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# Multidecadal North Atlantic climate variability and its effect on North American salmon abundance

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[1] Climate variability is now known to play a key role in the abundance of marine fisheries, and must be accounted for to implement sustainable management strategies. We show that North American Atlantic salmon abundance has fluctuated in parallel with the Atlantic Multidecadal Oscillation (AMO); a basin-wide, low frequency climate mode producing cold-warm-cold sea surface temperatures over the last century. During the AMO warm (cool) phase salmon abundance is lower (higher). Changes in sea surface temperature associated with the AMO are most pronounced in the winter season near the Grand Banks of Newfoundland, a known overwintering area for salmon and an important time for determining survival. A moratorium on salmon fishing was established in 1992, but has so far contributed few signs of improvement in stock size. This may be explained by a shift in the AMO to a positive phase, producing persistently warm temperatures in the marine environment. Our findings show that a continued warming near the Grand Banks of Newfoundland will have a detrimental impact on this already depleted stock despite the reduction in commercial fishing. **Citation:** Condron, A., R. DeConto, R. S. Bradley, and F. Juanes (2005), Multidecadal North Atlantic climate variability and its effect on North American salmon abundance, *Geophys. Res. Lett.*, *32*, L23703, doi:10.1029/2005GL024239.

## 1. Introduction

[2] In the 1970s, the International Council for the Exploitation of the Sea (ICES) estimated that there were 1.5 million wild North American salmon in the Atlantic. By 2000, that number had declined by more than two-thirds to 0.5 million [*International Council for the Exploration of the Sea* (*ICES*), 2003]. At the southern end of the range, salmon populations in eight rivers in Maine, USA, and thirty-three rivers of the inner Bay of Fundy, Canada, have been listed as endangered species [*ICES*, 2003]. A moratorium on salmon fishing, established in 1992, has contributed to few signs of improvement in stock size; with numbers continuing to remain below historic levels [*ICES*, 2003].

[3] Over the last decade, there has been growing evidence to suggest that climate change strongly affects the productivity of many marine fisheries throughout the world oceans [*Parsons and Lear*, 2001; *Chavez et al.*, 2003]. Most of these links have been observed at decadal (and longer) timescales, when mortality signals are less obscured by interannual biotic variability [*Francis et al.*, 1998]. For example, on the west coast of North America, salmon abundance shows a strong link to interdecadal climatic variability [*Mantua et al.*, 1997; *Beamish and Bouillon*, 1993; *Francis et al.*, 1998; *Finney et al.*, 2002]. Twentieth century commercial Pacific salmon catch records reveal abrupt 'regime' shifts from high to low production lasting several decades that are strongly correlated to changes in the phase of the Pacific Decadal Oscillation (PDO) and Aleutian Low Pressure Index [*Mantua et al.*, 1997; *Beamish and Bouillon*, 1993]. These climatic shifts alter the circulation intensity of the subarctic gyre in the northeast Pacific which in turn regulates the amount of upwelled nutrients available for salmon growth and survival [*Brodeur and Ware*, 1992; *Francis et al.*, 1998].

[4] In contrast to the Pacific region, the majority of research in the North Atlantic has focused on the influence of the interannual North Atlantic Oscillation (NAO) on marine ecosystems [e.g., *Parsons and Lear*, 2001], with very little attention given to the importance of other climate modes. As such, the role that long-term climate variability plays in the survival of wild North American Atlantic salmon stocks is poorly understood [*Friedland et al.*, 1993]. Synchronous declines in the number of Atlantic salmon returning to their natal rivers to spawn, and stable production levels from monitored rivers point towards the marine phase of the salmon life-cycle as an important period for determining survival [*Ritter*, 1993; *ICES*, 2003]. Salmon from the entire North American Atlantic spawning range, from the Connecticut River, USA, to Ungava Bay, Canada, come together to feed in the Labrador Sea in the summer and autumn, before migrating to the southern Labrador Sea and northern Grand Banks to overwinter [*Reddin and Shearer*, 1987]. After the first winter at sea, a proportion of salmon, known as 1 sea-winter (1SW) or grilse, become sexually mature and return to their natal river to spawn. The remaining salmon return to feed in the Labrador Sea during the summer, and typically mature after a second winter (2SW) at sea. It is the overwintering period that appears to play a key role in dictating salmon survival [*Friedland et al.*, 1993; *Beamish and Mahnken*, 2001].

