1996). This, in part, explains the nonlinear relationship and spatial heterogeneity found in the relationship between discharge and sediment flux in this study. For example, Chinese rivers such as Mekong, Yellow and Yangtze that originate in the high relief Himalayan areas and flow through highly erosive loess plateau, have proportionately larger increases in sediment flux than discharge. However, the climate warming-driven changes in vegetation patterns can also have effects on sediment loads due to the protection of soils against mechanical erosion (Ludwig and Probst, 1996), which is not considered in this analysis.

The aim of this study is to isolate the signal of climate on natural river discharge and sediment flux, hence the simulations are conducted under ‘Pristine’ conditions (see methodology). However, it is important to understand that human interventions and land use changes may have considerable, often dominating, effects on these predicted changes (Nienhuis et al., 2020). Thus, the absolute values for discharge and sediment loads or directions and magnitudes of projected changes discussed in this study may considerably change depending on human activities and may not necessarily be realized in the future. Dunn et al. (2019) investigated the change in sediment delivery to major river deltas in the world due to both climate change and anthropogenic drivers, using the WBMsed model with a representation of anthropogenic activities. They concluded that sediment fluxes will decline in a majority of river deltas considered, mainly owing to anthropogenic activities such as damming and changing land management practices offsetting the increases driven by climate change in the future. When WBMsed was run under RCPs and with currently existing anthropogenic influences, they found that 5 river deltas will experience decreases in sediment delivery in the 21st century under all RCPs. However, when only the signal of future climate change is considered under a pristine environment, our WBMsed model results show that some of the river deltas (e.g Nile, Chao Phraya, Magdalena) out of these 5, experience an increase in sediment delivery under all RCPs (Fig. 6). The reason is that existing anthropogenic activities (e.g. dams and other population and socioeconomic conditions prevailing in the river basins) are already trapping/reducing a large sediment load. Hence, even though our study shows that climate in the 21st century alone would increase the supply of sediment to the delta, existing human activities could hamper its original signal. This demonstrates the significance of isolating the signal of climate change without human interferences to the environment, so that appropriate actions regarding ongoing and planned human activities can be taken to prevent negative consequences. Thus, the main idea behind this paper is to advance our understanding about the changes that anthropogenic GHG emissions and associated temperature and precipitation patterns can bring about in large global rivers, and help informed decision making related to the management of large global rivers and formulate intelligent adaptation strategies for climate change impacts.

5. Conclusion

In order to isolate the signal of projected future climate change on global riverine water discharge and suspended sediment fluxes in the 21st century under pristine conditions, a numerical model (WBMsed) was forced with precipitation and temperature projections from five GCMs each driven by four RCPs. The results, based on an ensemble of model outputs, revealed that natural global river discharge and sediment fluxes are highly sensitive to anthropogenic climate change in the 21st century. These changes vary considerably spatially and temporally and are considerably responsive to increasing levels of GHG concentrations in the atmosphere (RCP scenarios). The forcing data used in the study shows that global land surface temperature increases toward the end of the century in all RCPs, and increases are larger with increasing warming scenarios. Global precipitation distribution varies between RCPs, leading to an overall increase in the mean global precipitation toward the end of the century in all scenarios.

Our results show that climate change is predicted to considerably increase river discharges in the Arctic, north and east Africa, Indian peninsula, Northern Europe and some parts of North and South America with increasing GHG-induced warming under pristine conditions. Decreases in river discharges are projected for southern and western Europe, Mediterranean regions, central and west Asia, much of north America and south America. Changes in sediment flux closely follow these patterns predicted for discharge. However, the relationship between discharge and sediment flux is nonlinear. The study reveals that while global warming-induced spatial and temporal variation in precipitation mainly drives discharge patterns and thus sediment dynamics under a changing climate, other factors such as relief and lithology can greatly amplify this effect.

