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Discussions

Illustrating a new approach to estimating potential reduction in fish species richness due to flow alteration on a global scale

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Abstract

Changes in river discharge due to human activities and climate change would affect the sustainability of freshwater ecosystem. In order to globally assess the future status of freshwater ecosystem under regime shifts in river discharge, global-scale hydrological simulations need to be connected with a model to estimate the soundness of freshwater ecosystem. However, the explicit combination of those two on a global scale is still in its infancy. A couple of statistical models are introduced here to link flow regimes to fish species richness (FSR): one based on a linear relationship between FSR and mean river discharge, and the other based on a relationship between FSR and ecologically relevant flow indices involving other several flow characteristics as well as mean river discharge. The former one has been sometimes used in global simulation studies, but the latter one is newly introduced here in the context of global simulation. These statistical models for estimating FSR were combined with a set of global river discharge simulations to evaluate the potential impact of flow alterations due to climate change on FSR changes. Generally, future reductions in FSR by the latter method are larger and much more scattered rather than by the former method. In arid regions, both models provide reductions in FSR because mean discharge is projected to decrease from past to future, although the magnitude of reduction in FSR is different. On the other hand, large reductions in FSR only by the latter model are detected in heavy-snow regions due to the increases of mean discharge and frequency of low and high flows. Although we need further research to conclude which is more relevant, this study demonstrates that the new model could show a considerably different behavior in assessing the global impact of flow alteration on freshwater ecosystem change.

1 Introduction

The collapse of freshwater ecosystem was identified as one of the major serious threats in the sustainability of the global freshwater system in an attempt to define planetary boundaries (Rockström et al., 2009). In their study, the collapse of freshwater ecosystem was discussed mainly in terms of global freshwater use that is one of the proposed 10 indices of planetary boundaries. However, two more indices out of 10 planetary boundaries, biodiversity loss and climate change, are undoubtedly linked to the collapse of freshwater ecosystem. Their study adopted a concept proposed by Smakhtin et al. (2004) and Smakhtin (2008) in which 20–50 % of mean annual river discharge is assigned as environmental flow to sustain freshwater ecosystem functioning. Hanasaki et al., (2008a, b) similarly but differently estimated a globally distributed monthly environmental flow requirement depending upon the climatic classification of each region. Such values have been estimated, however, without explicit linkage to freshwater ecosystem structure and function. Therefore, there is a strong need to find ways to incorporate the linkage for more adequately setting environmental flow on a global scale.

Species richness, as an indicator of biodiversity, has declined rapidly in freshwater ecosystem than in terrestrial or marine systems over the past 30 yr (Jenkins, 2003) possibly due to human activities and global climate change. The long-term trend of biodiversity decline in freshwater ecosystem was caused by multiple anthropogenic impacts such as water pollution, water extraction and transfer, and invasive species (Postel and Richter, 2003; IUCN, 2010). Furthermore, climate change would affect freshwater ecosystem not only by increasing temperature but also by alteration of river discharge (López-Moreno et al., 2013) and other flow characteristics. The flow alteration limits the distribution and abundance of freshwater species and regulates the ecological integrity of flowing water system (Poff et al., 1997).

To link flow regimes to freshwater biodiversity, Xenopoulos et al. (2005) established a linear relationship between fish species richness (FSR) and mean river discharge. By applying the relationship to outputs of a global hydrological model, Döll and Zhang (2010) showed the impact of the anthropogenic alteration of river flow regimes on the potential changes in number of fish species. In dealing with FSR, indices based on mean river discharge would not be enough. Thus, Iwasaki et al. (2012) proposed another regression-based relationship of FSR to ecologically relevant flow indices involving not only mean river discharge but also other flow characteristics. Given the likely impacts on freshwater ecosystem of the changes in various flow characteristics, it is worth applying the relationship obtained in Iwasaki et al. (2012) to estimate a global-scale future reduction in FSR.