[5] Instrumental temperature records from the Northern Hemisphere over the twentieth century reveal distinct multidecadal (broadly 50–70 years) trends centered over the North Atlantic [*Schlesinger and Ramankutty*, 1994; *Mann et al.*, 1998; *Kaplan et al.*, 1998; *Delworth and Mann*, 2000; *Kerr*, 2000]. Anomalously cold conditions prevailed across the region from 1905–1925 and 1970–1990, with warmer conditions from 1940–1960. This long-term climate oscillation has been referred to by [*Kerr*, 2000] as the Atlantic Multidecadal Oscillation (AMO). The AMO has been

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linked to multi-year precipitation anomalies over North America, Atlantic hurricane formation, African drought frequency, and winter temperatures in Europe [*Enfield et al.*, 2001; *Folland et al.*, 1986; *Goldenberg et al.*, 2001].

[6] While relatively short and spatially limited instrumental datasets before 100–150 years ago make it hard to validate the multidecadal oscillation, the analysis of proxy data (e.g. tree rings, ice cores, coral etc) has given a more robust insight into the long-term variability of this dominant climate mode; a tree-ring based reconstruction of the AMO shows that low frequency, multidecadal variability has been a consistent feature of North Atlantic climate for the past five centuries [*Gray et al.*, 2004], The AMO was isolated by [*Mann et al.*, 1998] in global land air/sea surface instrumental and surface temperature proxy data through principal component analysis. The multidecadal climate mode is described by the fifth principal component, and has persisted with a periodicity of 50–90 years since at least AD1650. Two independent, naturally forced integrations of the GFDL coupled ocean-atmosphere model [*Delworth and Mann*, 2000] reproduced the observed AMO patterns of variability described by *Mann et al.* [1998], showing the fluctuations to be a result of variations in the intensity of the Atlantic thermohaline circulation.

[7] In this study we focus on the northwest Atlantic, defined here as 40°–70°N, 80°–30°W, as the entire life history of the salmon takes place within this domain. We examine how salmon abundance fluctuates with the oceanic AMO by binning catch weights according to the phase of the multidecadal mode (positive or negative) and by regression analysis of sea-surface temperature (SST) data, available to us as monthly means at a 5° latitude by 5° longitude resolution from 1910–1991 from *Kaplan et al.* [1998], against the AMO.

## 2. Datasets

[8] In this study, we use the multidecadal oscillation as derived by *Mann et al.* [1998] as a measure of the AMO for the twentieth century. We reconstruct salmon abundance from 1910–2000 using a combination of fisheries catch data [*ICES*, 2003; *May and Lear*, 1971; *Baum*, 1997] and modeled salmon abundance [*ICES*, 2003]. Catch data are used in this analysis, rather than productivity (catch + spawning escapement) or survival data, because it is the only abundance measure that has been systematically collected since 1910. From 1910–1960, we use the total catch weight from the historical Canadian [*May and Lear*, 1971] and U.S.A. [*Baum*, 1997] fisheries as a proxy for eastern North American Atlantic salmon abundance. After 1960, immature 1SW salmon of North American origin began to be landed in the West Greenland fishery [*Shearer*, 1992]. Prior to this, North American salmon would have returned home the following year as considerably heavier maturing 2SW fish, and would have either spawned in their natal river or would have been caught by the Canadian and/or U.S. fisheries [*ICES*, 2003]. For each metric ton (t) of immature 1SW North American salmon removed by the West Greenland fishery, the loss in catch weight to the Canadian and U.S. fisheries is estimated to have been between 1.47–2.00 t [*Shearer*, 1992]. To compensate for the weight gain that would have occurred during the home migration, we increase the total catch weight of salmon landed in West Greenland by the mean value of 1.735 t. We contend that, to a first-order approximation, catches are indicative of salmon abundance, because the observed changes are too large to represent changes in fishing intensity [*Friedland et al.*, 1993]. Furthermore, over 90% of the total numbers of salmon caught were landed in commercial rather than recreational salmon fisheries [*Marshall*, 1986]. Following the onset of fishing restrictions in 1992, we believe catch records no longer reflect salmon abundance, and therefore, we limit our catch record to the period 1910–1991. After 1991, we use the ICES prefisheries abundance data (PFA) available from 1971–2001. The ICES data are derived from a run-reconstruction model developed by the Working Group on North Atlantic salmon to estimate the size of the maturing salmon population at sea in a given year [*ICES*, 2003].

