CLIMATE CHANGE AND RIVERINE COLD WATER FISH HABITAT IN THE NORTHEAST: A VULNERABILITY ASSESSMENT REVIEW

Manomet Center for Conservation Sciences and the National Wildlife Federation

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A Report to the Northeastern Association of Fish and Wildlife Agencies and to the North Atlantic Landscape Conservation Cooperative

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Executive Summary

- Historically, much of the riverine cold water fish habitat in the Northeast has been lost due to anthropogenic stressors, particularly habitat destruction and reduced access to spawning areas by the installation of dams. This has been most marked in the southern part of the habitat's range in the northeastern states, where losses may be as high as 50%.

- Climate change confronts this habitat with a new and important stressor. As air temperatures continue to warm, waterways may also warm beyond the physiological tolerances of cold water fish such as brook trout, brown trout, and other salmonids. Also, the projected increased frequency and severity of extreme events (floods and droughts, for example) may pose significant risks to this habitat type.

- A number of scientific studies over the last two decades have confirmed that riverine cold water fish habitat in the Northeast (the 13 states from Maine in the north to Virginia and West Virginia in the south) is vulnerable to increasing temperatures.

- Earlier scientific studies concluded that the habitat was likely to be largely extirpated in the Northeast under even relatively modest warming scenarios. These studies arrived at this conclusion making assumptions that may now, with the collection of empirical field data, be less well supported. Specifically, the relationship between air temperature and water temperature in waterbodies was initially assumed to approximate unity. However, empirical measurements have demonstrated that this varies widely among and within streams and may be lower than the previously assumed value.

- Streams and rivers differ in their air water temperature ratios due to a number of factors, the most important of which are the presence or absence of shading riparian vegetation and the amount of discharge to the waterway from cool subterranean aquifers.

- The earlier studies may also have underestimated the abilities of some cold water fish species to adapt to changing stream conditions, either through evolutionary change or behavior modification.

- The main conclusion of this review is that riverine cold water fish habitat in the Northeast <u>is</u> indeed vulnerable to climate change, but may not be as vulnerable as earlier studies may have suggested.

- Most habitat loss due to warming in the Northeast may occur in the southern part of the habitat's range (for example, Virginia and West Virginia) and at lower elevations (for example, coastal plain cold water streams from Massachusetts north into Maine). Further north and at higher elevations, riverine cold water fish habitat is likely to persist for substantially longer than earlier studies had suggested.

- This review confirms that significant uncertainties still affect our ability to project the impacts of climate change on cold water fish habitat and populations. Foremost among these are uncertainties in assumptions about the relationships between changing air and water temperatures; the existence or lack of adaptive capacities in exposed fish; relationships between climate change and other non-climate stressors, such as diseases and parasites, which could affect fish populations; and the impacts of an increased frequency and severity of extreme climatic events. Another potentially important uncertainty may arise from situations where the water temperature increases are not sufficient to reach the upper physiological limit for the fish, but which still may elicit chronic affects on growth and reproduction. How would such changes affect stream carrying capacities? Finally, increasing water temperatures may, in addition to having direct impacts on fish, fragment their habitats at a watershed scale and jeopardize connectivity. Our understanding of this potential impact is still relatively poor.

- This review includes mitigation measures that can be taken to reduce the impacts of warming on cold water fish habitat. These actions include the preservation and restoration of riparian shading vegetation along vulnerable streams and the prevention or removal of impervious surfaces adjacent to streams. Removal of dams to increase access to upland spawning areas could also be effective.

Introduction

There is growing evidence that climate change is already harming fish and wildlife and other ecological resources in the northeastern United States.[1] These observed changes have occurred under a mean annual temperature increase of only about 1.6 ^{o}F – a relatively modest degree of change. In contrast, the situation confronting us over the rest of this century is not one of subtle climatic shifts; the degree of change that will occur is likely to be severe. In the Northeast, the Northeastern Climate Impacts Assessment (2006) warns us to expect a mean annual temperature increase of up to 6 ^{o}F by the end of the century if greenhouse gas levels in the atmosphere double (a relatively optimistic scenario given current emissions rates), or by up to 10 ^{o}F if a tripling occurs. With such drastic changes, the climate in the Northeast will resemble those that are now characteristic of North or South Carolina, respectively (NECIA, 2006). These changes will be accompanied by a greater frequency, duration and intensity of severe droughts and flooding, reductions in snowpack, increased invasions and impacts by pest and invasive species, and a global sea level rise of between 0.5 meters and 1.5 meters, inundating many northeastern coastal areas.

It is likely that many of the habitats and species that occur in the Northeast will be highly sensitive to the projected changes in climate. Indeed, we are already seeing ecological effects that may be triggered by the changing climate, including changes in the timing of ecological events and distribution shifts in organisms. Vulnerability assessments in the Northeast and elsewhere (Glick *et al*., 2011) indicate that many important habitats will be threatened by climate change, and may be lost entirely or greatly reduced in their extent or quality. We have reasonable grounds for expecting that cold water fish habitat may be one of the more susceptible fish and wildlife habitats in the Northeast to climate change.

If we are to anticipate and mitigate the potential impacts of climate change on organisms and their habitats it is vital that we understand their relative vulnerabilities. Over the last 3–4 years a formal organizational framework has been developed for evaluating the vulnerabilities of species and ecological systems to climate change (Glick *et al*., 2011). This framework assumes that the vulnerabilities of species or systems are a function of three main components: their exposure, sensitivity, and adaptive capacity (Figure 1).

Exposure – an estimate of how much change in climate (or other stressors) a species or system may be exposed to.

Sensitivity – the extent to which a species or system is likely to be responsive to or affected by changes in exposure.

[1] Changes to the flowering seasons of plants and migration seasons of fish, and range shifts in birds are all known to be already occurring in the Northeast. These are early harbingers of the much more severe effects that will occur in natural systems in the future

Adaptive capacity – the ability of a species or system to adapt to and accommodate changes in exposure to stressors.

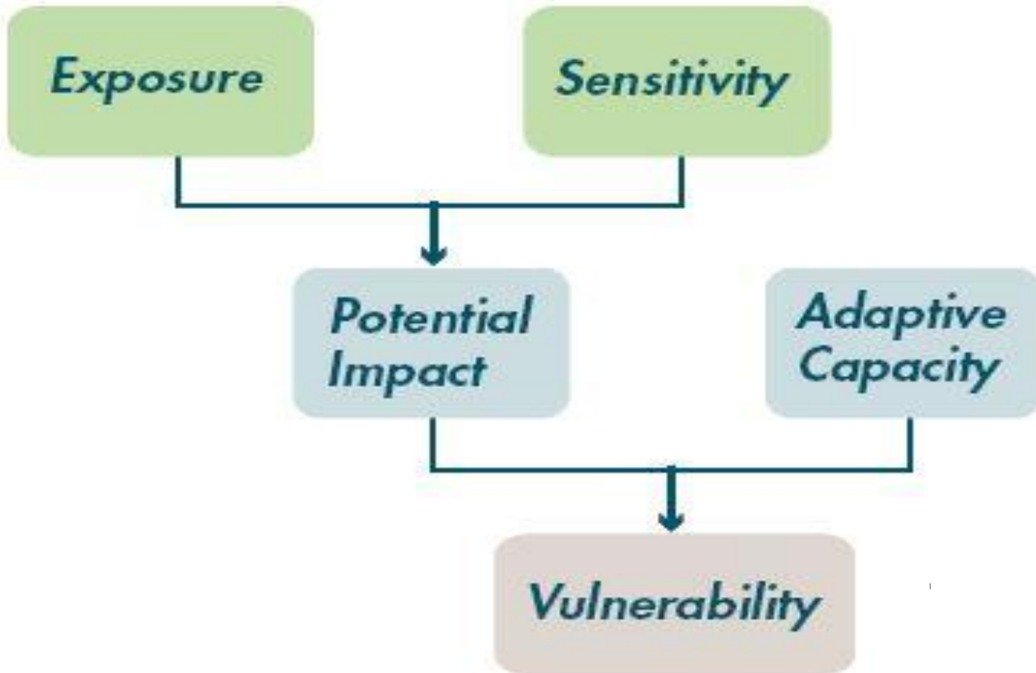

Figure 1. Vulnerability assessment organizational framework (from Glick *et al*., 2011).

When attempting to assess the vulnerabilities[2] of any species or habitat to the changing climate, it is important to consider, quantify (to the extent possible), and integrate all three components. The most used of the formal models that have been recently developed for estimating vulnerability—NatureServe's Climate Change Vulnerability Index Model (which focuses on species) and the Northeastern Association of Fish and Wildlife Agencies (NEAFWA) habitat vulnerability model—are both constructed around these components.

