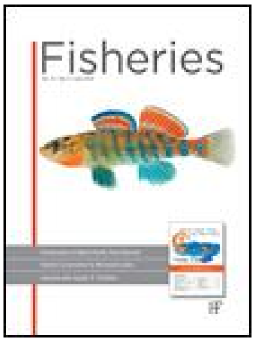

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# International Perspectives on the Effects of Climate Change on Inland Fisheries

**Ian J. Winfield, Claudio Baigún, Pavel A. Balykin, Barbara Becker, Yushun Chen, Ana F. Filipe, Yuri V. Gerasimov, Alexandre L. Godinho, Robert M. Hughes, John D. Koehn, Dmitry N. Kutsyn, Verónica Mendoza-Portillo, Thierry Oberdorff, Alexei M. Orlov, Andrey P. Pedchenko, Florian Pletterbauer, Ivo G. Prado, Roland Rösch & Shane J. Vatland**

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INTERNATIONAL FISHERIES SECTION

# International Perspectives on the Effects of Climate Change on Inland Fisheries

**Ian J. Winfield**
Lake Ecosystems Group, Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster, Lancashire LA1 4AP, U.K. E-mail: ijw@ceh.ac.uk

**Claudio Baigún**
Instituto de Investigación e Ingeniería Ambiental (3iA), Universidad Nacional de San Martín, Gral. San Martín, Buenos Aires, Argentina

**Pavel A. Balykin**
Southern Scientific Center of the Russian Academy of Sciences, Rostov-on-Don, Russia

**Barbara Becker**
Programa de Pós-Graduação em Biologia de Vertebrados, Pontifícia Universidade Católica de Minas Gerais, Belo Horizonte, Minas Gerais, Brazil

**Yushun Chen**
Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan, Hubei, China

**Ana F. Filipe**
Centro de Investigação em Biodiversidade e Recursos Genéticos, Universidade do Porto. Campus Agrário de Vairão, Vairão, Portugal; Centro de Ecologia Aplicada, Instituto Superior de Agronomia, Universidade de Lisboa, Tapada da Ajuda, Lisboa, Portugal

**Yuri V. Gerasimov**
I. D. Papanin, Institute for Biology of Inland Waters, Russian Academy of Sciences, Yaroslavl Region, Russia

**Alexandre L. Godinho**
Fish Passage Center, Federal University of Minas Gerais, Minas Gerais, Brazil

**Robert M. Hughes**
Amnis Opes Institute and Department of Fisheries & Wildlife, Oregon State University, Corvallis, OR

**John D. Koehn**
Arthur Rylah Institute for Environmental Research, Department of Environment, Land, Water & Planning, Heidelberg, VIC, Australia

**Dmitry N. Kutsyn**
Southern Scientific Center of the Russian Academy of Sciences, Rostov-on-Don, Russia

**Verónica Mendoza-Portillo**
Colección Nacional de Peces, Instituto de Biología, Universidad Nacional Autónoma de México, México, Distrito Federal, México

**Thierry Oberdorff**
UMR 'BOREA' CNRS 7208/IRD 207/MNHN/UPMC, UAG, UNICAEN, Muséum National d'Histoire Naturelle, Paris, France

**Alexei M. Orlov**
Russian Federal Research Institute of Fisheries and Oceanography, Moscow, Russia; A. N. Severtsov Institute of Ecology and Evolution, Russian Academy of Science, Moscow, Russia; Department of Ichthyology, Faculty of Biology, Dagestan State University, Makhachkala, Russia

**Andrey P. Pedchenko**
Berg State Research Institute on Lake and River Fisheries, Saint-Petersburg, Russia

**Florian Pletterbauer**
Institute of Hydrobiology and Aquatic Ecosystem Management, University of Natural Resources and Life Sciences Vienna (BOKU), Vienna, Austria

**Ivo G. Prado**
Fish Passage Center, Federal University of Minas Gerais, Minas Gerais, Brazil; Pisces-Consultoria e Serviços Ambientais, Lavras MG, Brazil

**Roland Rösch**
LAZBW, Fisheries Research Station Baden-Wuerttemberg, Langenargen, Germany

**Shane J. Vatland**
Research Division, Department of Fisheries Resources Management, Nez Perce Tribe, Joseph, OR

## INTRODUCTION

A range of perspectives is presented from the International Fisheries Section of the American Fisheries Society on climate change effects on inland fisheries from standing and flowing waters in Africa, Asia, Australia, Europe, and Latin America.