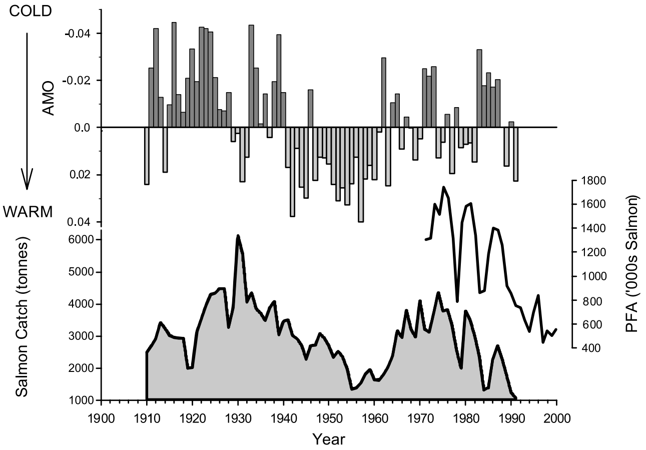

**Figure 1.** The AMO as reconstructed from Principal Component 5, North American Atlantic salmon catch, and Prefisheries Abundance (PFA). The scale on the AMO is reversed, with warm regimes shown in grey and cold regimes in dark grey.

## 3. Results

[9] The historical catch record of North American Atlantic salmon from 1910–1991 fluctuates in strong agreement with variations in the AMO (Figure 1), with a correlation coefficient of −0.41 ($p < 0.001$). North American salmon abundance was substantially higher during the two multidecadal cool periods (1905–1925 and 1970–1990), with catch weights averaging around 3200 t. The warm temperatures of the mid-century (1940–1960) were punctuated by lower abundance as shown by catch weights averaging 2700 t. The regression of sea-surface temperature data from *Kaplan et al.* [1998] shows anomalously cool SSTs dominate in the Gulf of St. Lawrence, Grand Banks of Newfoundland and Scotian Shelf during the cold phase of the oscillation with SSTs >−0.4°C below average. During the positive phase of the AMO, anomalously warm temperatures dominate much of the region, particularly on the Scotian Shelf and Grand Banks of Newfoundland, with temperatures +0.2°C above average.

[10] To understand how the AMO affects North American salmon abundance, Pearson's correlation was used to

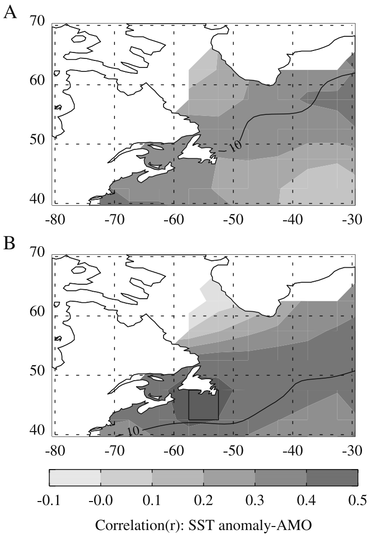

**Figure 2.** Seasonal correlations between summer (A) and winter (B) SST anomalies and the AMO for the northwest Atlantic. The box marks the location of the highest correlation (Box A in the text). The location of the 10°C temperature isotherm is shown to highlight the thermal southerly limit of the stock.

statistically compare temporal variations in the multidecadal oscillation to fluctuations in the study domain's summer (JJA) and winter (DJF) SSTs from 1910–1991 (Figure 2). The highest correlation is found during the winter in the vicinity of Newfoundland and the Grand Banks, where significant correlation coefficients of +0.44 ($p < 0.001$) are observed. Further north, in the Labrador Sea, the correlation is around zero and is not statistically significant. In summer the overall statistical correlation is much weaker than during the winter ($r = 0–0.1$), and no grid locations are found to be statistically significant. We approximate the southerly limit of the stock during the summer and winter based on an observed sharp reduction in commercial salmon catch above the 10°C SST isotherm [*Reddin*, 2002] (Figure 2). The position of the 10°C isotherm is reconstructed from the Levitus 1994 World Ocean Atlas [*Levitus and Boyer*, 1994], and lies in the southern Labrador Sea during the summer. To the north of this isotherm, the salmon stock is located in water temperatures showing no significant statistical correlation to the AMO. However, during the winter the southern limit of water temperatures frequently occupied by salmon in the marine environment encompasses those SSTs highly correlated with the phase of the AMO. We highlight the region of highest statistical correlation in Figure 2 with 'Box A', which is located over the Grand banks of Newfoundland and has an r-value >+0.4. The overlap of the high statistical correlation with water temperatures frequently occupied by salmon during the winter strongly supports the notion that the Grand Banks is an overwinter location for salmon [*Reddin and Shearer*, 1987] and that this time and location plays a critical role in influencing salmon abundance the following spring.