In practice, there is another component that should either be addressed separately or that should permeate all stages of attempts to evaluate vulnerabilities – the analysis of uncertainties. All attempts to project the vulnerabilities of ecological resources to current and future climate change are, necessarily, beset with a number of uncertainties. These arise from uncertainties inherent in the modeling of future climates (particularly in projections of changes in precipitation and extreme events), uncertainties about future

[2] Vulnerability in this context refers to the likelihood that a species or system is likely to be affected by the changing climate. It is important to note that depending on the species or system being affected such effects can be either adverse or beneficial.

greenhouse gas emissions rates, uncertainties concerning the adaptive capacities and sensitivities of organisms or systems, and uncertainties about how societies might respond to the changing climate, or to its impacts. Some form of uncertainty analysis should be included in all vulnerability assessment models (as is the case in the NatureServe and NEAFWA models identified above). Ideally, the best approach is to provide within the vulnerability assessment model a systematic approach to evaluating the impacts of uncertainties on the inputs and outputs of the models – the vulnerability assumptions and statements. Thus, the modeling process could be modified by the user by entering differing uncertainty assumptions. This is possible with single species vulnerability models (and it is already part of the NatureServe process) but is much more problematic with multi-species or habitat models.

In this analysis, we attempt to estimate the likely vulnerability to climate change of riverine habitat for cold water fish in the NEAFWA Region[3]. This is also the approximate area that is the focus of the North Atlantic Landscape Conservation Cooperative (NALCC), and the Eastern Brook Trout Joint Venture (EBTJV)[4]. Riverine cold water fish communities in this area comprise a number of species, primarily salmonids, including brook, brown, and rainbow trout, all of which are restricted to waters that are consistently cold (<20–24 ^{o}C) and well-oxygenated. Our time scale for this assessment is the remainder of this century. Within that period, the timing of adverse effects will depend on how quickly or slowly we emit greenhouse gases. We have chosen to focus on the riverine habitat of the cold water fish community because:

1. Many laboratory and field studies have added to our knowledge about the relationships between cold water fish species' survival, productivity, etc., and climatic factors;

2. Our understanding of the physiology, ecology, and geographical distribution of these species indicates that they are likely to be sensitive to the changing climate;

3. The community can be viewed as a suitable indicator for the entire riverine cold water ecosystem in a changing climate;

4. These fish are iconic and appreciated by the general public as being representative of "healthy" steam ecosystems; and

5. They are recreationally, economically, and culturally important species.

In the remainder of this report we evaluate the potential vulnerability of this important fish habitat in the Northeast to future climate change using the framework outlined above,

[3] Comprising the 13 states of Maine, New Hampshire, Vermont, New York, Massachusetts, Connecticut, Rhode Island, Pennsylvania, New Jersey, Delaware, Maryland, Virginia and West Virginia, and the District of Colombia.

[4] While lentic cold water fish habitats also exist in the NEAFWA region, their ecologies are very different from the riverine habitats, and for the sake of clarity we have chosen to focus on the latter. A vulnerability assessment of climate change and lentic habitats is, however, needed.

with its components of sensitivity, adaptive capacity, exposure, and uncertainty analysis. To the extent possible, we also attempt to draw conclusions about vulnerabilities at the subregional scale (e.g., individual states or clusters of states).

We begin with a description of the distribution of the habitat in the Northeast Region and its general and thermal ecology, and historic anthropogenic impacts. We then review previous attempts to model the vulnerability of this habitat and its fish in the Northeast to climate change. Following that, we describe how current exposures to climate variables are likely to change in the future, the extent to which the habitat and its fish may be sensitive or resilient to and able to adapt to these climatic changes, and the resulting vulnerabilities of this habitat to climate change. Throughout these analyses we identify and discuss the major uncertainties that affect vulnerability projections, adaptive capacity, for example. Finally, we discuss how these uncertainties affect vulnerability assessment, and suggest further work that could reduce these uncertainties to arrive at a better, more dependable, estimate of the true vulnerability of this habitat type to the changing climate, and how it might be conserved and managed in the Northeast.

Distribution, Ecology, and Impacts on Cold Water Fish Habitat in the Northeast Region

In the Northeast Region native brook trout and introduced brown and rainbow trout are distributed along the entire length of the Appalachian Mountains (Figure 2) in cold and well-oxygenated streams (Gilbert and Williams, 2002). In the southernmost and warmer part of this range they are typically at higher elevations in the cooler headwater reaches, but in the north they extend down to lower elevations. Since the European colonization, cold water habitat suitable for these species has been fragmented and eliminated.

For example, brook trout habitat has been lost from approximately 20–25% of the watersheds in which they once existed (Hudy *et al*., 2005; Figure 3). These losses have been greatest in the central and southern Appalachians, particularly in western New York, Maryland, Pennsylvania, Virginia, North and South Carolina, Tennessee, and Georgia (Figure 3). Losses have been due largely to anthropogenic habitat destruction and conversion: streams have been dammed, eliminating access to headwaters spawning areas; riparian vegetation that once shaded and cooled streams has been destroyed to make way for agricultural, residential or commercial development; impermeable surfaces (acting as heating areas for rainfall before it enters streams) have been built close to streams; and competition from introduced species has intensified (Hudy *et al*., 2005).

Even in those southern watersheds that still support self-sustaining brook trout populations, Hudy *et al*. (2005) found that almost half had lost over 50% of habitat and a further 15% of watersheds had lost between 10% and 25% of habitat. The least impacted of the northeastern states are in New England (Maine, New Hampshire, Vermont, Massachusetts and Connecticut), and eastern New York.

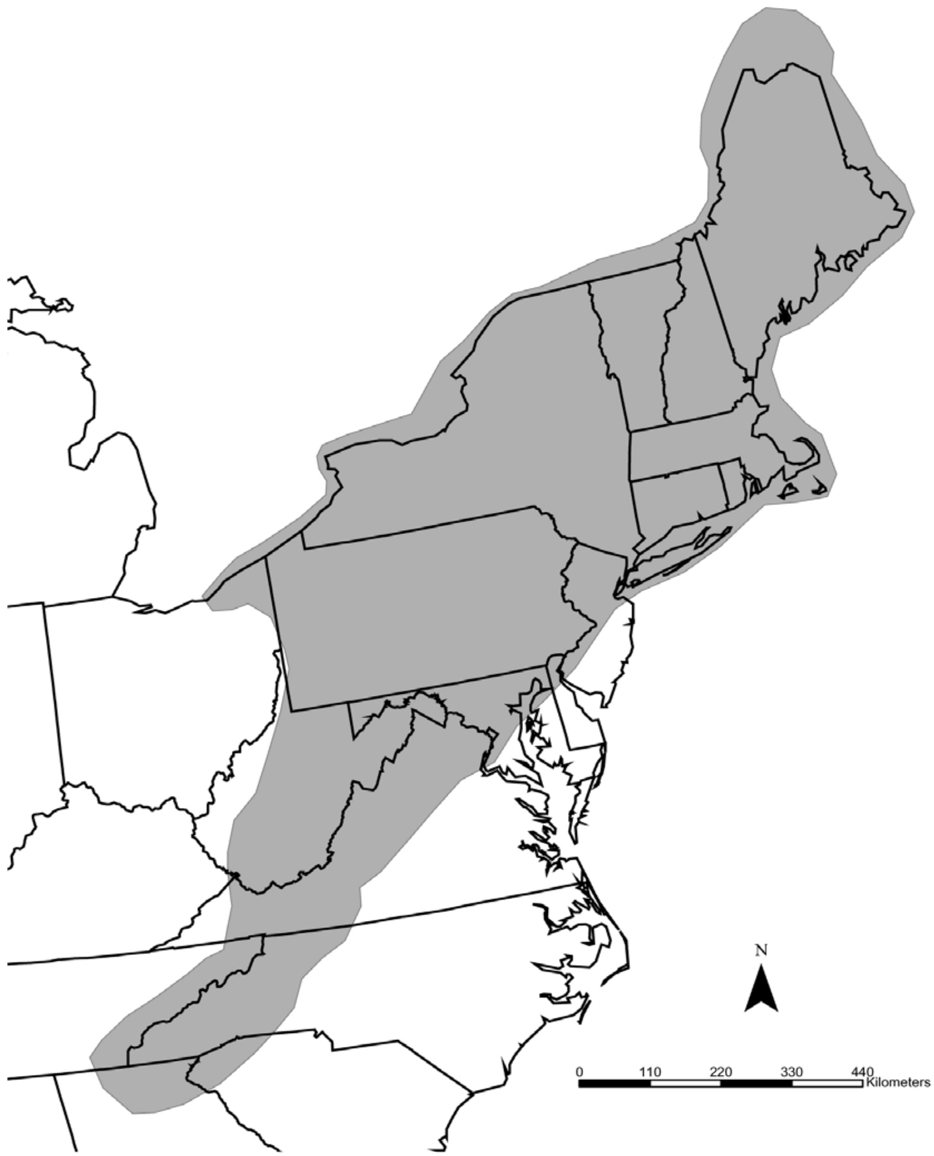

Figure 2. Historic range of brook trout in the eastern U.S. From Hudy *et al*. (2005). This approximates the distribution of suitable habitat for cold water fish species.

