**Atlantic salmon, *Salmo salar***

**Background**

Atlantic salmon inhabit the temperate and arctic zones in the northern hemisphere. In the western North Atlantic the species ranges north to 70°N off western Greenland (Reddin and Shearer 1987), and from northern Quebec (http://www.iobis.org/) to Connecticut (Scott and Scott 1988) in North America. Comprehensive species accounts were given by Scott and Scott (1988) and Kocik and Friedland (2002). These fish are anadromous, living in fresh water for at least the first two years of life before becoming "smolts" and migrating to sea (in May and June in the Gulf of Maine) where they feed, grow, and mature over one or more years before returning to their natal river or stream from April to October to spawn. In Canadian waters salmon spawn in October and November. While at sea most salmon populations concentrate in the upper few metres of the water column (Dutil and Coutu 1988) of the Labrador Sea, the Grand Bank, and off west Greenland (Reddin and Shearer 1987). At sea younger salmon feed mainly on pelagic invertebrates and larger salmon on fishes. Because of their homing nature for reproduction salmon are divided into numerous distinct populations.

Atlantic salmon are in serious decline through much of their range (WWF 2001, National Marine Fisheries Service and U.S. Fish and Wildlife Service 2004). Threats are many (Cairns 2001, National Recovery Team 2002), but there is no consensus on the causes. On the U.S. coast Atlantic salmon have been extirpated in 42 of 50 historic salmon rivers, and are in critical condition in eight. Remaining populations in the Gulf of Maine have been listed as endangered by the federal government. The populations of many rivers of the inner Bay of Fundy have been designated as endangered by the Canadian Committee on the Status of Endangered Wildlife (COSEWIC 2005). On the Atlantic coast of Nova Scotia 14 rivers have completely lost their salmon runs and approximately 40 others have been seriously impacted by acid rain (DFO 2002). The historical North American commercial fishery for Atlantic salmon has been closed, and the highly popular recreational fishery has been closed (e.g. inner Bay of Fundy - Gross and Robertson 2005 MS) or is carefully controlled.

**Temperature limits, critical thresholds, vulnerability, and barriers to adaptation**

Sea surface temperatures within the salmon's current marine distribution range from a February minimum of -2.1ºC to an August maximum of 20.6ºC.

Atlantic salmon is a sub-arctic to boreal species. While at sea salmon inhabit waters of 2ºC (Danie, Trial and Stanley 1984) to 12ºC (Scott and Scott 1988), but prefer temperatures of 4ºC (Reddin and Shearer 1987) to 12$^{o}$C (Scott and Scott 1988). Lethal temperatures for at-sea fish are -0.7$^{\circ}$C (Saunders *et al.* 1975) and higher than 28ºC, though temperatures of 20ºC and higher reduce disease resistance and are therefore indirectly lethal. Juveniles at sea are found most commonly from 4-8ºC (Reddin and Shearer 1987).

In our sensitivity analysis salmon ranked the most vulnerable of the fishes examined, with the lowest mobility due to the stationary nature of its eggs and yolk sac larvae buried in gravel, with nearly the most stenothermal status, and with its northern distribution indicating a preference for cool temperatures. Juveniles represent the most vulnerable marine life stage to global warming since they usually are found in waters from 4-8ºC.

**Impacts**

Atlantic salmon are anadromous and are likely to be impacted by global warming in both their marine and fresh water habitats. Our investigation into the impact of climate change on the distribution of Atlantic salmon was restricted to the marine realm. However, salmon exhibit great vulnerability to climate change during their freshwater life. Impacts on freshwater juveniles (summarized by Friedland 1998) are mediated via higher water temperatures and reduced stream flow, and are most threatening to southern populations now experiencing near lethal thermal conditions in summer. Freshwater impacts on juveniles and returning adults include decreasing productivity and increasing mortality through effects on parr behaviour (Breau 2004), size (Swansburg *et al*. 2004), growth (Swansburg *et al*. 2002, 2004), smolt age (Minns *et al.* 1995), timing of smolt emigration (McCormick, *et al.* 1999), timing of adult spawning runs and headwater spawning accessibility (Swansburg *et al.* 2004), perhaps adult mortality (Moore *et al.* 2004), and physical and biological aspects of water quality (Friedland 1998).