This paper shows the first trial to combine two FSR models, Iwasaki et al. (2012) and Xenopoulos et al. (2005), with a set of global-scale hydrological simulations. Specifically, as an example of the application, we show the potential impact of flow alterations due to climate change on the changes in FSR for 26 rivers worldwide. The intention of this short paper is not to demonstrate a definitive result on the impact of climate change on freshwater ecosystem. Rather, we try to show similarities and differences in the outputs of two methods. The results of this study could provide a clue for the adequate incorporation of a method for estimating the threat to freshwater ecosystem into global-scale hydrological simulations.

2 Data and methodology

2.1 Data

For the calibration of regression-based models in the Sect. 2.2., we obtained gauge-based daily river discharge data of Global Runoff Data Centre (GRDC) for 26 river basins during the period of 1971–1985. The target period for calculating flow metrics was necessary for hydrological analysis at least 15 yr (Kennard et al., 2010). Simultaneously, the basin area and latitude of each station where river discharge was measured were obtained from the GRDC database.

For the estimation of the potential impact of climate change as described in the Sect. 3, we also obtained a set of simulated daily river discharge data of Hirabayashi et al. (2013) in which river routing was computed by a global river routing model, the Catchment-based Macro-scale Floodplain (CaMa-Flood) model (Yamazaki et al., 2011), utilizing latest outputs of 11 coupled atmosphere–ocean general circulation

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models (AOGCMs). As shown in Yamazaki et al. (2011), the CaMa-Flood model more reasonably represents temporal and peaks of river discharge, as compared to previous global river routing model such as Miller et al. (1994) and Oki et al. (1999), because the model adopts a diffusive equation and also represents inundation dynamics. From the whole simulation period, 15 yr periods from 1971 to 1985 and 2036 to 2050 were selected to represent the "past" and "future", respectively. In this study, we took up the simulation forced by only the representative concentration pathway (RCP) 8.5 scenario which is characterized by increasing greenhouse gas emissions over time.

We note that the current CaMa-Flood model does not consider the effects of anthropogenic water use and regulation such as irrigation water use from river source and dam operation. In addition, we did not apply any bias correction to the outputs of AOGCMs in this study which could require a lot of additional computation resources. Nevertheless, the difference in the estimated FSRs between Xenopoulos's method based only on mean river discharge and Iwasaki's method based on both mean river discharge and some indices of daily flow variations would show meaningful implications.

2.2 Basin-scale fish species richness

Mean river discharge at the river mouth have been well related to basin-scale FSR on a global scale (Oberdorff et al., 1995, 2011) as well as continental scale (Livingstone et al., 1982; Hugueny, 1989). Hugueny et al. (2010) suggests mean river discharge is a reasonable predictor of the log-log linear relationship to obtain basin-scale FSR. Conceptually, river discharge is a proxy of the habitat size for fishes (Hugueny et al., 2010; Oberdorff et al., 2011).

According to these previous studies, Xenopoulos et al., (2005) calculated future reductions in FSR on a global scale. They combined the species–discharge relationship with projected losses in river discharge due to climate change

$$\mathrm{FSR} = \exp(0.4 \times \log \text{mean annual discharge}(\mathrm{m^3\,s^{-1}}) + 0.6242) \quad (1)$$

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The species–discharge relationship may be the best available approach for the projection of future FSR change (Xenopoulos and Lodge, 2006) and only mean river discharge was considered in above studies. However, the flow can be described from five aspects of its regime (magnitude, frequency, duration, timing and rate of change of flow events) which is ecologically relevant (Richter et al., 1996; Poff et al., 1997) and many flow indices have been proposed as ecologically important one (Olden and Poff, 2003; Richter et al., 1996). Therefore, not only mean river discharge, but also other flow characteristics, e.g. high/low flow and flow variation, could play a vital role in sustaining freshwater ecosystem (Acreman and Dunbar, 2004; Poff et al., 1996). A considerable challenge for quantitative associations of such flow characteristics with ecological indicators such as species richness is incorporating them in a future projection of hydrology.