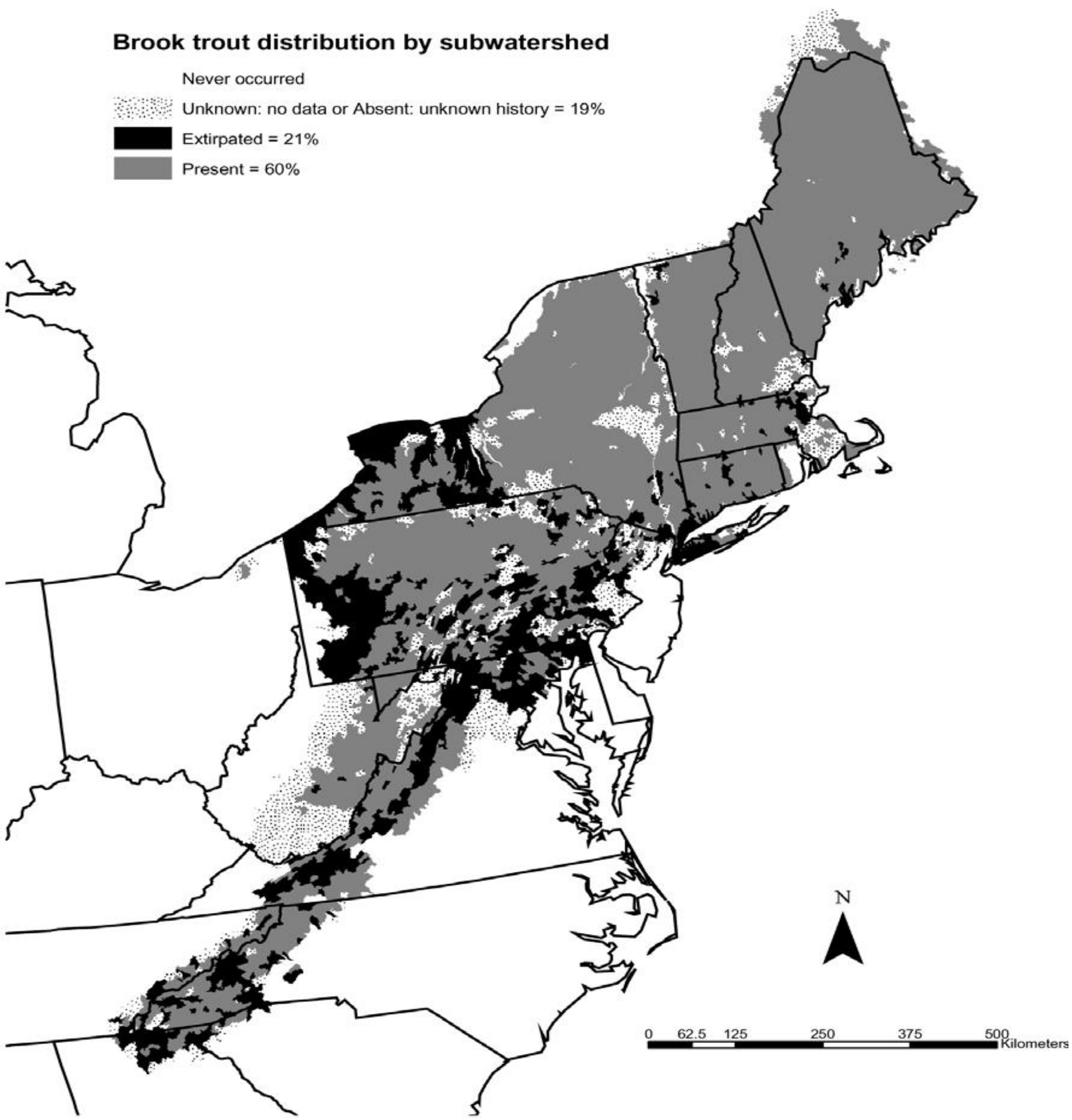

Figure 3. Distribution of subwatersheds in the eastern United States where brook trout are present (60%), extirpated (21%) or of unknown status (19%). Subwatersheds classified as "never occurred" are not included in the percentage calculations.

Exposure Analysis

Appendix A to this report presents detailed information from the scientific literature on how the climate of the Northeast Region is likely to change over the remainder of the century. In summary, the most recent and comprehensive down-scaled projections of future climate change indicate that a number of factors that are highly relevant to cold water fish are likely to change greatly[5], and that at least some of these changes will vary with latitude within the Northeast Region:

- Mean annual air temperatures are projected to increase by the end of the century by between 5 ^{o}F and 8 ^{o}F, depending on future emissions assumptions. The degree of warming will be greatest during the winter months and in the more northern states. The implications of this increase for water temperatures in cold water fish streams could be that more habitat will be lost as conditions suitable for a cold water fish community are converted to warmer waters.

- Mean annual precipitation is also projected to increase by the end of the century by about 7–9% or 8–14%, depending on the emissions assumptions. The greatest changes are likely to occur during the winter months, with much smaller changes projected for the summer. As a consequence of the increasing ambient temperatures, much less precipitation during the fall–spring months will fall as snow, and more as rain. This is likely to shift stream hydrographs as they become less dominated by early spring run-off. Also, since the summer precipitation is not projected to increase greatly and the evapotranspiration rate due to increased air temperatures will increase there is likely to be less water flowing through existing cold water streams than at present, compounding the effects of seasonal drought (see below).

- Extreme events (floods and summer droughts) are projected to increase in their frequency, severity and duration, especially in the more northern states of the region.

- The outcomes of all of the above changes on the hydrologies of streams and rivers are projected to be that the peak spring flows will be earlier (due to smaller snowpack and more consistent precipitation falling as rain during the winter months) by about 10–14 days depending on the emissions assumptions. Also, summer low flow conditions will be more severe and last longer than they presently do.

[5] It should be recognized that modeling long-term climatic change is beset with a number of major uncertainties. This is especially the case in modeling future precipitation and extreme event patterns. Our current climate models produce our best possible estimates, not facts.

Sensitivity Analysis

In riverine habitats, salmonids are largely limited to unpolluted, cold, and well-oxygenated streams (and some lakes). They comprise a guild of species with similar physiological and ecological requirements. Their spawning success, rearing, productivity, growth, and adult survival are highest in streams where water temperatures do not exceed about 20 ^{o}C (MacCrimmon and Campbell, 1969; Raleigh, 1982). Above this threshold, mortality among adults, eggs and fry increases. Even within their thermal range, recent research has shown that growth and survival decrease with increasing summer temperatures (Letcher, 2013). These temperature requirements limit the distribution of this guild in the eastern United States: for example, MacCrimmon and Campbell (1969) postulated that the southern limit to brook trout distribution is determined by the mean July air temperatures not exceeding 21 ^{o}C, and Meisner (1990) maintained that the southern portions of the species' range in the Appalachians is dependent on a cool groundwater contribution to the flow of higher elevation streams. Also, while we may be able to model the direct impacts of increasing temperatures on fish and their habitats, warming may also fragment habitats at a watershed scale and reduce connectivity. We are as yet less able to project such effects.

Given their limiting thermal habitat requirements, it is feasible that cold water fish might be among the more sensitive of fish species in the U.S. to climate change impacts on their thermal habitats. The earliest and greatest impacts might be expected at the southern edges of their range and at lower elevations, where streams that are currently maintained below the critical 20 ^{o}C threshold (review in EPA, 1995), either by lower air temperatures and/or groundwater inflows, may be least buffered against warming. Several vulnerability modeling studies have focused on this putative relationship between current and future climate change, water temperatures, and cold water fish thermal habitat and populations. They are reviewed below.