The marine phase of Atlantic salmon is critical to post-smolt growth, survival, and thus abundance, and total salmon abundance is related to the availability and timing of favourable marine thermal habitat (Friedland 1998). Because most North American salmon populations spend their marine phase in the cold waters of the Labrador Sea, off western Greenland, and to a lesser extent on or near the Grand Bank, it seems plausible that global warming will result in earlier onset and greater availability of favourable thermal habitat in those waters, which should benefit salmon abundance. However, several model/scenario combinations in our analysis project a cooling trend in these waters, so favourable marine thermal habitat may actually decrease. It is also important to note that, whether they are cooling or warming, changing temperatures could alter orientation cues, routes, and timing for migrating adults and affect maturity schedules (Narayanan *et al.* 1995, Friedland *et al.* 2003). The results may be additive to other mortality effects, intensifying the impacts of climate change on Atlantic salmon (Friedland *et al.* 2003).

A 4ºC rise in global temperature will impact future distributions of Atlantic salmon in Canadian Atlantic waters. Results from all models and scenarios show potential loss of habitat to varying degrees in the southern part of the current range, from Cape Cod to the tail of the Grand Bank, and in the southern Gulf of St. Lawrence. No northward gain of habitat is indicated in our study area, which does not extend to salmon's northern limit. Marine stages of Atlantic salmon do not inhabit waters exhibiting the February minimum at that time, thus the predicted loss of habitat is due to a shift northward of the August maximum currently experienced by salmon in the southern part of their range.

During the salmon's marine phase our methodology is appropriate for 1) all marine stages of "inner Bay of Fundy" (iBoF) populations, whose post-smolts and adults appear to remain in Bay of Fundy, northern Gulf of Maine, and local marine waters to grow and mature, 2) all marine stages of populations migrating to the Grand Bank to grow and mature, and 3) migrating stages of all other western North Atlantic populations – post-smolts moving to west Greenland or Labrador waters (lying outside waters encompassed in this study) to grow and mature, and adults returning to fresh water to spawn (Amiro *et al.* 2003, Gross and Robertson 2005 MS, Reddin and Shearer 1987).

Potential impacts of the predicted northward shifts in SSTs due to a 4ºC increase in global temperature will vary among salmon populations. These impacts are presented below for populations likely to be affected.

*New England salmon populations*

SSTs in the Cape Cod and Georges Bank region will exceed those currently experienced by Atlantic salmon, presenting a barrier to adults of New England populations returning to fresh water in the summer and early fall to spawn. These fish may experience similar unfavourable conditions when migrating through Scotian Shelf waters. Migrating adults may be able to adapt to the changing thermal environment by migrating earlier or later in the year (Narayanan *et al.* 1995), but this could have adverse effects on spawning success.

Smolts emigrate from fresh water to the sea in late spring and summer (Hansen and Quinn 1998). Warmer temperatures in these southern waters should not be a barrier to smolts emigrating from adjacent rivers and estuaries, as either emigration is too early in the year for these critical temperatures, or if later, smolts already are acclimatized to warm water from their rivers and estuaries. However, Friedland *et al.* (2003) speculated that since spring air temperatures in the Gulf of Maine have increased over the past century, smolt emigrations, which are cued partly by temperature, may be earlier in the year. Earlier emigrations may be decoupled from the timing of oceanographic conditions to which Gulf of Maine salmon have adapted, affecting survival. Continued warming would exacerbate this situation. Should post-smolts attempt to avoid undesirable temperatures during marine migration, they must swim harder or further and may develop energy deficits (Friedland 1998).