It is also evident that with increasing atmospheric warming, more extreme changes (either increasing or decreasing) can be expected in both natural discharge and sediment flux, as well as in precipitation. We have found that more rivers will experience these climate-driven extreme changes (increasing or decreasing) as the planet gets warmer over the 21st century. Despite regional differences, at a global scale, both mean natural river discharge and sediment flux show a net increase at the end of the 21st century under all RCP scenarios and the increases are generally larger with increasing RCPs (Table 1). However, in the mid-21st century, RCP 4.5 and 6.0 moderate warming scenarios generate the largest discharge and sediment flux to the oceans at a global scale. The rates of change per decade in total global river discharge and sediment delivery to the oceans under pristine conditions in the 21st century due to climate change are also projected to increase as warming increases (Table 2). In addition to the magnitudes, inter-annual variability in both river discharge and sediment flux also increases with increased GHG-induced warming.

It is important to understand that anthropogenic alterations of fluvial systems and land cover will considerably alter future discharge and sediment. Therefore, the predictions generated by this study, which do not take these into consideration, will not necessarily be realized in the future. The findings of this study are useful to isolate the changes that anthropogenic global warming-induced temperatures and precipitation can bring about in large global rivers under pristine conditions. This will help informed decision making related to the management of large global rivers and formulating intelligent adaptation strategies for climate change impacts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We express our gratitude to Dr. Hamid Moradkhani and Dr. Sarah Praskievicz for their constructive comments, and the anonymous reviewers for their valuable suggestions that helped us to improve the quality of this paper. This research was partly funded by the University Corporation for Atmospheric Research (UCAR), United States grant number SUBAWD000837.

References

Aerts, J.C.J.H., Renssen, H., Ward, P.J., De Moel, H., Odada, E., Bouwer, L.M., Goosse, H., 2006. Sensitivity of global river discharges under Holocene and future climate conditions. Geophys. Res. Lett. 33 (19).

Arnell, N.W., 2003. Effects of IPCC SRES* emissions scenarios on river runoff: a global perspective. Hydrol. Earth Syst. Sci. Discuss. 7 (5), 619–641.

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. (Eds.), 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC Secretariat, Geneva.

Bjørnæs, C., 2013. A Guide to Representative Concentration Pathways. CICERO. Center for International Climate and Environmental Research.

Cai, X., Wang, D., Zhu, T., Ringler, C., 2009. Assessing the regional variability of GCM simulations. Geophys. Res. Lett. 36 (2).

Cohen, S., Kettner, A.J., Syvitski, J.P., Fekete, B.M., 2013. WBMsed, a distributed global-scale riverine sediment flux model: model description and validation. Comput. Geosci. 53, 80–93.

Cohen, S., Kettner, A.J., Syvitski, J.P., 2014. Global suspended sediment and water discharge dynamics between 1960 and 2010: Continental trends and intra-basin sensitivity. Glob. Planet. Chang. 115, 44–58.

Coulthard, T.J., Ramirez, J., Fowler, H.J., Glenis, V., 2012. Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield. Hydrol. Earth Syst. Sci. 16 (11), 4401.

Dai, A., Fung, I.Y., Del Genio, A.D., 1997. Surface observed global land precipitation variations during 1900–88. J. Clim. 10 (11), 2943–2962.

Dai, A., Qian, T., Trenberth, K.E., Milliman, J.D., 2009. Changes in continental freshwater discharge from 1948 to 2004. J. Clim. 22 (10), 2773–2792.

Darby, S.E., Dunn, F.E., Nicholls, R.J., Rahman, M., Riddy, L., 2015. A first look at the influence of anthropogenic climate change on the future delivery of fluvial sediment to the Ganges–Brahmaputra–Meghna delta. Environ Sci Process Impacts 17 (9), 1587–1600.

Dunn, F.E., Darby, S.E., Nicholls, R.J., Cohen, S., Zarfl, C., Fekete, B.M., 2019. Projections of declining fluvial sediment delivery to major deltas worldwide in response to climate change and anthropogenic stress. Environ. Res. Lett. 14 (8), 084034.