Potential Impacts - Previous Vulnerability Analyses

Between the mid-1990s and the present there have been several vulnerability analyses of cold water fish in the Northeast Region. While these studies may not address all of the vulnerability assessment components described in Figure 1, they do provide important information from which we can deduce vulnerability. In addition, there are completed and ongoing studies that provide data crucial to the elucidation of components of habitat vulnerability (e.g., exposure, adaptive capacity). All such studies are reviewed below and their assumptions and conclusions discussed.

(1) Meisner, J.D. 1990. Effect of climatic warming on the southern margin of the native range of brook trout, Salvelinus fontinalis. Can. J. Fish. Aqua, Sci. 47:1065–1070. In this, the earliest study of brook trout vulnerability to climate change in the Northeast, Meisner (1990) proposed that the southernmost limit of brook trout distribution is related to the 15 ^{o}C groundwater isotherm. Meisner (1990) based this on a modeled relationship between minimum elevations at which brook trout occur in this part of the native range and elevation, latitude, and groundwater temperature. He estimated minimum elevations for brook trout under the warming scenario of the Goddard Institute for Space Studies climate model (GISS), projecting a 3.8 ^{o}C increase in mean annual temperature. He presented a map of the areas remaining available to brook trout as "potential habitat" under the GISS scenario, but was unable to provide details. He selected the lowest site in each drainage that had brook trout from state inventories, and consequently did not have the entire inventory data set available for the projection. According to Meisner's study, the distribution of brook trout in North Carolina and Virginia under the GISS scenario would become increasingly fragmented, and trout would disappear entirely from South Carolina and Georgia, the southernmost outposts of their distribution.

(2) EPA, 1995. Ecological Impacts from Climate Change: an Economic Analysis of Freshwater Recreational Fishing. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Climate Change Division. EPA 220-R-95-004 April, 1995. As part of this national study of the economic impacts of climate change on recreational fishing, the investigators modeled northeastern cold water fish exposure to climate change, their sensitivities to changed temperatures, and their vulnerabilities based on three emissions scenarios and four General Circulation Models (GCMs): the GFDL, OSU, UKMO, and GISS models[6]. The endpoint of the study was change in the distribution and extent of suitable thermal habitat. They assumed that:

1. The atmospheric concentrations of CO_2 would double (the emissions scenario analysis was to estimate <u>when</u> that doubling would be arrived at).

[6] GFDL: Geophysical Fluid Dynamics Laboratory; GISS: Goddard Institute for Space Studies; OSU: Oregon State University; UKMO: United Kingdom British Meteorological Office.

2. A doubling of CO_2 would result in average maximum weekly air temperatures increasing by 1.8–3.5 ^{o}C.

3. The Fish-Temperature Data Matching System (FTDMS) 95th percentile value of 70 ^{o}F (21 ^{o}C) was an appropriate estimate of the upper bound of suitable thermal habitat for brook trout (which were used as an indicator for the entire cold water guild).

4. Three emissions scenarios (IS92a, IS92c, and IS92e). These are similar to the SRES scenarios that later replaced them in that IS92c approximates the B1 scenario, IS92e the A1 scenario, and IS92a a median scenario.

5. Average weekly maximum water temperatures were identical to average weekly maximum air temperatures (i.e., an air:water temperature coefficient of 1.0).

6. The ability of cold water fish to adapt to these changes would be minimal.

Depending on the GCM used, this study projected large-scale reductions in the extent of cold water fish thermal habitat in the Northeast, especially for the more southern states where reductions of 50–99% were projected (Table 1). Such reductions would effectively greatly reduce or eliminate the habitat available for the species.

Table 1. Results of EPA (1995) Vulnerability Analysis.

GCM	**RESULTS (% reduction in trout thermal habitat)**	
OSU	1–49% for NY, VT	50–99% for ME, NH, MA, CT, RI, PA, VA, WV
GFDL	1–49% reduction for VT	50–99% reduction for ME, NH, NY, MA, CT, RI, PA, VA, WV
GISS	1–49% reduction for VT	50–99% reduction for ME, NH, NY, MA, CT, RI, PA, VA, WV
OKMO	1–49% reduction for NH, VT	50–99% reduction for MA, CT, RI, NY, PA, VA, WV

The thermal habitat for brown trout was projected to be lost from 100% of the areas where it currently occurs, and rainbow trout habitat would suffer between 50% and 100% habitat loss.

(3) Ries, R.D. and S.A. Perry, 1995. Potential effects of global climate warming on brook trout growth and prey consumption in central Appalachian streams, USA. Clim. Res. 5: 197–206. This study examined the hypothesis that brook trout might benefit from warming in the early part of the year by having faster growth rates, and the implications of this potential result on food requirements. The authors found that up to an assumed 2^{o} C annual mean temperature increase, the growth rates of brook trout in West Virginia streams might indeed increase, potentially offsetting adverse impacts in the hotter months, but that this would require an increase in the food consumption rate of 15-20%.

Above a 2^{o} C increase much greater increases in food consumption would be required (>30%) and that this might be problematic for the fish.

(4) Flebbe, P.A., L.D. Roghair, and J.L. Bruggink. 2006. Spatial modeling to project Southern Appalachian trout distribution in a warmer climate. Trans. Am. Fish Soc. 135: 1371–1382. In this study, the authors modeled the current distribution of trout habitat (combining brook trout, rainbow trout and brown trout into a "trout guild") in the southern Appalachians (VA and WV south to GA). They then used this distribution to estimate the current elevation-latitude range boundary as a function of ambient temperature, and then applied the Hadley and Canadian Climate Center General Circulation Models to project range changes over the remainder of the present century up to a maximum temperature increase of 5.5 ^{o}C. Additional modeling attributes were that the authors used land cover data to eliminate non-suitable trout habitat (ditches, pipelines, canals, etc.) from the current range map, and they assumed an air temperature/water temperature coefficient of 1.0. The study did not incorporate future flow changes into the modeling process as the GCM outputs were considered too uncertain in this regard.

The main results of the study were that the extent of trout habitat (stream length and habitat area) are projected to decrease with increasing temperature, that this relationship will be non-linear, and that habitat loss may vary between about 22% and 97% depending on the assumed temperature increase (Table 2).

Table 2. Habitat loss estimated by Flebbe et al. (2006).

GCM	**+T ^{o}C**	**% Loss in stream-miles of habitat**	**% Loss in area of trout habitat**
Hadley	+1.5 ^{o}C	29	21.6
Hadley	+2.5 ^{o}C	65	52.9
Canadian Climate Center	+4.5 ^{o}C	96	92
Canadian Climate Center	+5.5 ^{o}C	99	97.3

Habitat fragmentation also was projected under the warming scenarios, with the larger habitat patches becoming broken up and eventually disappearing first, followed by the intermediate and smaller patches.

(5) Trumbo, B.A. 2010. Sensitivity and Exposure of Brook Trout (Salvelinus fontinalis) Habitat to Climate Change. A thesis submitted to the Graduate Faculty of James Madison University. In Partial Fulfillment of the Requirements for the Degree of Master of Science, Department of Biology. In this important study, the author addressed uncertainties about the relationships between air temperatures and water temperatures in Virginia streams in 2009 and 2010 using paired measurements. He also elucidated the effects of other environmental variables in determining water temperature, and, lastly, classified Virginia brook trout watersheds in terms of their sensitivities between air and water temperatures, their exposure to increased temperatures and their likely

vulnerabilities to future climate change. He found that a "one-size-fits-all" approach to the sensitivities of water temperatures was misleading and that individual habitat patches showed widely different relationships, casting some doubt on vulnerability analyses that generalize across wide areas and different watersheds.

Using thermographs installed at 77 different watersheds Trumbo (2010) recorded air and water temperatures every 30 minutes during the critical low flow period (July-September). He then extracted from the resulting data Daily Maximum Water and Air Temperatures. Using these data, he then established sensitivity metrics for each site where sensitivity is the measured increase in water temperature for each measured increase in air temperature and found that the median sensitivity score was 0.38^{o}C, much lower than has been previously assumed, and that it varied between sites (range: 0.06 – 0.81)[7]. He also found that for any one site the sensitivity could also vary with temperature range (i.e., it was not a linear relationship), and between years.

The Trumbo (2010) analysis of other environmental factors contributing to stream temperatures identified elevation, groundwater flow, and forest cover (shading) as being important contributors to lower temperatures and these variables explained much of the variation in sensitivity measurements.

When he classified his sample sites and watersheds in terms of their likely vulnerabilities to future climate change (using his empirical data), Trumbo (2010) was able to establish that approximately 52% of habitat patches in Virginia were likely to be most vulnerable (High Sensitivity and High Exposure), about 30% were likely to be resistant to the effects of climate change, and about 18% had intermediate risk. The more vulnerable sites were generally at lower elevations, with higher ambient air temperatures, less shading, and lower groundwater flow.