*Nova Scotia salmon populations outside the Bay of Fundy*

Sea surface temperatures on the Scotian Shelf, to an extent varying with the model and scenario, will exceed the August maximum temperature limit currently experienced by salmon. This will present a barrier to migrating adults of Nova Scotia (and New England) salmon populations returning from the Grand Bank or more northern waters to spawn. Because salmon populations follow hereditary migration routes and timetables (Atlantic Salmon Federation 2004), it is questionable whether returning salmon will be able to alter them and spawn successfully. However, Narayanan *et al.* (1995) suggested that adults can shift their migration period and route if necessary. If post-smolts swim through the warmer Scotian Shelf offshore waters during their northward migration, they will be acclimatized to cooler marine temperatures. Thus, warmer Scotian Shelf waters will be a barrier during their seaward migration. Whether these post-smolts will alter their seaward migration routes or timing to avoid warmer SSTs is open to question**.** Yet if migration routes are altered, the extra swimming may create energy deficits (Friedland 1998).

Increasing spring air temperatures in Nova Scotia waters over the past century, as in the Gulf of Maine, may have caused smolts to emigrate from fresh water earlier in the year, with consequent phenological shifts in conditions to which Nova Scotia salmon have adapted (Friedland *et al.* 2003). Continued warming would exacerbate this situation. Most eastern shore Nova Scotia rivers have been impacted by acid precipitation (Ritter 2000). Warming of Scotian Shelf waters would be an additional stressor to salmon originating in Nova Scotia rivers.

*Inner Bay of Fundy salmon populations*

Inner Bay of Fundy salmon populations have experienced significant decline since 1989, primarily due to reduced marine survival (Amiro 2003).

During their marine phase iBoF salmon appear to remain in Bay of Fundy, northern Gulf of Maine, and local marine waters (National Recovery Team 2002 and references therein, Gross and Robertson 2005 MS). In all models except CCSR, scenario A2, critical SST maxima for salmon occur in waters southward of apparent post-smolt and adult marine range and migration routes. Therefore, the marine distribution of iBoF salmon should not be affected by climate-induced warming at the level investigated. This conclusion is in contrast to outcomes suggested by the National Recovery Team (2002), whereby migration routes may be altered and survival depressed.

Should the traditional marine range of iBoF populations include Scotian Shelf waters (Amiro *et al.* 2003), salmon may be able to shift their distribution to avoid the higher temperatures and still find suitable habitat. Narayanan *et al.* (1995) found evidence for such shifts in inshore Newfoundland waters in response to cold water temperatures. Alternatively, iBoF salmon may have warmer temperature preferences than salmon elsewhere in the North Atlantic (Amiro *et al.* 2003), reducing the impact of warming SSTs over the Scotian Shelf.

Climate change may have important indirect effects on iBoF salmon populations. Smolt emigrations into salt water may happen earlier in the year, decoupling from the timing of oceanographic conditions and impacting survival, as in other populations. Other negative impacts are predicted from their local and southern marine distribution (Irvine 2004). Marine survival will be reduced through food chain effects and increased competition and predation due to northward shifts in the distribution of warm water species. Freshwater survival will be reduced through possible adult migration delays due to reduced flows and increased temperatures, decreased spawning success because of increased sedimentation or scouring, and lower growth in summer because of poorer feeding conditions from increased summer temperatures and reduced flows.

*Gulf of St. Lawrence salmon populations*

Southern Gulf of St. Lawrence waters are relatively warm for the Canadian Atlantic, making them sensitive to climate change. We predict that August maximum SSTs in these waters will exceed critical values for Atlantic salmon in transit there. The southern Gulf drains some of Canada's most important Atlantic salmon rivers: the Miramichi, Kouchibouguac, Kouchibouguacis, Richibucto, Buctouche, Cocagne, and Shediac. The higher temperatures will be a significant barrier to migrating adults, blocking access to these rivers for spawning. It seems reasonable that increased SSTs will not be a barrier to smolts leaving fresh water, as in New England populations. However, the timing of smolts emigrating into the Gulf of St. Lawrence appears relatively unchanged over the past century, though spring water temperatures have been warming (Friedland *et al.* 2003). These authors found the warmer spring temperatures were associated with poorer salmon survival, apparently due to phenological shifts during first entry into salt water. Global warming would worsen the effect.