Frieler, K., Lange, S., Piontek, F., Reyer, C.P., Schewe, J., Warszawski, L., Zhao, F., Chini, L., Denvil, S., Emanuel, K., Geiger, T., 2017. Assessing the impacts of 1.5 C global warming–simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b). Geosci. Model Dev. 10, 4321–4345.

Fryirs, K., 2013. (Dis) Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem. Earth Surf. Process. Landf. 38 (1), 30–46.

Haarsma, R.J., Selten, F.M., Weber, S.L., Kliphuis, M., 2005. Sahel rainfall variability and response to greenhouse warming. Geophys. Res. Lett. 32 (17).

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. 111 (9), 3251–3256.

Hagemann, S., Chen, C., Clark, D.B., Folwell, S., Gosling, S.N., Haddeland, I., Hanasaki, N., Heinke, J., Ludwig, F., Voss, F., Wiltshire, A.J., 2013. Climate change impact on available water resources obtained using multiple global climate and hydrology models. Earth Syst. Dyn. 4 (1), 129–144.

Hattermann, F.F., Vetter, T., Breuer, L., Su, B., Daggupati, P., Donnelly, C., Fekete, B., Flörke, F., Gosling, S.N., Hoffmann, P., Liersch, S., 2018. Sources of uncertainty in hydrological climate impact assessment: a cross-scale study. Environ. Res. Lett. 13 (1), 015006.

Hempel, S., Frieler, K., Warszawski, L., Schewe, J., Piontek, F., 2013. A trend-preserving bias correction–the ISI-MIP approach. Earth Syst. Dyn. 4 (2), 219–236.

Hirabayashi, Y., Kanae, S., Emori, S., Oki, T., Kimoto, M., 2008. Global projections of changing risks of floods and droughts in a changing climate. Hydrol. Sci. J. 53 (4), 754–772.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (Eds.)]. IPCC, Geneva, Switzerland, pp. 151.

ISIMIP, 2019. Inter-Sectoral Impact Model Intercomparison Project (accessed 03/29/2018). https://www.isimip.org/gettingstarted/details/10/.

Knox, J.C., 1993. Large increases in flood magnitude in response to modest changes in climate. Nature 361 (6411), 430–432.

Knutti, R., Sedláček, J., 2013. Robustness and uncertainties in the new CMIP5 climate model projections. Nat. Clim. Chang. 3 (4), 369.

Krakauer, N.Y., Fekete, B.M., 2014. Are climate model simulations useful for forecasting precipitation trends? Hindcast and synthetic-data experiments. Environ. Res. Lett. 9 (2), 024009.

Lange, S., 2019. Trend-preserving bias adjustment and statistical downscaling with ISIMIP3BASD (v1. 0). J. Geosci. Mod. Dev. Discuss. 12 (7), 3055–3070 (In review).

López, J.C.R., Torregroza, A.C., 2017. Suspended sediment load in northwestern South America (Colombia): a new view on variability and fluxes into the Caribbean Sea. J. S. Am. Earth Sci. 80, 340–352.

Lu, X.X., Ran, L.S., Liu, S., Jiang, T., Zhang, S.R., Wang, J.J., 2013. Sediment loads response to climate change: a preliminary study of eight large Chinese rivers. Int. J. Sed. Res. 28 (1), 1–14.

Ludwig, W., Probst, J.L., 1996. A global modelling of the climatic, morphological, and lithological control of river sediment discharges to the oceans. In: IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences. 236. pp. 21–22.

Materia, S., Dirmeyer, P.A., Guo, Z., Alessandri, A., Navarra, A., 2010. The sensitivity of simulated river discharge to land surface representation and meteorological forcings. J. Hydrometeorol. 11 (2), 334–351.

McSweeney, C.F., Jones, R.G., 2016. How representative is the spread of climate projections from the 5 CMIP5 GCMs used in ISI-MIP? Clim. Serv. 1, 24–29.