More recently, Iwasaki et al. (2012) calculated a comprehensive set of 36 flow metrics belonging to the five aspects based on daily discharge data observed at the outlets of 72 rivers worldwide, and statistically estimated relationships between the flow metrics and basin-scale FSR. The study served the first empirical evidence that specific low- and high-flow characteristics may be necessary in predicting the basin-scale FSR. There, FSR was estimated as follows Eq. (2)

$$\begin{aligned}\mathrm{FSR} = \exp(&3.948 - 0.03420 \cdot \mathrm{LAT} + 0.2732 \cdot \mathrm{Area} + 0.3734 \cdot \mathrm{Meandis} \\ &-1.573 \cdot \mathrm{FL2} + 0.8318 \cdot \mathrm{TH3} - 0.1163 \times \mathrm{TL2})\end{aligned} \tag{2}$$

where LAT, Area, Meandis, FL2, TH3, and TL2 correspond to absolute value of latitude at the river outlet (degree), basin area (km^2), mean river discharge ($m^3\,s^{-1}$), coefficient of variation (CV) of low flow (25th percentile), maximum proportion of the year (number of days/365) during which no 1.67 yr floods have ever occurred, and CV in the Julian date of annual minimum flow, respectively. Iwasaki et al. (2012) tested the importance of river basin area in accounting for variations in FSR, as river basin area may provide a potential for the diversity of fish species (Hugueny, 1989).

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3 Results

The future reduction in FSR due to climate change was computed by applying Iwasaki's and Xenopoulos's methods to the simulated river discharge data introduced in the former section. The global distribution of median values of the future reduction in FSR for 26 basins is presented in Fig. 1a (by Iwasaki's method) and Fig. 1b (by Xenopoulos's method). Iwasaki et al. (2012) took into account not only mean river discharge but also indices obtained from temporal variations of daily river discharge such as frequency of low-flow; thus, the spatial pattern is different if we compare Fig. 1a with 1b. Iwasaki's method, concerning several aspects of river discharge data, tends to show a larger reduction in FSR for each basin. In addition to the spatial distribution, we illustrate the range/spreads of reductions in FSR among 11 AOGCMs for each basin by showing box plots (Fig. 2). Spreads are generally much larger by Iwasaki's method, also possibly because of the incorporation of more aspects of river discharge data in addition to mean discharge.

In Iwasaki's method (Fig. 1a), 10 of the total 26 basins would suffer from a decrease in FSR if we judge it by the median of 11 AOGCM-based results. Some of the median values of reduction in FSR are less than −10 % such as −22 % in the Ob and −20 % in the Saskatchewan (Fig. 1a). The reductions in FSR are found across basins of North America, South America, Northeast Eurasia and Oceania, especially in heavy-snow regions and semi-arid regions. On average, the median value of FSR decreases by −7 %. The heights of the box plot (±1 standard deviation) showing reduction in FSR are projected to be about −50–0 % (Fig. 2). The ranges of the reductions were spread out in several rivers (the Platte, the Saskatchewan and the Rio Grande rivers of North America, the Darling and the Barwon rivers of Oceania, and the Dnieper river of Europe).

In Xenopoulos's method (Fig. 1b), 6 of the total 26 basins would suffer from a reduction in FSR. The reduction of less than −5 % is limited to −8 % in the Platte river basin and −10 % in the Rio Grande river basin. Reductions in FSR are only shown

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in semi-arid regions of Oceania, and central and southern North America. Thus, the potential reduction in FSR due to climate change is not detected in Northern Eurasia, Europe, South America, and north and east of North America excluding the Platte, the Rio Grande, the Missouri and the Saskatchewan rivers. On average, the median value of FSR decreases by −3 %. The heights of the box plots are projected to be about −25–0 %. The ranges of the reductions were spread out in basins in Oceania and the Rio Grande.