Dutil and Coutu (1988) found many post-smolts in nearshore waters of the northern Gulf of St. Lawrence from late summer to early fall at SSTs less than 20ºC. Juvenile salmon may utilize parts of the northern Gulf as a nursery area (F. Whoriskey, pers. comm.). We estimate that August surface-water maxima for the northern Gulf generally will not exceed salmon's critical maximum of approximately 20ºC, thus the presence of post-smolts there should be unaffected.

*Various salmon populations*

The tail of the Grand Bank is another location where global warming will create unfavourable August surface temperatures for salmon. These temperatures will create a barrier of warmer water to the migration of post-smolts or adults moving to or from the Labrador Sea or western Greenland waters. Some Atlantic salmon spend their marine phase on the tail of the Grand Bank, and may be able to shift their distribution to avoid the higher temperatures and still find suitable habitat.

Free-living larvae of the nematode *Anisakis simplex*, a parasite of Atlantic salmon (Margolis and Arthur 1979), are pelagic and widespread in Canadian Atlantic waters (Brattey and Clark 1992). These larvae experience declining survival at 10ºC, and cannot survive 13ºC or higher (Hojgaard 1998). Therefore, surface waters from Newfoundland southward will become less hospitable to this parasite during summer and fall with global warming.

**Economic impacts**

The temperature regime shifts predicted herein may affect all aspects of the marine phase of Atlantic salmon – post-smolt migration, feeding and growth, competition for resources or predation, adult spawning migration, and ultimately survival of individuals and populations. There likely will be no impact on commercial salmon fisheries as they are closed throughout the western North Atlantic and have little chance of reopening in the coming decades. Climate change impacts on the fish probably will preclude recovery of the stocks to levels supporting commercial fisheries. However, the freshwater recreational salmon fishery is very important in Canada, and could be impacted to varying degrees. A warming climate will result in more frequent temporary closures of rivers to fishing due to warm water temperatures (Dempson *et al*. 2001). The famous fisheries of the rivers entering the southern Gulf of St. Lawrence may be most affected, both in terms of river closures and overly warm marine waters impacting post-smolt survival or blocking adult migrations.

A warming climate may benefit aquaculture at the expense of wild iBoF salmon populations (Irvine 2004). In addition higher winter water temperatures may enable expansion of salmon aquaculture into waters of northern Nova Scotia, southern Newfoundland, and the Gulf of St. Lawrence (Frank *et al.* 1990) where the latter is not too warm in summer (Page and Robinson 1997, this study). Page and Robinson (1997) and Milewski (2002) summarized oceanographic variables having potential impact on salmon aquaculture with global warming.

The temperature regime shifts we foresee likely will seriously hinder attempts at the recovery of endangered Atlantic salmon populations, and the restoration of historic salmon runs where populations have been extirpated.

**References:**

Amiro, P.G. 2003. Population status of inner Bay of Fundy Atlantic salmon (*Salmo salar*), to 1999. Canadian Technical Report of Fisheries and Aquatic Sciences No. 2488, 39 + v p.

Amiro, P.G., J.Gibson, and K. Drinkwater. 2003. Identification and exploration of some methods for designation of critical habitat for survival and recovery of inner Bay of Fundy Atlantic salmon (*Salmo salar*). Canada Department of Fisheries Oceans.

Brattey, J., and K.J. Clark. 1992. Effect of temperature on egg hatching and survival of larvae of *Anisakis simplex* B (Nematoda: Ascaridoidea). Canadian Journal of Zoology 70: 274-279.