Milliman, J.D., Syvitski, J.P., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. J. Geol. 100 (5), 525–544.

Milly, P.C., Dunne, K.A., Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438 (7066), 347.

Morehead, M.D., Syvitski, J.P., Hutton, E.W., Peckham, S.D., 2003. Modeling the temporal variability in the flux of sediment from ungauged river basins. Glob. Planet. Chang. 39 (1–2), 95–110.

Mukundan, R., Pradhanang, S.M., Schneiderman, E.M., Pierson, D.C., Anandhi, A., Zion, M.S., Matonse, A.H., Lounsbury, D.G., Steenhuis, T.S., 2013. Suspended sediment source areas and future climate impact on soil erosion and sediment yield in a New York City water supply watershed, USA. Geomorphology 183, 110–119.

Nakaegawa, T., Kitoh, A., Hosaka, M., 2013. Discharge of major global rivers in the late 21st century climate projected with the high horizontal resolution MRI - AGCMs. Hydrol. Process. 27 (23), 3301–3318.

New, M., Todd, M., Hulme, M., Jones, P., 2001. Precipitation measurements and trends in the twentieth century. Int. J. Climatol. 21 (15), 1889–1922.

Nienhuis, J.H., Ashton, A.D., Edmonds, D.A., Hoitink, A.J.F., Kettner, A.J., Rowland, J.C., Törnqvist, T.E., 2020. Global-scale human impact on delta morphology has led to net land area gain. Nature 577 (7791), 514–518.

Nijssen, B., O'donnell, G.M., Hamlet, A.F., Lettenmaier, D.P., 2001. Hydrologic sensitivity of global rivers to climate change. Clim. Chang. 50 (1–2), 143–175.

Nohara, D., Kitoh, A., Hosaka, M., Oki, T., 2006. Impact of climate change on river discharge projected by multimodel ensemble. J. Hydrometeorol. 7 (5), 1076–1089.

Oki, T., Kanae, S., 2006. Global hydrological cycles and world water resources. Science 313 (5790), 1068–1072.

Pelletier, J.D., 2012. A spatially distributed model for the long-term suspended sediment discharge and delivery ratio of drainage basins. J. Geophys. Res. Earth Surf. 117 (F2).

Pendergrass, A.G., Knutti, R., Lehner, F., Deser, C., Sanderson, B.M., 2017. Precipitation variability increases in a warmer climate. Sci. Rep. 7 (1), 17966.

Rodríguez-Blanco, M.L., Arias, R., Taboada-Castro, M.M., Nunes, J.P., Keizer, J.J., Taboada-Castro, M.T., 2016. Potential impact of climate change on suspended sediment yield in NW Spain: a case study on the Corbeira catchment. Water 8 (10), 444.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N.W., Clark, D.B., Dankers, R., Eisner, S., Fekete, B.M., Colón-González, F.J., Gosling, S.N., Kim, H., Liu, X., Masaki, Y., Portmann, F.T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., Wisser, D., Albrecht, T., Frieler, K., Piontek, F., Warszawski, L., Kabat, P., 2013. Multimodel assessment of water scarcity under climate change. Proc. Natl. Acad. Sci. 111 (9), 3245–3250.

Shrestha, B., Cochrane, T.A., Caruso, B.S., Arias, M.E., Piman, T., 2016. Uncertainty in flow and sediment projections due to future climate scenarios for the 3S Rivers in the Mekong Basin. J. Hydrol. 540, 1088–1104.

Sperna Weiland, F.C., Van Beek, L.P.H., Kwadijk, J.C.J., Bierkens, M.F.P., 2012. Global patterns of change in discharge regimes for 2100. Hydrol. Earth Syst. Sci. 16, 1047–1062.

Sylla, M.B., Nikiema, P.M., Gibba, P., Kebe, I., Klutse, N.A.B., 2016. Climate change over West Africa: recent trends and future projections. In: Adaptation to Climate Change and Variability in Rural West Africa. Springer, Cham, pp. 25–40.