Comparing the above observation for each method, we briefly summarize the differences by Iwasaki's method and by Xenopoulos's method. The future reductions by Iwasaki's method are generally larger than those by Xenopoulos's method. In addition, the future reductions in FSR by Iwasaki's method represent more scattered changes (−50–0 %) among 11 AOGCMs rather than Xenopoulos's method (−25–0 %). In South America and central United States and Oceania, reductions in FSR were projected to decrease in both methods, but the magnitudes are different. However, in heavy-snow regions of Northeast Eurasia and North America, reductions in FSR by Iwasaki's method were projected large, whereas those by Xenopoulos's method were minor.

4 Discussion and concluding remarks

As was noted above, in South America, Oceania and semi-arid region of North America, reductions in FSR were projected by both methods although the magnitudes and spreads are different. Coinstantaneously, *Meandis* (see detail in Appendix including Fig. A1) were decreased from past to future. It can thus be implied that the decrease in total discharge due to climate change affected the future reduction in FSR in these regions. In addition, the obvious difference in the magnitudes and spreads between two methods could be originated from the changes in flow indices except for mean discharge (Figs. A2–A4), as only Iwasaki's method is sensitive to those indices.

In heavy-snow regions of Northeast Eurasia and North America such as the Ob and the Saskatchewan, reductions in FSR by Iwasaki's method are much greater than

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those by Xenopoulos's method presumably due to increased FL2 and TL2 in addition to increased Meandis (see details Appendix in including Fig. A1–A3). In these regions, despite annual precipitation and discharge were projected to increase (Hirabayashi et al., 2013), frequencies of low-flow and high-flow were also projected to increase. As a consequence, FSR was decreased by Iwasaki's method. It is thus implied that FSR is affected by higher river flows in winter, earlier spring flows, and reduced summer low flows which can be caused warmer and shorter future snow season. In fact, Battin et al. (2007) also indicated strongly increased winter peak flows may lead to a decline in fish population in Pacific Northwest of United States. In addition, those changes in flow indices in addition to mean discharge could have caused larger spreads in the outputs of Iwasaki's method.

One of the drawbacks of this study is associated with simulated river discharge data in our framework, such as biases in runoff data from 11 AOGCMs and potential for better calibration of the CaMa-Flood model. Additionally, the current CaMa-Flood model in this study is not integrated in a global water resource model that incorporates the effects of anthropogenic water use and regulation. However, Döll et al. (2009) argued that river flow alterations are strongest in semi-arid regions with extensive irrigation but also in downstream of large dams during the past decade. In order to have a comprehensive future assessment, the impact of water use and regulation should be incorporated into this framework in a relevant manner such as in Döll et al. (2009), Hanasaki et al. (2012) and Yoshikawa et al. (2013).

There is also uncertainty in the estimation of FSR with only river discharge. Iwasaki's method was solely based on the statistical correlation (not casual relationships) between flow metrics and FSR. In addition, Iwasaki et al. (2012) did not consider other physical (e.g., damming) and chemical factors (e.g., organic pollution) that should have affected basin-scale FSR and may have confounded the interpretation of the statistical model.

Other related issues include more careful selection of flow metrics, appropriateness of using river discharge at the river outlet as a representative for river flow regimes.

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Additionally, we showed reductions in FSR only. Regarding increased FSR, Xenopoulos et al. (2005) noted that the consequences of increased discharge on fish species richness are highly uncertain, but that increases of discharge might allow the establishment of new non-indigenous species if they were introduced by humans. Poff and Zimmerman (2010), however, identified consistent negative fish responses not only to decreased but also to increased average discharge.