Atlantic Salmon Federation. 2004. http://www.asf.ca/Overall/atlsalm.html.

Breau, C. 2004. The effects of high water temperatures on the ecophysiology and the behaviour of juvenile Atlantic salmon (*Salmo salar*). Proceedings of climate change impacts and adaptation: water resources and fisheries in New Brunswick. Moncton, New Brunswick, 15-16 March 2004.

Cairns, D.K. 2001. An evaluation of possible causes of the decline in pre-fishery abundance of North American Atlantic salmon. Canadian Technical Report of Fisheries and Aquatic Sciences No. 2358.

COSEWIC. 2005. Canadian species at risk. Committee on the Status of Endangered Wildlife in Canada. 64 p.

Danie, D.S., J.G. Trial, and J.G. Stanley. 1984. Species profiles: life histories and environmental requirements of coastal fishes and invertebrates (north Atlantic): Atlantic salmon. U.S. Fish and Wildlife Service Biological Services Program FWS/OBS-82/11.22. U.S. Army Corps of Engineers, TR EL-82-4. 19 p.

Dempson, J.B., M.F. O'Connell, and N.M. Cochrane. 2001. Potential impact of climate warming on recreational fishing opportunities for Atlantic salmon, *Salmo salar* L., Newfoundland, Canada. Fisheries Management and Ecology 8(1): 69-82.

DFO. 2002. The effects of acid rain on the Atlantic salmon of the Southern Upland of Nova Scotia. DFO Maritimes Regional Habitat Status Report 2000/2E, 19 p.

Dutil, J.-D., and J.M. Coutu. 1988. Early marine life of Atlantic salmon, *Salmo salar*, postsmolts in the northern Gulf of St. Lawrence. Fishery Bulletin 86: 197-212.

Frank, K.T., R.I. Perry, and K.F. Drinkwater. 1990. Predicted response of northwest Atlantic invertebrate and fish stocks to $CO_2$-induced climate change. Transactions of the American Fisheries Society 119: 353-365.

Friedland, K. 1998. Ocean climate influences on critical Atlantic salmon (*Salmo salar*) life history events. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 119-130.

Friedland, K., D.G. Reddin, J.R. McMenemy, and K.F. Drinkwater. 2003. Multidecadal trends in North American Atlantic salmon (*Salmo salar*) stocks and climate trends relevant to juvenile survival. Canadian Journal of Fisheries and Aquatic Sciences 60: 563-583.

Gross, M.R., and C.T. Robertson. 2005 MS. COSEWIC status report on Atlantic salmon Inner Bay of Fundy populations *Salmo salar*. February 28, 2005 draft report to the Committee on the Status of Endangered Wildlife in Canada, 44 p.

Hansen, L.P., and T.P. Quinn. 1998. The marine phase of the Atlantic salmon (*Salmo salar*) life cycle, with comparisons to Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 104-118.

Højgaard, D.P. 1998. Impact of temperature, salinity and light on hatching of eggs of *Anisakis simplex* (Nematoda, Anisakidae), isolated by a new method, and some remarks on survival of larvae. Sarsia 83: 21-28.

Irvine, J. 2004. Climate Change, Adaptation, and 'Endangered' Salmon in Canada. Proceedings of the Species at Risk 2004 Pathways to Recovery Conference, March 2-6, 2004, Victoria, B.C.

Kocik, J.F., and K.D. Friedland. 2002. Salmons and trouts. Family Salmonidae, p. 170-181. In: B.B. Collette and G. Klein-MacPhee (eds.). Bigelow and Schroeder's fishes of the Gulf of Maine, third edition. Smithsonian Institution Press, Washington and London. xxxiv + 748 p.

Margolis, L., and J.R. Arthur. 1979. Synopsis of the parasites of Fishes of Canada. Bulletin of the Fisheries Research Board of Canada No. 199. 269p.