Many of the world's inland fisheries face common threats, such as eutrophication, overfishing, species introductions, and water development projects (Youn et al. 2014), which have essentially local solutions. However, most fisheries also face effects from the inherently global problem of climate change, which only can be understood and ultimately managed from a truly international perspective. The potential extent and range of such effects were illustrated by Xenopoulos et al. (2005), who, assuming the A2 model for climate change, predicted a loss of 0% to 75% of the fish species in a variety of the world's river basins but with an uncertain time lag (Tedesco et al. 2013). Here, we provide a range of perspectives from the International Fisheries Section of the American Fisheries Society on climate change effects on inland fisheries from standing and flowing waters in Africa, Asia, Australia, Europe, and Latin America.

## AFRICA

Most tropical fishes are eurythermal and able to tolerate high temperatures, and most climate change scenarios predict little temperature increase in tropical Africa. Consequently, relatively small effects might be expected. However, many tropical fishes live in waters with low dissolved oxygen levels, where temperature fluctuations approach upper lethal limits (Ficke et al. 2007). Thus, temperature increases of only 1°C to 2°C are likely to affect swimming ability, growth rates, and reproduction, which in turn are likely to affect wild fish and aquaculture production. Fish species extinctions due to reduced water availability arising from climate change in arid and semi-arid regions of northern Africa are very likely before the end of this century (Tedesco et al. 2013).

Even large African lakes with considerable buffering capacities are likely to be affected by climate change. For example, the fishery catch of Lake Naivasha in Kenya is strongly correlated with water level (Hickley et al. 2002), and water level is likely to be affected by anticipated reductions in precipitation. Similar impacts of climate change are also anticipated in Lake Victoria (East Africa), where changes in interannual and interseasonal variability in rainfall and temperature could affect the survival of aquatic life, increasing the variability of fish catches (Johnson 2009; Sewagudde 2009).

## ASIA

Climate change may affect the hydrology and fisheries of inland waters through increased precipitation, air temperature, and glacier melting in the Qinghai–Tibet Plateau (QTP). The QTP has many lakes and contains the glacier-fed headwaters of the Yangtze, Yellow, and Mekong rivers. The QTP has warmed in recent decades (e.g., Wang et al. 2015; Yang et al. 2015), stimulating increased glacial melting (Krause et al. 2010; Wang et al. 2013). In some QTP regions, increased precipitation may have affected runoff more than increased air temperature (e.g., Qian et al. 2014). In lakes, fish may need to adapt to habitat changes associated with rising lake levels and altered thermal stratification and mixing. In rivers, particularly the headwaters, increased discharge may change local habitat and deliver more terrestrial inputs downstream, with eventual effects on riverine fisheries.

The Caspian Sea is the world's largest inland sea, and a century-long shift in the abundance and composition of its fishery is correlated with a change in the local climate and sea environment. Specifically, increased air temperatures coupled with decreased precipitation and winter ice covers are associated with increased salinity and decreased sea level. From 1900 to 1933, annual fish catches in the Caspian Sea were often over 600,000 tons. Semi-anadromous (Vobla *Rutilus caspicus*, Common Bream *Abramis brama*, Pikeperch *Sander lucioperca*, Common Carp *Cyprinus carpio*) and anadromous (sturgeons, shads, Inconnu *Stenodus leucichthys*) fishes made up 79% and 16%, respectively, of the catch (Kuranova and Moiseev 1973). In the first years of the 21st century, catches of semi-anadromous and anadromous fishes declined dramatically and are significantly correlated with reduced Volga River discharges into the sea, lower sea levels, and higher salinities (Zhidovinov et al. 1985; Katunin and Strubalina 1986).

Inland fisheries occur across most areas of the Asian part of Russia and are particularly important, susceptible to climate change, and well-studied in Lake Baikal (Siberia). The most important fisheries species in this lake is Baikal Omul *Coregonus migratorius*, where catches increase 4 to 5 years after high water levels (Smirnov et al. 2015). There is a strong negative correlation between ice cover in the Arctic Ocean in the second half of August and Baikal Omul catches (Figure 1). During periods of low winter temperatures and long ice cover, conditions for Baikal Omul production improve because of increases in river flow, lake level, and subsequent juvenile survival (Smirnov et al. 2015).

## AUSTRALIA

Australia is a large, dry continent that spans tropical to temperate zones. Its freshwater fishes and their habitats have suffered considerable degradation in many regions, leading to range reductions and reduced and fragmented populations. Consequently, a large proportion of Australia's endemic freshwater fishes are of conservation concern. Rainfall and river discharge patterns are highly variable with increasingly unpredictable intense droughts and floods forecasted (Hobday and Lough 2011). Such changes combined with other pressures pose serious threats to fishes and fisheries.