Despite the drawbacks and uncertainties discussed above, the new model on FSR proposed by Iwasaki et al. (2012) has a potential to be used in assessing the impact of flow alteration on freshwater ecosystem change. We note again that there are considerable differences in the results by Xenopoulos's method and Iwasaki's method. We found that impactive and vulnerable regions of future reductions in FSR by Iwasaki's method were obviously different from those by Xenopoulos's method, such as in snow regions. Even if the direction of change is the same, the magnitude and spread of change is different between two methods. Further research on global FSR modeling including Xenopoulos's models is necessary, but it is sure that the examinations of a model dealing with various flow characteristics such as Iwasaki's model need to be encouraged because its response is different from the one based on mean river discharge.

Appendix

Four flow metrics (Meandis, FL2, TH3 and TL2) were computed, and their magnitude due to climate change of future were compared to those of past. Overall, there was no noticeable signal in Meandis between past and future (Fig. A1). However, there are obvious changes in FL2, TH3 and TL2 between past and future (Figs. A2–A4).

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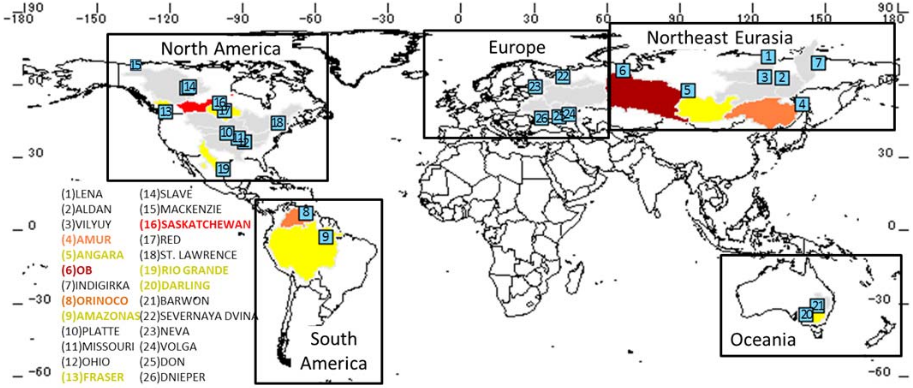
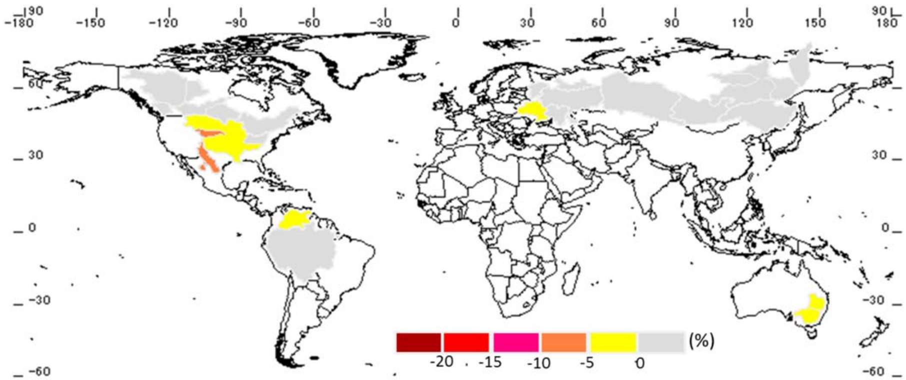


(a)



(b)

Fig. 1. Global distributions of median value of future reductions in fish species richness (min(0, future–past in % of past)) in main basins and sub-basins scales. **(a)** Iwasaki's- and **(b)** Xenopoulos's method. Basin map in **(a)** with locations and names of the 26 rivers indicated by locations of river numbers.