[11] Spatially averaged winter SSTs from Box A are smoothed with a two-year running mean to account for 1SW and 2SW salmon overwintering in this location and are statistically compared to the salmon PFA data from 1971–2001 (Figure 3). Over the last 30-years SSTs have risen dramatically in this location by more than +1.5°C, and correlate extremely well with the persistent decline in salmon abundance ($r = -0.81$, $p < 0.001$), accounting for over 65% of the recent decline.

## 4. Discussion

[12] The physical oceanographic conditions in Box A are highly influenced by the interaction between the cold, fresh Labrador Current and the warm, saline Gulf Stream, which creates a strong thermal gradient and productive frontal zone [*Murawski*, 1993]. Multidecadal fluctuations in the Labrador Current have been observed over the last century from moored buoys, and create two characteristic circulation modes on the Scotian shelf and Grand Banks [*Petrie and Drinkwater*, 1993; *Drinkwater et al.*, 1999]. The first mode is associated with an intensified flow of the Labrador Current and a southward migration of the north wall of the Gulf Stream, increasing the volume of fresh, cold Labrador Slope Water on the shelf. This reduces SSTs and produces conditions more conducive for survival. The second circulation mode is characterized by a reduction in the volume of cold Labrador Slope Water, the Gulf Stream positioned further northward, and less favorable conditions for survival.

[13] The variation in SSTs associated with the phase of the AMO are almost certainly too small to have directly influenced salmon survival over the last century. We speculate that SST variability associated with the AMO, affects salmon survival by altering the abundance, concentration, and location of key zooplankton species along with predator-prey relationships in the overwintering region. While a lack of in-situ observations in this location prevents us from determining a complete climate-productivity-salmon relationship, our study suggests that as salmon move south to

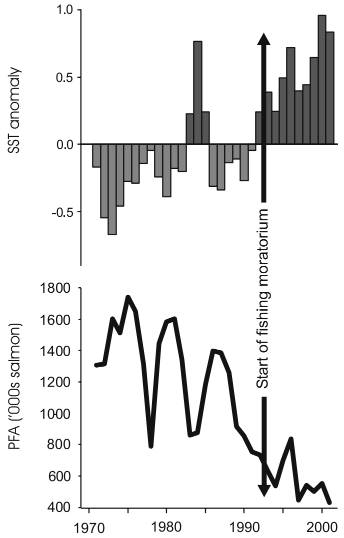

**Figure 3.** SST anomalies from Box A over the Grand Banks of Newfoundland during the winter and PFA from 1971–2001. The 1992 fishing moratorium highlights how temperatures in the salmon overwintering area on the Grand Banks have continued to warm since this period, coincident with a switch in the AMO to a positive, warm phase. The SSTs are smoothed with a two-year running. See color version of this figure at back of this issue.

overwinter near the Grand Banks, the AMO will play an increasingly dominant role in controlling survival.

[14] Since the early 1990s, anomalously warm SSTs have persisted over the Grand Banks of Newfoundland (Figure 3), with a remarkable increase in temperature of +0.87°C during this period. The persistent warming may be explained by an apparent shift in the AMO to a warmer, positive phase [*Enfield et al.*, 2001; *Gray et al.*, 2004]. The timing of this shift coincides with the moratorium on salmon fishing established in 1992, and may explain the lack of improvement in stock size despite the reduction in fishing pressure. If the warm phase of the AMO persists, marine temperatures in the overwintering environment could be set to warm for a further 25–30 years. If this is the case, we might not expect a recovery to the salmon stock until around the year 2025–2030, by which time the less productive marine conditions are likely to have had a detrimental impact on this already depleted stock. This, of cause, makes no account of increased warming due to anthropogenic activity.

[15] With rising temperatures in the marine environment creating increasingly less favorable conditions for salmon survival, especially at the southern end of the range, it is essential that resources are carefully managed to minimize the impact of climate change and ensure the long-term sustainability of this population. Over the last 30 years, $150 million alone was spent on stocking 68 million salmon to the Connecticut River in southern New England, over which time less than 0.01% of this total returned to spawn [*U.S. Salmon Assessment Committee*, 2000]. In this case, resources may be better spent on restoring natural freshwater habitats in order to minimize the impact of climate change. If the AMO continues to operate with the same variability then its influence on the abundance of North American Atlantic salmon in the marine environment could be forecast several years in advance, allowing fisheries managers to better spend resources to manage the remaining wild stocks.

[16] **Acknowledgment.** We would like to thank Frank Keimig at the University of Massachusetts for assistance in retrieving the sea surface temperature data.

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