Though climate change may affect fishes directly (e.g., effects of increased temperatures on reproduction and early life stages), changes in water availability and reliability alter freshwater habitats and indirectly affect fishes and fisheries (Morrongiello et al. 2011). Changes in fish distributions are predicted (Bond et al. 2011), but there are limited opportunities for species to move upstream to cooler higher altitudes because Australia has few high mountains.

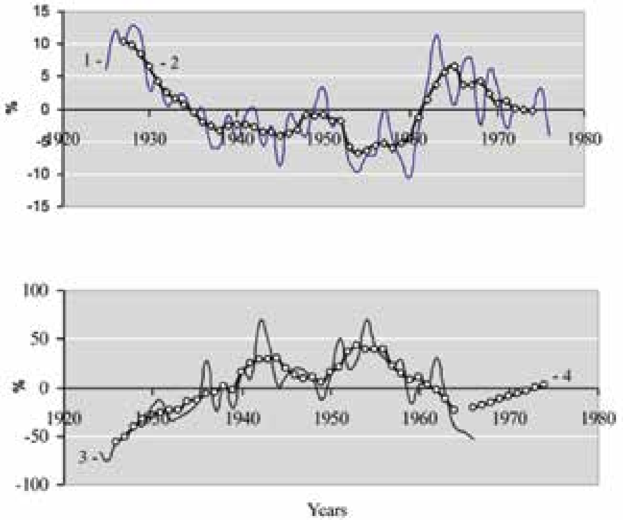

Figure 1. Square of Arctic Ocean ice cover in the second half of August as a percentage deviation from the mean for 1925 to 1976 (upper panel) and annual Baikal Omul commercial catches in feeding areas as a percentage deviation from the mean for 1925 to 1966 (lower panel). Lines 1 and 3 are 5-year means, and lines 2 and 4 are annual means (after Smirnov et al. 2015).

Climate-driven changes to popular recreational fisheries may have significant economic and social impacts, as well as indirect effects causing unexpected outcomes (Koehn et al. 2011). This complexity presents considerable challenges for water resource management (Kingsford 2011; Lester et al. 2011), within which prioritization must be given to the most vulnerable species, locations, and ecosystems (e.g., Barred Galaxias *Galaxias fuscus*; Crook et al. 2010). There is still considerable work to do in adapting management to the changed climate regime of Australia. The management of freshwater fishes under climate change must be undertaken in conjunction with existing stressors, including fisheries management and reforms to water extraction (Koehn 2015).

## EUROPE

Europe contains great variability in climates and hydrological regimes, from northern alpine to southern Mediterranean; those regions are expected to be affected differently by climate change (Arnell 1999). A general reduction of annual discharge in the southern regions and an increase in the northern and higher altitude regions are anticipated. The duration, frequency, and intensity of floods and droughts will be exacerbated in the south (Figure 2), and runoff increases in winter and flow decreases in spring will be more frequent in northern and higher altitude areas (Arnell 1999; Christensen and Christensen 2003; Filipe et al. 2013a).

Fishes are expected to be affected strongly by climate change, tending toward local extirpations or displacements to higher elevations and more northern latitudes (Filipe et al. 2013a; Pletterbauer et al. 2016). This implies a decrease in local species richness and major changes in the structure of assemblages for some regions, with the most favored species being those that are alien or common and having low conservation or commercial importance (Buisson et al. 2008). For one of the most threatened species, Brown Trout *Salmo trutta* (Freyhof 2010), distribution forecasts for the Ebro, Elbe, and Danube river basins indicate that 64% of stream reaches will become unsuitable by the 2080s, with the highest risk of extirpation in the Elbe Basin (Filipe et al. 2013b). The greatest changes in fish assemblages are expected for the southern regions by the 2050s and 2080s, whereas boreal assemblages will change less over the same periods (Tedesco et al. 2013; Pletterbauer et al. 2015).

Fisheries provide important food sources and recreational opportunities throughout most of Europe and undoubtedly will be affected by climate change. Such changes will be particularly intense in areas such as the southern regions, which host many endemic and threatened fishes that already are under great stress from a range of anthropogenic pressures (Smith and Darwall 2006). Those pressures must be successfully managed along with restoration of stream connectivity, establishment of conservation areas, and improved water infrastructure planning (Hermoso et al. 2015a, 2015b).