Trumbo (2010) concluded from his data that accurately estimating the vulnerabilities of brook trout had to be carried out on a site-by-site basis, that the relationships between air and water temperatures had to be known for the site, and that information on groundwater flow, elevation, and shading also had to be available.

(6) Jones, R., Travers, C., Rodgers, C., Lazar, B., English, E., Lipton, J., Vogel, J., Strzepek, K., Martinich, J. 2013. Climate change impacts of freshwater recreational fishing in the United States. Mitig. Adapt. Strateg. Glob. Change. 18:731-758. This national study was undertaken partly to revisit the 1995 EPA analysis using more sophisticated methodologies and more recent sets of assumptions. For example, instead of *assuming* a hypothetical air-water temperature coefficient of 0.8 or 1.0, actual empirical data were gathered from weather stations and river gauges and used to project water temperatures from air temperatures. Also, flow data were used in conjunction with modeled temperature data to project change in fish habitat extent and distribution.

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[7] These comparisons should be treated with some caution, however, since Trumbo was quantifying the relationships between maximum water and air temperatures on a given day, while other studies looked at longer term equilibrium relationships. Nevertheless, the Trumbo (2010) study does show that the air and water temperature coefficient is not likely to be as high as previously assumed.

Using three emissions scenarios (B1, A1FI, and A1B) and the mean projections of 10 GCMs, future air temperatures were projected for watersheds across the United States. Three projections were carried out for 2030, 2050 and 2100, and the results compared. For the cold water fish guild, temperature thresholds were developed using Maximum Weekly Average Temperature (MWAT) data derived from a database of observations of fish species presence together with maximum weekly average stream temperature. Maximum thermal thresholds were based on the temperature tolerance of the most tolerant species in the guild. For the cold water guild this was brown trout with a maximum temperature tolerance of 24.1 ^{o}C. This is higher than the customarily used brook trout tolerance level of 20 ^{o}C.

National maps showing the results of conversion of colder water habitats into warmer habitats are displayed in this paper and it is possible to use these to focus in on projected changes in the 13 northeastern states. One such map (for 2100 under the three emissions scenarios) is reproduced here as Figure 4. For the cold water guild these maps show cold water habitat that is projected to remain cold water, or that will convert to warm water habitat.

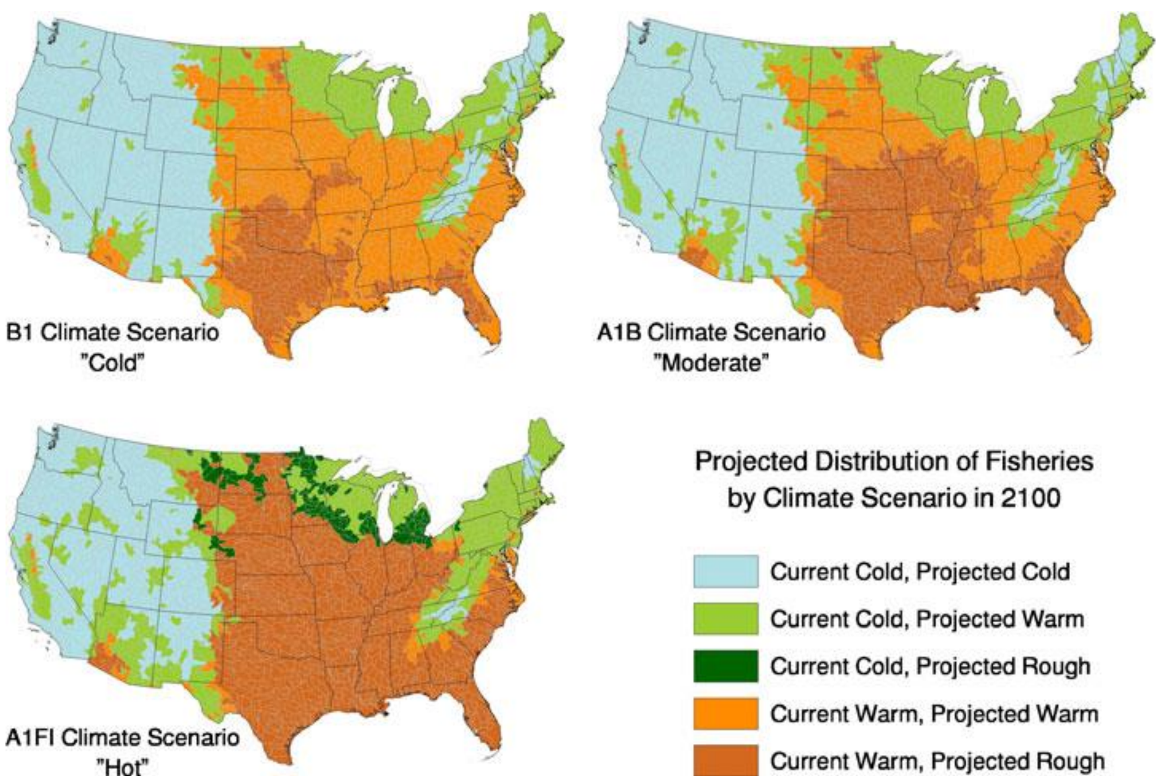

Figure 4. Projections of change in the distributions of thermal habitats for fish water temperature guilds by 2100 under three greenhouse gas emissions scenarios (from Jones *et al*. 2013).

Although the actual statistics on which these maps are based are not provided in the paper, it is possible to approximate by sight the change in cold water habitat extent under the three scenario and timeline assumptions. When this is done the following results are obtained:

- 2030: the only northeastern cold water habitats converted to warmer water are in low-lying areas of eastern MA, and in CT, RI, and NJ. This conversion approximates less than 5% of the total cold water area. The pattern of change is similar for all three emissions scenarios.

- 2050: all three emissions scenarios are similar in that the projections are for approximately 25% of the current cold water habitat to be converted to warmer water habitat. This occurs across most of MA, CT and RI, in northern ME, much of western NY and NW PA, and in southern WV.

- 2100: Between 60 and 90% of cold water habitat is converted under the three emissions scenarios (Figure 4): for the B1 scenario it is 60%, for A1B it is about 70%, and for A1FI it is 90%.

Thus, the losses of cold water habitat become greater the further into the future the projections are made and at the higher emissions scenarios (although differences in the results for these scenarios only become apparent in the latter half of the century). In the worst case, by 2100 virtually the entire habitat in the Northeast is lost. The most optimistic case (B1) is for more than half of the habitat to be lost.

These projections are based on change in water temperature only. It makes little difference when flow projections are added to the analysis. Overall, the flow in the Northeast Region is projected to increase by 10–20% by 2100. The only occasion that this makes a difference to habitat extent is for a small area of western ME where, under the A1FI scenario, the increased flow protects an area of cold water habitat that is being threatened by temperature increase.

(7) U.S. Forest Service, Southern Research Station, Virginia. *Ongoing*. In this continuing study, the researchers (led by Andrew Dolloff of the U.S. Forest Service) have been examining the relationships among air and water temperatures in seven southeastern states, including Maryland, Virginia, and West Virginia. Beginning in 2009, and using thermographs installed at 50 sites in Virginia, the researchers have found that the air/water temperature coefficient of 0.8 that is often assumed is not borne out by the empirical measurements. It varied between 0.3 and 0.5 and, in some streams where there was significant inflow from cool groundwater, there was no relationship at all (a coefficient of 0). This study has not yet been completed but the results thus far shed an interesting light on the potential problems of evaluating risks posed by a changing climate to cold water fish.

(8) Application of the NatureServe Climate Change Vulnerability Index Model (CCVI). Three northeastern states (West Virginia, New York, and Maryland) have used the CCVI

model to evaluate the vulnerabilities of cold water fish species, primarily brook trout, to the changing climate. The CCVI model utilizes expert elicitation in a formal process to arrive at its vulnerability results and has now been used and tested at a number of different areas across the U.S. Two of these analyses (West Virginia and New York) scored brook trout as being "Highly Vulnerable" to climate change. This indicates that it is likely that the abundance or range of the species in the three states will decrease significantly by 2050 (Schlesinger *et al*., 2011; Byers and Norris, 2011). Maryland scored the brook trout as "Extremely Vulnerable", indicating that it is extremely likely that the abundance or range of the species in the state will be substantially reduced or will be eradicated (Dana Limpert, MD Department of Natural Resources, *pers comm*.).
In Maine a somewhat similar approach to evaluating brook trout vulnerability to climate change was developed. The state vulnerability assessment created three vulnerability categories:

- 1–Low Vulnerability: little negative impact; <33% loss or a positive impact on this species' range area and/or population size in Maine over next 50 to 100 years
- 2–Medium Vulnerability: intermediate impact; 33–66% loss of this species' range and/or population size in Maine over next 50 to 100 years)
- 3–High Vulnerability: large negative impact; >66% loss of this species' range area and/or population size in Maine over the next 50 to 100 years, including potential state-level extirpation).