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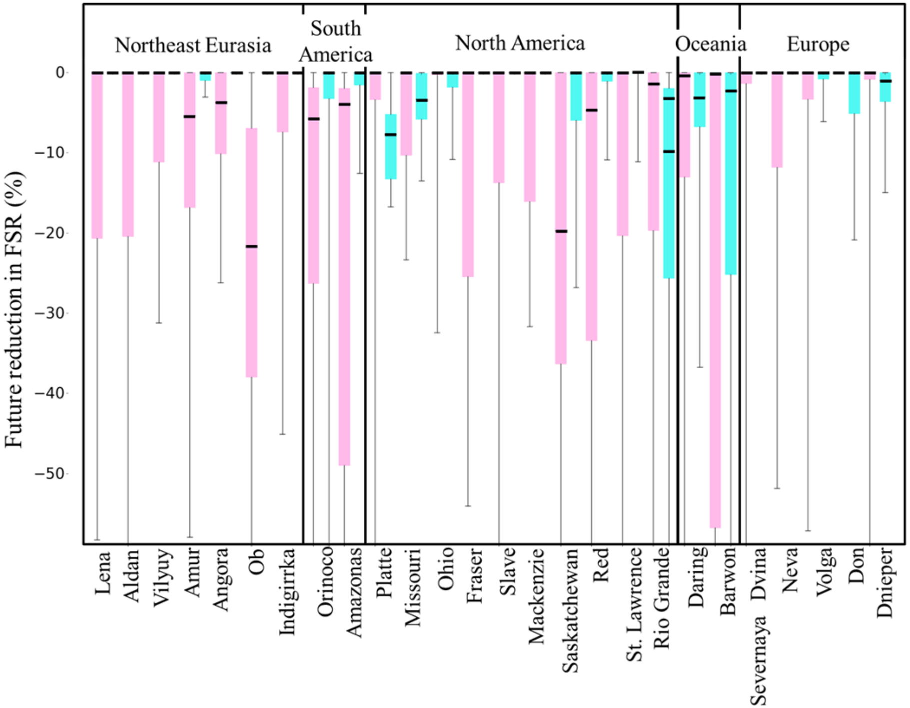

Fig. 2. Box plot of median value of future reductions in fish species richness by Iwasaki's- (pink color box) and Xenopoulos methods (blue color box) at the 26 river basins. The height of each box indicates the interquartile range (75th–25th percentile) and bold line within each box indicates the median value. The solid thin lines represent the maximum and minimum of the reduction in fish species richness for all of the atmosphere–ocean general circulation models.

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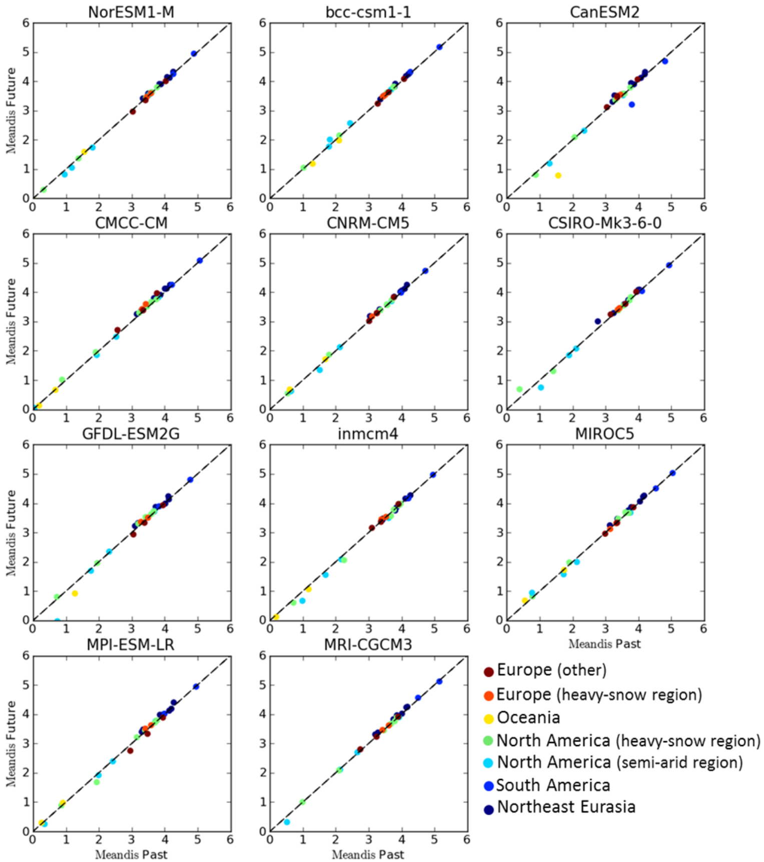