Climate change effects also are likely in the European part of Russia, including the Great Lakes of Ladoga, Onega, Ilmen, and Peipsi, where fisheries target whitefishes (Coregonidae), Burbot *Lota lota*, European Perch *Perca fluviatilis*, Northern Pike *Esox lucius*, Roach *Rutilus rutilus*, and other species (Kudersky and Ivanov 2011). Catch dynamics depend on climatic factors associated with increasing frequencies of W- and E-types of atmospheric circulation over the North Atlantic (Dubravin and Pedchenko 2010; Pedchenko 2011). In particular, more frequent E-type atmospheric circulation (low winter temperatures and long ice cover) is consistent with the dynamics of the total fish catch (Pedchenko, in press). Similar species are exploited in Rybinsk Reservoir, together with European Smelt *Osmerus eperlanus* and the invasive Black and Caspian Sea Sprat *Clupeonella cultriventris* (Gerasimov 2015). Since 1995, freezing-over has shifted from early November to late December (Litvinov and Roshchupko 2010), coinciding with a decline of coldwater species including Burbot and European smelt and an increase in Black and Caspian Sea Sprat. Growth rates of Burbot and other coldwater species have decreased, and warming-induced lowered oxygen availability has reduced benthic species such as Ruff *Gymnocephalus cernuus* (Wrona et al. 2006; Rijnsdorp et al. 2009). Like the Caspian Sea, the Azov Sea has been affected by increased air temperatures, decreased precipitation and winter ice covers, increased salinity, and decreased level, resulting in reduced commercial catches of Pikeperch and Common Bream (Goptarev et al. 1991).

In central Europe, the transnational Lake Constance of Germany, Switzerland, and Austria has a long history of inland fisheries, particularly for European Whitefish *Coregonus lavaretus* and European Perch. Over the last 40 years, water temperature has increased by about 1.5°C (Jeppesen et al. 2012), and populations of several species including European Whitefish (Thomas et al. 2010) and European Perch (Eckmann et al. 2006) have changed. Recently, fisheries yields have decreased drastically (Rösch 2014), and in 2015 yield fell by approximately 50% from the already low yield of 2014.

**Figure 2. The Ardila River in the Guadiana Basin, southern Portugal, in which the hydrological regime is highly seasonal and expected to become even more strongly affected by extreme floods and droughts. The two photographs were taken less than 1 day apart. Photo credit: Patrícia Tiago.**

Since about 2014, pelagic expansion of the lake's unexploited Threespine Stickleback *Gasterosteus aculeatus* has occurred and comprised more than 80% of pelagic fish in 2015, increasing the possibility of competition with European Whitefish for zooplankton and predation on larval European Whitefish and European Perch. Although corresponding information is not available for European Whitefish, preliminary data indicate that the 2014 year class of European Perch is extremely weak. The reason for this expansion of Threespine Stickleback into the pelagic zone is uncertain, but its recent observation in Lake Constance suggests that it may result at least in part from climate change.

In the United Kingdom, investigations of climate change effects have centered on the glacial lake of Windermere for three main reasons: co-occurrence of coldwater salmonids and warmwater cyprinids (Winfield et al. 2006), 70 years of fish population studies (e.g., Craig et al. 2015), and diverse fisheries, including historical commercial fisheries, which are rare in U.K. inland waters (Winfield 2016). As Windermere has warmed since the late 1980s, Arctic Charr *Salvelinus alpinus* has declined to the detriment of a traditional recreational fishery for this native salmonid (Figure 3), whereas introduced Roach has expanded to the benefit of angling for this warmwater cyprinid (Winfield et al. 2008). Similar declines in Arctic Charr have occurred in other U.K. lakes and are thought to have resulted in part from climate change (Winfield et al. 2010). Warming also has changed Windermere's Northern Pike population by shifting the length structure of this top predator toward an increased proportion of medium-sized individuals (Vindenes et al. 2014). Climate change also has had wider impacts on the Windermere ecosystem. Expansion of a pathogen of European Perch into the lake has acted synergistically with warming to induce a regime shift within its European Perch–Northern Pike interaction, triggering a trophic cascade (Edeline et al. 2016). Trophic levels have responded differently to warming such that Windermere's phytoplankton, zooplankton, and timing of European Perch spawning have become desynchronized (Thackeray et al. 2013). Finally, age–size truncation of European Perch induced by the pathogen has altered the consequences of this phenological mismatch for fish survival (Ohlberger et al. 2014).