Syvitski, J.P., 2002. Sediment discharge variability in Arctic rivers: implications for a warmer future. Polar Res. 21 (2), 323–330.

Syvitski, J.P., 2003a. The influence of climate on the flux of sediment to the coastal ocean. In: OCEANS 2003. Proceedings. Vol. 2. IEEE, pp. 981–985 September.

Syvitski, J.P., 2003b. Supply and flux of sediment along hydrological pathways: research for the 21st century. Glob. Planet. Chang. 39 (1), 1–11.

Syvitski, J.P., Milliman, J.D., 2007. Geology, geography, and humans battle for dominance over the delivery of fluvial sediment to the coastal ocean. J. Geol. 115 (1), 1–19.

Syvitski, J.P., Peckham, S.D., Hilberman, R., Mulder, T., 2003. Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective. Sediment. Geol. 162 (1), 5–24.

Syvitski, J.P., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308 (5720), 376–380.

Syvitski, J.P., Cohen, S., Kettner, A.J., Brakenridge, G.R., 2014. How important and different are tropical rivers?—an overview. Geomorphology 227, 5–17.

Syvitski, J., Cohen, S., Miara, A., Best, J., 2019. River temperature and the thermal-dynamic transport of sediment. Glob. Planet. Chang. 178, 168–183.

Taylor, P.G., Wieder, W.R., Weintraub, S., Cohen, S., Cleveland, C.C., Townsend, A.R., 2015. Organic forms dominate hydrologic nitrogen export from a lowland tropical watershed. Ecology 96 (5), 1229–1241.

Teng, J., Vaze, J., Chiew, F.H., Wang, B., Perraud, J.M., 2012. Estimating the relative uncertainties sourced from GCMs and hydrological models in modeling climate change impact on runoff. J. Hydrometeorol. 13 (1), 122–139.

Trenberth, K.E., 2011. Changes in precipitation with climate change. Clim. Res. 47 (1–2), 123–138.

U.S. Geological Survey, 2018. National Water Information System data (Water Data for the Nation) (accessed 05/06/2018). http://waterdata.usgs.gov/nwis/.

van Vliet, M.T., Franssen, W.H., Yearsley, J.R., Ludwig, F., Haddeland, I., Lettenmaier, D.P., Kabat, P., 2013. Global river discharge and water temperature under climate change. Glob. Environ. Chang. 23 (2), 450–464.

Vercruysse, K., Grabowski, R.C., Rickson, R.J., 2017. Suspended sediment transport dynamics in rivers: multi-scale drivers of temporal variation. Earth Sci. Rev. 166, 38–52.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., Syvitski, J.P.M., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Glob. Planet. Chang. 39 (1–2), 169–190.

Walling, D.E., 2009. The Impact of Global Change on Erosion and Sediment Transport by Rivers: Current Progress and Future Challenges. UNESCO.

Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Glob. Planet. Chang. 39, 111–126.

Wang, H., Saito, Y., Zhang, Y., Bi, N., Sun, X., Yang, Z., 2011. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. Earth Sci. Rev. 108 (1–2), 80–100.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J., 2014. The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. Proc. Natl. Acad. Sci. 111 (9), 3228–3232.

Yang, S.L., Xu, K.H., Milliman, J.D., Yang, H.F., Wu, C.S., 2015. Decline of Yangtze River water and sediment discharge: Impact from natural and anthropogenic changes. Sci. Rep. 5, 12581.

Wisser, D., Fekete, B.M., Vörösmarty, C.J., Schumann, A.H., 2010. Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network-Hydrology (GTN-H). Hydrology & Earth System Sciences 14 (1), 1–24.

Zhu, Y.M., Lu, X.X., Zhou, Y., 2008. Sediment flux sensitivity to climate change: a case study in the Longchuanjiang catchment of the upper Yangtze River, China. Glob. Planet. Chang. 60 (3–4), 429–442.