Expert opinion was then elicited to determine the vulnerabilities of species. For the brook trout the outcome was that the species scored 2.5, indicating that significant impacts on population distribution and status were expected but that eradication was less likely. Thus the Maine results were similar to those obtained in West Virginia and New York, but not as drastic as those from Maryland.

All of these studies agreed that the most important factors leading to the relatively high vulnerability scores were a combination of the species' intrinsic physiological thermal limitations, land use trends leading to loss of suitable thermal habitat, and ongoing fragmentation and loss of populations.

Potential Impacts - Interactions of Climate and Non-Climate Stressors

Climate change is the latest in a long history of anthropogenic stressors that have affected the cold water fish habitat in the Northeast. Damming, preventing access to spawning areas, destroying riparian vegetation, introducing exotic species, and constructing impervious surfaces adjacent to streams (which had the effect of warming runoff into the streams) have all exacted a toll on this habitat type. Also, parasites and disease have affected and are affecting fish communities. These stressors have not been replaced by climate change; this new stressor will impact this sensitive habitat in conjunction with the already existing stressors. The potential for negative interaction is high as warming waters act in concert with hindered access, lack of shading, diseases, parasites, etc. to exacerbate and magnify the overall impacts on the habitat. Paradoxically, the existence of this mix of stressors offers some opportunities for mitigating the effects of warming. We may not be able to prevent further warming, and our record in this endeavor is woefully poor, but by removing some of these other stressors we may be able to reduce the overall future impacts.

Adaptive Capacities of Cold Water Fish

The adaptive capacity of an organism, population, or community is its ability to adapt to a stressor (e.g., climate change) *in situ*, thereby mitigating its harmful effects. Adaptation can be evolutionary, as the organism evolves adaptive traits such as changes in morphology and/or physiology (this could mean that populations with higher levels of genetic diversity may be more able to adapt (Letcher *et al.*, 2007)), epigenetic, as the environment within which the organisms lives modifies gene expression, or they can be phenotypic and include acclimation, and/or behavioral change (Dawson *et al*., 2011). At least some species are known to have shown such adaptive plasticity during previous climate change events (Dawson *et al*., 2011) and tolerated the changing conditions. Many previous approaches to evaluating a species' or community's vulnerability have, however, more or less disregarded this capacity to adapt and change. This has been particularly so in the use of climate envelope models which estimate the climatic envelope or habitat of an organism based on its current and presumed past distribution, then combine this with GCM climate change projections to characterize vulnerability or map future geographical shifts in species/community distributions. In addition, it is feasible that if fish populations are being reduced by a stressor, such as climate change, the population may have the ability to compensate through density dependent increased reproductive rates or survival. Without including considerations about adaptive capacity, modeling exercises and other vulnerability studies run the risk of overestimating vulnerability and future distributional change.

The extent to which cold water fish species in the Northeast will be able to adapt *in situ* to climate change is largely unknown. It is known that some salmonids have behavioral traits that can buffer them from the effects of warming temperatures. For example, in more marginal habitats they may seek out and inhabit colder water thermal refugia during warmer months (High *et al*., 2006). They may also adjust their timing of migration to avoid periods of warmer water (Goniea, *et al*., 2006). It has also been hypothesized (Reis and Perry, 1995) that brook trout may be able to compensate for some degree of warming by increasing their food consumption rates (and energy budgets). In contrast, it is also likely that the latitudinal and elevational limits to some species' distributions in the southern Appalachians, brook trout, for example, are set by ambient temperatures, indicating that the adaptive capacities of such organisms are finite (Burrows *et al.*, 2011). However, apart from these observations, the adaptive capacities of cold water fish in the Northeast are only poorly understood. One important but unknown factor is the rate at which water temperature and flow changes may occur in the future. If the projected changes occur over a time scale of many decades the fish may be better able to adapt (genotypically, phenotypically and/or behaviorally) than if they are more sudden. While we can project the types of changes that are occurring and are likely to continue, estimating their rates is much more problematic.

These unknowns about adaptive capacity need to be better understood if we are to strengthen our vulnerability estimates. However, given the rate of climatic change, we cannot afford to conclude that we should not act until we have a perfect understanding of adaptive capacity. If we are to preserve the habitats that are left we must take action now, despite some uncertainties.

Summary of Likely Vulnerability of Cold Water Fish Habitat in the Northeast

The studies reviewed above agree in that cold water fish habitat in the northeast is vulnerable to climate change. They also largely agree that the risks posed to this habitat type are due to its current rate of loss to anthropogenic development, habitat destruction and fragmentation (leading to loss of connectivity), and the cold water fish species' intrinsic physiological limitations to cold water habitat. Many of them (Meisner, 1990; EPA, 1995; Reis and Perry, 1995; Flebbe *et al*., 2006; Trumbo, 2010; Jones *et al*., 2013; CCVI studies performed in West Virginia, Maryland, New York and Maine) specifically identify climate change as a source of current and future potential risk to cold water fish populations. However, more recent work suggests an evolution in our thinking about the magnitude of the risk posed by climate change.

Earlier and larger scale studies (Meisner, 1990; EPA, 1995) projected large habitat reductions (generally greater than 50%, and up to 100%), depending on the emissions scenario, the time scale, and the GCMs used. However, the results of some recent studies that have focused closely on individual watersheds and sub-watersheds, and that have collected empirical data that examines the relationship between air and water temperatures, may lead to less drastic conclusions about the fate of thermal habitat for cold water fish in the northeast (O'Driscoll and Dewalle, 2006; Trumbo, 2010; Kelleher *et al.*, 2012; Kanno *et al.*, 2013; U.S. Forest Service, ongoing). These studies are finding that changes in future water temperatures under climate change are likely to be more complex than is suggested using the air/water temperature ratios that were previously assumed. It seems that many streams may be better buffered against air temperature increases than previously appreciated, and that this is due to site-specific non-climatic factors, such as groundwater inflow rate, adjacent land-use, and stream shading.[8,9] These factors may help slow the rate of increase in groundwater temperature once it becomes exposed to surface temperatures. The good news to be derived from this is that climate change may not have such drastic effects as were previously imagined on cold water fish populations in the Northeast. The bad news may be that climate change will have an adverse effect, particularly on lower elevation and southern streams, and that "traditional stressors," which have already resulted in significant habitat losses, will continue to exert their effects. The cumulative impacts of climate change and the "traditional" stressors might result in rates of habitat loss for fish populations that are greater than previously experienced. All of our projections about vulnerabilities need to be considered, however, against the backdrop of major uncertainties about adaptive capacity (see previous section).

[8] Bogan *et al*. (2003) found that the water inflows of almost 10% of streams were dominated by cold water inputs from groundwater aquifers. This result probably underestimates the proportions of streams where such inflow is an important (though not dominating) modifying influence.
[9] Other studies may not be so clear cut about the relationship, or lack thereof, between air and water temperatures. For example Mohseni and Stefan (2003) found a roughly linear relationship with a regression coefficient of approximately 1 up to 20^{o}C, decreasing to a slope of 0.5–1 thereafter.

It is when we go beyond the general question of whether the northeastern cold water fish community is vulnerable to climate change and ask where the most vulnerable areas are, where the greatest habitat losses may occur, and how we might conserve the community, that we encounter significant challenges. The extent of habitat loss and its locations are difficult to project because, as the recent research has indicated, its vulnerability is likely to vary on much smaller geographical scales than previously appreciated. Large scale studies (e.g. EPA, 1995) do not tell us much about the vulnerabilities at the watershed and reach scale. This is because the vulnerabilities of streams are a function of environmental and land use characteristics that can vary over relatively small geographical scales: how effectively shaded a stream or stream reach is; the presence or absence of impermeable surfaces in the watershed; and the magnitude of the contribution of groundwater discharge to flow all may exert local modifying effects on water temperature. Also, as discussed above, we are relatively ignorant about the abilities of cold water fish to adapt to and tolerate the changes that are expected to occur.