Further north, the Arctic region has experienced more and faster climatic changes (warming waters and shorter durations of ice cover) than other European regions. Unlike temperate regions, warming in the Arctic is projected to improve conditions for anadromous and diadromous fishes such as Atlantic Salmon *Salmo salar* and Arctic Charr, as long as there is sufficient water in spawning and rearing streams (Nordeng 1983; Nielsen et al. 2013).

## LATIN AMERICA

Even more than Europe, Latin America contains great variability in climates and hydrological regimes, including alpine, desert, savannah, and tropical rainforest. Tropical parts of South America are likely to experience climate change effects similar to those already described above for tropical Africa, whereas alpine regions are expected to follow patterns similar to Europe. Reductions in annual precipitation are predicted for semi-arid regions, as well as in humid basins such as the Amazon Basin (Saatchi et al. 2012; Oberdorff et al. 2015). Semi-arid and humid regions are predicted to experience increased incidence of extreme precipitation periods (droughts, floods), meaning less predictable water bodies and artisanal fisheries (Marengo et al. 2013; Castello and Macedo 2016). Nonetheless, Xenopoulos et al. (2005) and Oberdorff et al. (2015) predicted very few losses of Amazon drainage fish species.

**Figure 3. Recreational anglers fishing traditionally for the threatened coldwater Arctic Charr *Salvelinus alpinus* on Windermere, UK. Photograph: Ian J. Winfield.**

In Mexico, Mendoza-Portillo (2014) conducted a fish faunal inventory in the Sierra Madre Occidental and related current distributions of 16 endemic species to current environmental conditions. Based on those relationships and future climate scenarios, she projected species distributions in 2020, 2050, and 2080. Precipitation seasonality, elevation, and minimum temperature of the coldest period explained most of the variability in current species distributions. Future climate (temperature and precipitation) predictions indicated a reduction of viable ranges for 10 of the 16 endemic species, displacement of viable range to the north for one species, and increased viable ranges for two species by 2080. She proposed making the Yaqui, San Pedro, Nazas, Santiago, and Bravo catchments priority conservation areas or refuges because they support the greatest fish faunal diversity in the Sierra Madre Occidental and have the greatest probability of suitable sites and the greatest potential for species migrations.

Reduction in rainfall and increase in temperature due to climate change will affect recruitment of migratory fishes in the Rio São Francisco (RSF), Minas Gerais, Brazil, with significant implications for fisheries. Aggregation of young migratory fishes occurs annually in the tailrace of Três Marias Dam on the RSF (Godinho and Kynard 2006). The number of fish involved varies yearly (Prado et al., in press); usually there are low numbers (<3 fish per cast net, i.e., 162 fish in 80 casts), but in some years there are large numbers (up to 27 fish per cast net, i.e., 878 fish in 33 casts). Since 2005, large aggregations have occurred only twice, and Prado et al. (in press) determined that those occurred only after two consecutive years of major floods (>5,000 $m^3/s$), which allowed for successful floodplain rearing and escape back to the river by young-of-the-year fish. Large aggregations did not occur in years of major flood preceded and/or followed by years of low or medium flood. Two consecutive years of major flood also increased the fish catch of RSF artisanal fishers from 3 kg/fisher/d to 25 kg/fisher/d only after two consecutive years of major flood (Godinho, unpublished data). Three kilograms of fish per day is insufficient for providing a livelihood for artisanal fishers. Marengo et al. (2012) predicted a 25% reduction in summer (fish spawning season) rainfall and annual mean temperature increase of 2.8°C for the RSF Basin by 2041–2070. Such reduction in summer rainfall will increase the recurrence interval of two consecutive years of major flood from 2 years to 10 years. Higher temperatures may increase mortality of young-of-the-year migratory fishes because of reduced nursery habitat area due to evaporation. Both climate changes suggest a drastic reduction in migratory fish recruitment to a level that will not support the thousands of professional fishers along the middle RSF.

The Furnas Reservoir is the fourth in a series of 12 dams on the Rio Grande, Minas Gerais, Brazil. Becker (2010) sampled fish from 1996 to 2009, which encompassed a severe drought in 1998 and 1999 that reduced the reservoir volume by 75% from 1999 to 2002. Annual catch per unit effort was negatively correlated with reservoir volume, and total species richness declined after the drought. However, the species richness and abundance of alien species increased during and after the drought, and the fish assemblage composition was significantly different following it. If predicted reductions in rainfall for the Rio Grande Basin and other Brazilian basins occur (IPCC 2015), similar fish assemblage changes are likely in other reservoirs.