Fig. A1. Comparisons of mean river discharge (Meandis) between past and future in each of the 11 coupled atmosphere–ocean general circulation models.

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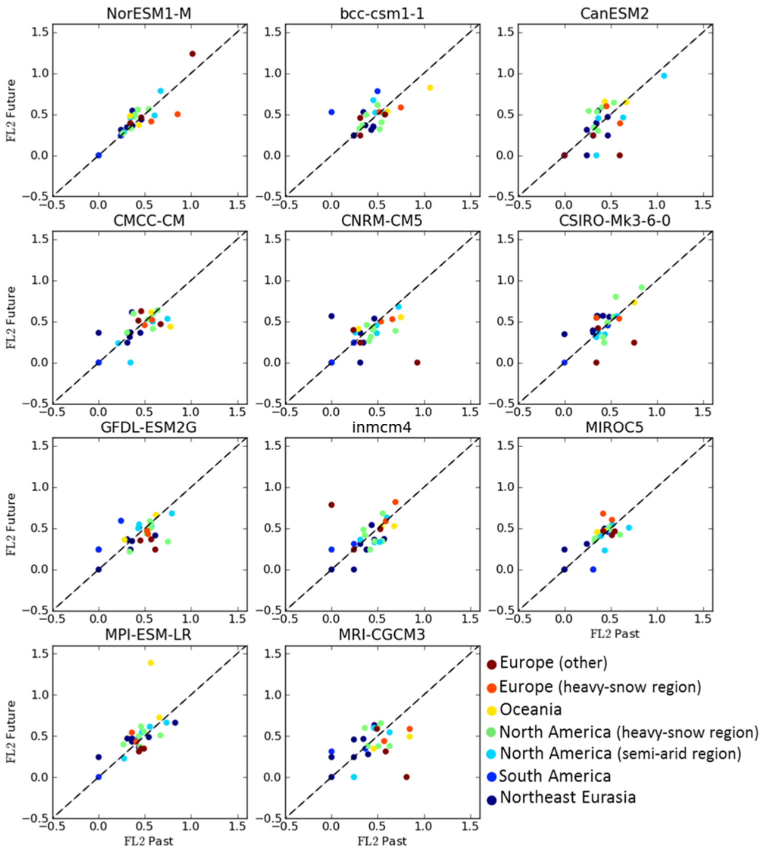

Fig. A2. Comparisons of coefficient of variation of low flow (FL2) between past and future in each of the 11 coupled atmosphere–ocean general circulation models.