Based on existing studies and data, the farthest we can push our current knowledge about risk and vulnerability is that we can be confident that the habitat is vulnerable throughout the Northeast. This may be translated into large-scale habitat loss, particularly in southern areas and at low elevations where the cold water fish community may already be at the thermal limits of its range and the habitats that currently exist are highly fragmented. In the more northern states, where the community is more widespread and less fragmented in its distribution (Northern New England and New York), habitat loss may be less severe, though likely to occur at lower elevations, or where upland streams have had their shading cover or adjacent land use modified, or where the contribution of groundwater to the flow is limited.

Our existing information and data do not allow us to answer questions about the specific vulnerabilities of every watershed or stream in the Northeast Region. Nevertheless, our ability to conserve and manage cold water fish populations under climate change is contingent on being able to do exactly this.

Uncertainties and Future Research Needs

Based on what we have learned from experimental and field studies, the northeastern cold water fish community is temperature-sensitive. Also, based on what we can reasonably assume about the magnitude of current and future climate change, there can be little doubt that this community is at risk through direct physiological impacts and habitat change. Indeed, it is possible that this may be one of the more at-risk habitats and communities in the Northeast. However, beyond these generalizations, there are eight major areas of uncertainty. These uncertainties complicate our ability to translate our general knowledge about community vulnerability into conservation policy and action.

First, we need to be more realistic in mapping potential habitat vulnerability across the region. As already discussed, identifying the future vulnerabilities of cold water fish habitats in the northeast will be complex. It is not just a function of mapping projected increasing air temperatures, but must also include the environmental factors that mitigate or exacerbate the stream warming process. To begin to achieve this we first need an accurate map of the current regional relationships among air and water temperatures.[10] With enough sites this would enable us to develop a vulnerability "base map," and then develop an overlay of the mitigating environmental factors identified above: shading, aspect, altitude, impermeable surfaces, etc. By combining these two results and by making reasonably defensible assumptions about future temperature change, we would then be more able to develop an accurate spatial model of habitat resilience and a predictive model of how climate change could impact habitat persistence at individual and unstudied streams.

Given the community mapping work that has been undertaken recently in the northeast,[11] we may be relatively close to being able to develop such an analysis and map. Land use, riparian shading, and impermeable surfaces should be relatively easy to incorporate, groundwater discharge may, however, be more problematic. We need to explore the possibility of using empirical flow information[12] and geological information to model groundwater input to watersheds and streams.

Second, while we have detailed knowledge about the physiological sensitivities of cold water fish species in the Northeast to temperature, and we know the thresholds at which adverse effects may be expected to occur in the life histories of these fish, we are less well informed about their capacities to adapt to changing water temperatures over decadal time scales. This complicates our understanding of which watersheds or streams or populations are likely to be more or less vulnerable to the changing climate. It is unlikely

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[10] To achieve all of this we would need to develop a temperature monitoring program similar to the USGS flow gauge system.

[11] The Boston office of The Nature Conservancy Council (TNC) has recently developed detailed maps of the distributions of terrestrial and aquatic habitats in the Northeast Region. One such map details the distribution of waterways and has already been used to map cold water streams across the region. This could provide a basis for future vulnerability/resilience mapping (similar to the resilience mapping that is already being conducted for terrestrial habitats by TNC).

[12] It is now possible to continuously monitor stream temperatures along lengthy transects using fiber optic cables.

that we will be able to reduce our uncertainty about the adaptive capacities of cold water fish species without conducting extensive and intensive, long-term field studies and laboratory experiments. Specifically, we need to understand better how the intrinsic adaptive capacities of fish change across the landscape, and why. Shedding light on this might require large scale spatial studies of the relationships among genetic diversity, population resilience, and air/water temperature relationships (is adaptive capacity affected by genetic diversity and, in turn, by changing selective pressures under differing temperature regimes?), as well as laboratory studies and experiments into the relationships among temperature and epigenetic factors.

Third, while future extreme events, such as floods and droughts, may have major impacts on populations and habitats, our ability to quantify these in vulnerability assessment is constrained by the limitations of climate models in projecting future conditions. While it is conceivable that the performance of climate models in addressing extreme events will be improved in the future, trying to impose patterns on what are stochastic events will likely remain problematic.

Fourth, we know that climate change will probably interact with existing stressors, but the degree to which this might happen is not certain for some, particularly diseases and parasites. We need a better data set and understanding of how increasing water temperatures might affect these factors, and potential changes in the carrying capacities of riverine habitats for cold water fish species. We also know little about the potential adaptation by fish to these stressors under climate change. We also know relatively little about how colder water fish may fare when faced with increasing competitive interactions with warmer water species.

Fifth, while, with site-specific data, we may be able to model the likely impact of warming on the carrying capacities of streams *in situ*, we may be less able to project effects further downstream. Cold water sections of streams may not only provide suitable habitat for fish, they may also moderate temperature changes further downstream. Our understanding of how climate change might affect this ecological service is poor.

Sixth, warming temperatures may affect fish directly, but it also may fragment their habitats at a watershed or regional scale, thereby reducing the connectivity that may be essential for recolonization and the survival of populations. This aspect of the potential impacts of the changing climate is little understood and needs attention.

Seventh, while we continue to gain understanding of stream water-air temperature relationships, we are far from having a predictive model for them. The coefficient seems to vary widely and may even vary depending on the current stream temperature (Mohseni and Stefan, 2003). Some studies from outside of the Northeast suggest that the coefficient may be closer to unity than some other studies suggest (e.g., Kocan *et al.*, 2004; Bartholow, 2005). If we are to be able to model the likely impacts of climate change on particular streams we need a better understanding of temporal and geographic variability in this relationship.

Last, current research is showing that we do not need to exceed the upper temperature limits for cold water fish to cause changes. Smaller increases that remain below the upper limit may still affect growth and reproduction. Thus, chronic exposures to somewhat elevated water temperatures might affect the ability of a stream system to continue supporting cold water fish. So, if we are concerned about maintaining fish populations, what are our thermal targets and how do we achieve them? It may not be as “simple” as ensuring that the upper temperature limits are not exceeded.

In general, McCullough et al. (2009) pointed out that if we are to better understand the potential impacts of climate change on fish and their habitats we need to integrate studies at five different levels: molecular; organisms, population/species/; community and ecosystems; and policy issues. At least three of these (organism, populations/species, and community/ecosystems) should be the focus of future research in the Northeast.

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Appendix A – Results Of Downscaled Analyses Of Future Northeastern Climate

Downscaled climate projections for the Northeast Region have shown that there is likely to be a degree of intraregional variation in how the climate may change over this century (e.g., Hayhoe *et al*. 2006). Exposures of systems and species will, therefore, also vary geographically. If the vulnerabilities of ecological resources are to be understood, these variations in exposure must be taken into account. This section presents information from the literature describing how the exposures of brook trout may change and vary geographically over this century. This is not intended to be an exhaustive analysis of future climate change. Rather, it uses existing data to provide vulnerability assessment with background information describing likely climate futures.

The data have been gathered from two sources – the Northeast Climate Impacts Assessment (NECIA), and the web-based tool, ClimateWizard. NECIA (2006) was a major effort to describe plausible climate futures in the Northeast by statistically downscaling 3 Global Circulation Models (GCMs) to a 1/8 degree scale. The results were presented in a project report (NECIA, 2006), several scientific papers (e.g., Hayhoe *et al.* 2006 and 2008), and in an interactive website (http://www.northeastclimatedata.org/). ClimateWizard is a web-based interactive tool (http://www.climatewizard.org/) developed by The Nature Conservancy and the Universities of Washington and Southern Mississippi. It uses various combinations of the output of 16 GCMs to statistically downscale information to a 12 km grid scale. Both sources provide the most recent and thorough downscaled analyses of how the climate may change in the Northeast Region over the remainder of this century.

The southern boundary of the NECIA study area included the southern states of the NEAFWA area. However, for some variables (temperature, precipitation, evapotranspiration, soil moisture, snow cover days, drought, runoff, and stream flow) it excluded the southern portions of Virginia and West Virginia. ClimateWizard was used to fill this gap in coverage for the first two variables.

The temperature and precipitation metrics that can be addressed using ClimateWizard do not exactly match those that can be derived from the NECIA dataset (for example, the NECIA upper emissions estimates (Nakienovi *et al*. 2000) are based on the A1Fi emissions scenario, while ClimateWizard generally uses the A2 scenario). However, they are close enough for an acceptable match for the purposes of vulnerability assessment. Furthermore, the NECIA analyses cover a wider range of variables (temperature, precipitation, growing seasons, stream flow, snow cover, etc.) than are available in ClimateWizard, which is restricted to temperature and precipitation. We used both analytical tools to develop a comprehensive appraisal of how relevant northeastern climatic and climate-related parameters will likely change over this century.