McCormick, S.D., R.A. Cunjak, B. Dempson, M.F. O'Dea, and J.B. Carey. 1999. Temperature-related loss of smolt characteristics in Atlantic salmon (*Salmo salar*) in the wild. Canadian Journal of Fisheries and Aquatic Sciences 56(9): 1649-1667.

Milewski, I. 2002. Climate change and salmon aquaculture in the Gulf of Maine/Bay of Fundy: Some implications. Symposium: Climate Change and Fisheries in the Gulf of Maine, Sierra Club National Marine Wildlife and Habitat Committee, April 5, 2002. www.sierraclub.org/marine/fisheries/.

Minns, C.K., R.G. Randall, E.M.P. Chadwick, J.E. Moore, and R. Green. 1995. Potential impact of climate change on the habitat and population dynamics of juvenile Atlantic salmon (*Salmo salar*) in eastern Canada. In: Beamish, R.J. (Ed.). Climate change and northern fish populations. Canadian Special Publcations of Fisheries and Aquatic Sciences 121: 699-708.

Moore, D., D. Caissie, J. Hayward, and C. Breau. 2004. Towards an understanding of the associations between adult Atlantic salmon mortalities and environmental conditions in fresh water. Proceedings, Climate change impacts and adaptation: water resources and fisheries in New Brunswick, Moncton, N.B., 15-16 March 2004.

Narayanan, S., J. Carscadden, J.B. Dempson, M.F. O'Connell, S. Prinsenberg, D.G. Reddin, and N. Shackell. 1995. Marine climate off Newfoundland and its influence on salmon (*Salmo salar*) and capelin (*Mallotus villosus*). Canadian Special Publications of Fisheries and Aquatic Sciences 121: 461-474.

National Marine Fisheries Service and U.S. Fish and Wildlife Service. 2004. Draft recovery plan for the Gulf of Maine distinct population segment of Atlantic salmon (*Salmo salar*). National Marine Fisheries Service, Silver Spring, MD.

National Recovery Team for Inner Bay of Fundy Atlantic Salmon Populations. 2002. National Recovery Strategy for Inner Bay of Fundy Atlantic Salmon (*Salmo salar*) Populations. National Recovery Strategy, Recovery of Nationally Endangered Wildlife (RENEW), Ottawa. 57 pp.

Page, F.H., and S.M.C. Robinson. 1997. Climate variability and aquaculture. In: Shaw, R.W. (Ed.). Proceedings, Climate variability and climate change in Atlantic Canada, Halifax, N.S., 3-6 December 1996. Occasional Reports of Environment Canada No. 9: 215-219

Reddin, D.G., and W.H. Shearer. 1987. Sea-surface temperature and distribution of Atlantic salmon in the northwest Atlantic Ocean. American Fisheries Society Symposium 1: 162-275.
Ritter, J. 2000. The effects of acid rain on Atlantic salmon of the Southern Upland of Nova Scotia. DFO Maritimes regional habitat status report 2000/2E, 19 p.
Saunders, R.L., B.C. Muise, and E.B. Henderson. 1975. Mortality of salmonids cultured at low temperature in sea water. Aquaculture 5(3): 243-252.
Scott, W.B., and M.G. Scott. 1988. Atlantic fishes of Canada. Canadian Bulletin of Fisheries and Aquatic Sciences No. 219, 731 p.
Swansburg, E.O., G. Chaput, D. Moore, D. Caissie, and N. El-Jabi. 2002. Size variability of juvenile Atlantic salmon: links to environmental conditions. Journal of Fish Biology 61(3): 661-683.
Swansburg, E.O., G. Chaput, N. Savoie, C. Hebert, N. El-Jabi, and D. Caissie. 2004. Proceedings, Climate change impacts and adaptation: water resources and fisheries in New Brunswick, Moncton, 15-16 March 2004.
WWF. 2001. The status of wild Atlantic salmon: a river by river assessment. World Wildlife Fund.