Climate change in Argentinean inland waters will affect fish assemblages and most relevant target species and related fisheries. In Patagonia, predicted air temperature increase and precipitation reduction will reduce salmonid recreational fisheries because of reduced abundance and distribution of salmonids (Aigo et al. 2008). In turn, in the shallow Pampean lakes located in the east-central region of the country, Pejerrey *Odontesthes bonariensis* populations support very important recreational fisheries that could be affected because that species displays a temperature-dependent sex determination. Finally, in the La Plata Basin, increased water temperatures will promote the movement of Brazilian species southward and colonization by alien species currently inhabiting the upper basin. Flow augmentation and controls in response to increased temperatures and droughts are likely to have impacts on important artisanal and recreational fisheries mainly based on migratory species (Baigún 2015).

## CLOSING REMARKS

The preceding sections amply illustrate the diverse and pervasive effects of climate change anticipated and in many cases already experienced by inland fisheries around the world. The long-term studies of lake and river fisheries described above demonstrate the value of such studies for teasing out the mechanisms of fish and fisheries losses, whereas the spatially extensive studies demonstrate their importance for estimating the extent of predicted changes. Moreover, it is now known that our global climate temperatures and precipitation patterns will continue to change even if carbon emissions decline or cease altogether (IPCC 2015). Therefore, it is imperative that other anthropogenic pressures on inland fisheries (such as migration barriers, land use/abuse, fisheries overexploitation, excessive and poorly planned stocking of hatchery fish, alien species introductions, and physical and chemical habitat alteration), which are driven by continued human population and economic growth (Limburg et al. 2011), be limited to the maximum degree possible. In fact, Tedesco et al. (2013) reported that such pressures apparently explained more fish taxonomic biodiversity losses than did reduced habitat availability from climate change. Nonetheless, Xenopoulos et al. (2005) predicted greater taxonomic biodiversity losses from climate change than from water withdrawal in many rivers. However, in other rivers the reverse was predicted, for example in the Euphrates (Iraq), Kura (Azerbaijan), Murgab (Afghanistan), Murray-Darling (Australia), and Rio Grande (United States). Examining functional versus taxonomic diversity, Buisson et al. (2013) reported that climate change is expected to yield substantial declines in the functional diversity of fish assemblages. Clearly, the combined effects of climate change and existing anthropogenic pressures are major challenges to freshwater fish biodiversity and fisheries in much of the world (Travis 2003; Dudgeon et al. 2006), and the scope of this challenge necessitates both local and international solutions.

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INTRODUCED FISH SECTION

# What Can We Expect from Climate Change for Species Invasions?

**J. S. Rehage**
Earth and Environment Department, Florida International University, AHC 5 365, 11200 SW 8th Street, Miami, FL 33199.
E-mail: rehagej@fiu.edu

**J. R. Blanchard**
Earth and Environment Department, Florida International University, Miami, FL

The coming decades are expected to bring unprecedented climatological changes, with profound implications for inland fishes (Lynch et al., this issue), including for the many established nonnative (NN) species and new ones to invade (Diez et al. 2012; Sorte et al. 2013). Of interest are the effects of climate change on water resources: higher temperatures; changes to the timing, type, and intensity of precipitation; and alterations to extreme climates. For North American aquatic ecosystems, this translates to warmer waters, increased evapotranspiration, reduced ice cover, wetter conditions in the northern regions, drier conditions in the south, altered hydrological regimes, and changes to the frequency, timing and severity of extreme events, such as droughts and storms (Rahel and Olden 2008; Karl et al. 2009; Garcia et al. 2014). From the perspective of the Introduced Fish Section, major questions surrounding climate change center on (1) how will these changes tip the balance of fish invasions (i.e., under what conditions will NN species be favored) and (2) how do NN invasions interact with other anthropogenic stressors to affect native fish diversity?

## LOCAL VS. REGIONAL EFFECTS OF CLIMATE CHANGE ON FISHES

Changes to climate averages and extremes will present major challenges to native biodiversity, affecting habitat suitability at both local and regional scales (Garcia et al. 2014). Locally, these changing conditions will affect the physiology, morphology, and behavior of fishes and ultimately cascade to demographic parameters and the strength of interactions with other species (Garcia et al. 2014; Lynch et al., this issue). For instance, temperature is a "master" variable, with an overarching effect on physicochemical and biological processes in aquatic systems, particularly for ectothermic taxa such as