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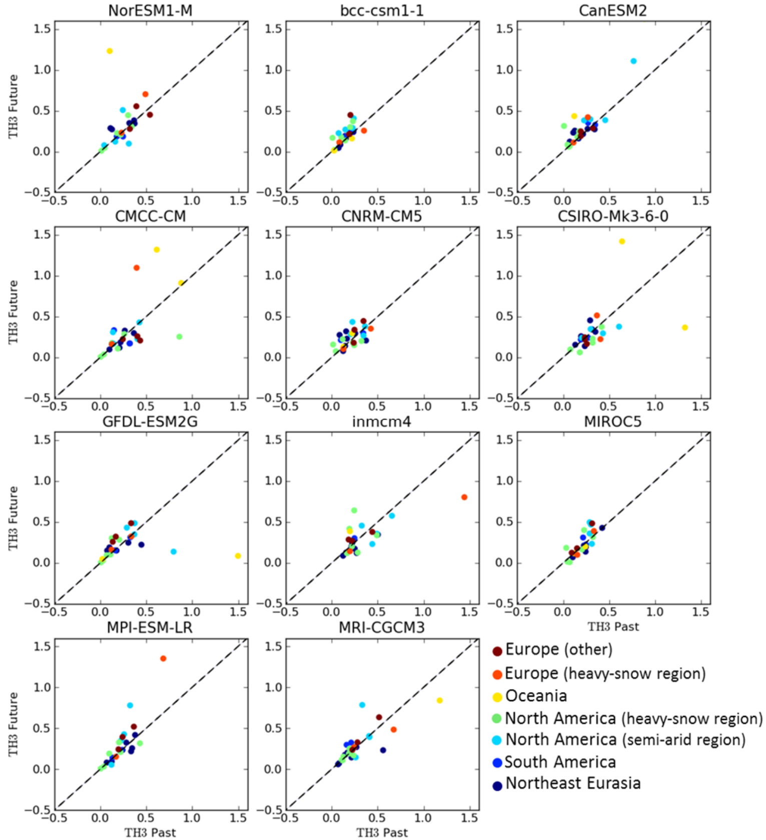

Fig. A3. Comparisons of maximum proportion of the year during which no 1.67 yr floods have ever occurred (TH3) between past and future in each of the 11 coupled atmosphere–ocean general circulation models.

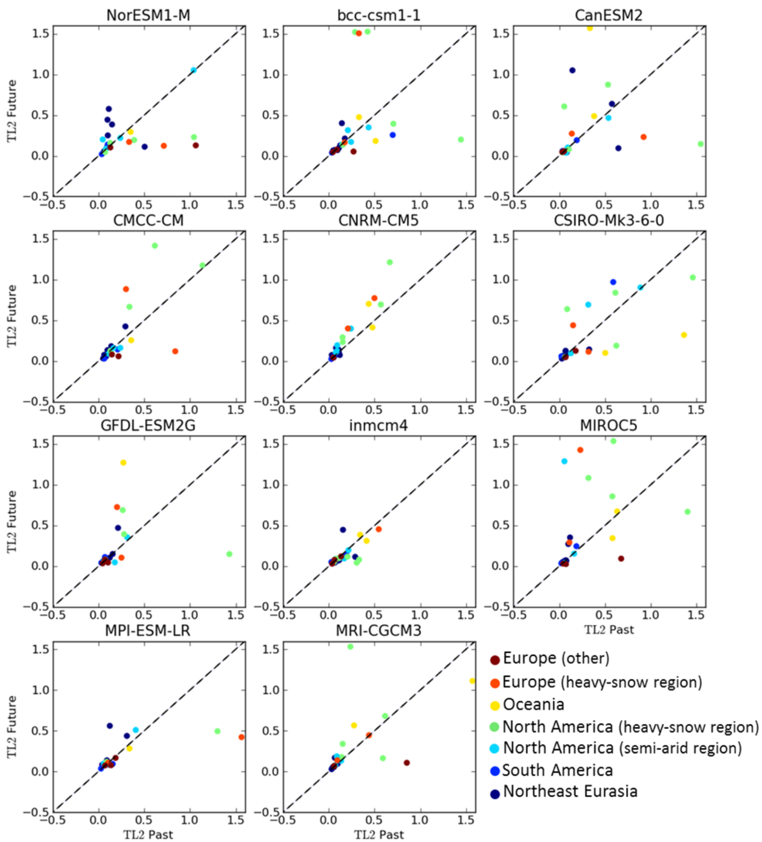

Fig. A4. Comparisons of coefficient of variation in the Julian date of annual minimum flow (TL2) between past and future in each of the 11 coupled atmosphere–ocean general circulation models.

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Potential reduction in fish species richness due to flow alteration

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