We have focused on those climatic variables that are most likely to affect the distribution and viability of brook trout populations: temperature change and precipitation change. These are the climatic factors that are most likely to affect flow and stream temperature and, therefore, habitat suitability for brook trout. We discuss both the degrees of change, geographical variation in projected change, changes in seasonality, and the chronology of these changes over the remainder of this century.

The results of both downscaling analyses for the northeastern region are shown in Table 1 and in Figures 2–14. Table 1 presents the key, biologically relevant findings of the NECIA study for the region. Figures 2 through 4 describe how temperature and precipitation regimes are expected to alter over the next decades assuming low, medium-high, and high emissions scenarios. Figure 5 projects future drought frequencies. Figures 6–10 project future changes in stream flow, runoff and low and high flow periods over the remainder of the century. Figures 11–14 use ClimateWizard analyses to project temperature and precipitation changes for the states of Virginia and West Virginia (these states were not covered in the NECIA analyses). In these data sets we have assumed two contrasting future emissions scenarios (SRES, 2000): the B1 scenario is one in which human societies begin to reduce their rates of greenhouse gas (GHG) emissions in the first part of the 21st Century, leading to an approximate doubling of atmospheric concentrations by the end of the century; the A2 scenario approximates a "business as usual" scenario in which societies continue to burn fossil fuels at approximately current rates, leading to an approximate tripling of GHGs by the end of the century.[13]

[13] Doubling and tripling refer to projected levels of GHGs above the pre-industrial atmospheric concentration of approximately 275 ppm. That concentration has now increased to almost 400ppm, an increase of about 45%. We are well on schedule for at least a doubling of GHG concentrations by the end of the century.

Table 1. Projected changes in climatic factors for the Northeast Region for the periods 2035-2064 and 2070-2099 (from NECIA, 2006).

		1961-1990	2035-2064			2070-2099		
	UNITS	20C3M	B1	A2	A1FI	B1	A2	A1FI
Temperature								
Annual	°C	7.8	+2.1	+2.5	+2.9	+2.9	+4.5	+5.3
Winter (DJF)	°C	-4.8	+1.1	+1.7	+3.1	+1.7	+3.7	+5.4
Summer (JJA)	°C	20.0	+1.6	+2.2	+3.1	+2.4	+4.3	+5.9
Precipitation								
Annual	cm (%)	102.9	+5%	+6%	+8%	+7%	+9%	+14%
Winter (DJF)	cm (%)	20.95	+6%	+8%	+16%	+12%	+14%	+30%
Summer (JJA)	cm (%)	28.03	-1%	-1%	+3%	-1%	-2%	0%
Sea Surface Temperatures[1]								
Gulf of Maine	°C	11.6[1]	+1.3[1]	+1.5[2]	–	+1.9[1]	+3.3[2]	–
Gulf Stream	°C	23.4[1]	+0.9[1]	+1.3[2]	–	+1.2[1]	+2.3[2]	–
Terrestrial Hydrology								
Evaporation	mm/day	1.80	+0.10	–	+0.16	+0.16	–	+0.20
Runoff	mm/day	1.14	+0.12	–	+0.09	+0.21	–	+0.18
Soil Moisture	% sat	55.0	+0.4	–	+0.02	+1.0	–	-0.07
Streamflow								
Timing of spring peak flow centroid	days	84.5	-5	–	-8	-11	–	-13
Low flow days (Q<0.0367 m3/s/km2)	days	65.5	-14	–	-1.5	-26	–	+22
7-Day low flow amount	%	100%	-4	–	-1	-4	–	-11
Drought Frequency								
Short	no. of droughts per 30 years	12.61	+5.12	–	+7.19	+3.06	–	+9.99
Med	no. of droughts per 30 years	0.57	+0.03	–	+0.51	+0.39	–	+2.21
Long	no. of droughts per 30 years	0.03	+0.03	–	+0.11	+0.04	–	+0.39
Snow								
Total SWE	mm	11.0	-4.4	–	-5.5	-5.9	–	-9.3
Number of snow days	days/mnth	5.2	-1.7	–	-2.2	-2.4	–	-3.8
Growing Season[2]								
First frost (autumn)	day	295	+1	+16	–	+6	+20	–
Last frost (spring)	day	111	-8	-14	–	-16	-23	–
Length of growing season	days	184	+12	+27	–	+29	+43	–
Spring Indices[2]								
First leaf	day	98.8	-3.0	-5.2	-3.9	-6.7	-15	-15
First bloom	day	128.8	-3.7	-6.0	-5.6	-6.3	-15	-16

[1] Based on SST output ("tos") from HadCM3, MIROC, CGCM CCSM, and PCM only

[2] Time periods restricted by output availability to 2047-2065 and 2082-2099.

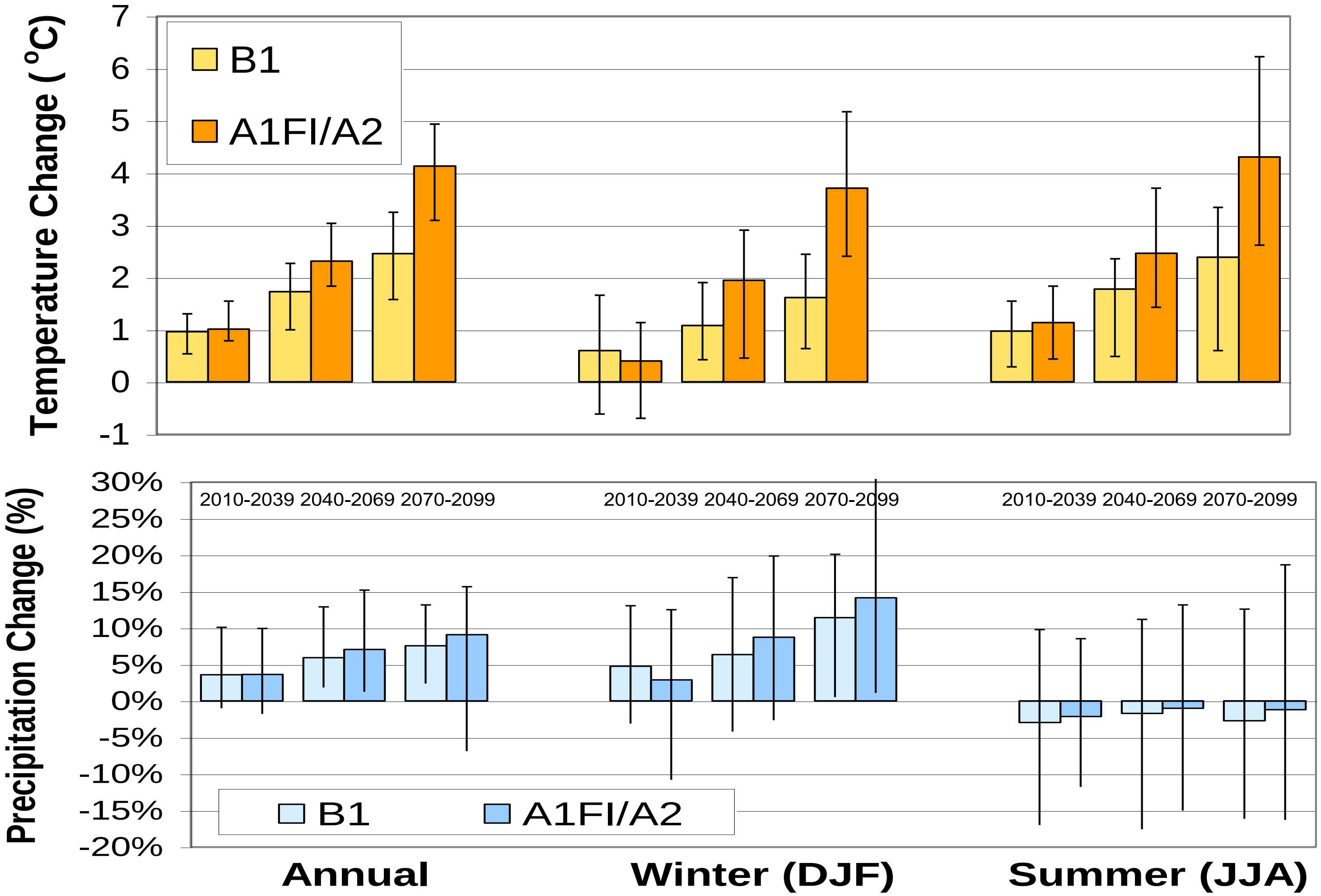

Figure 2. Projected mean annual temperature and precipitation change across entire Northeast Region under two emissions scenarios and in three time periods. From NECIA, 2006.

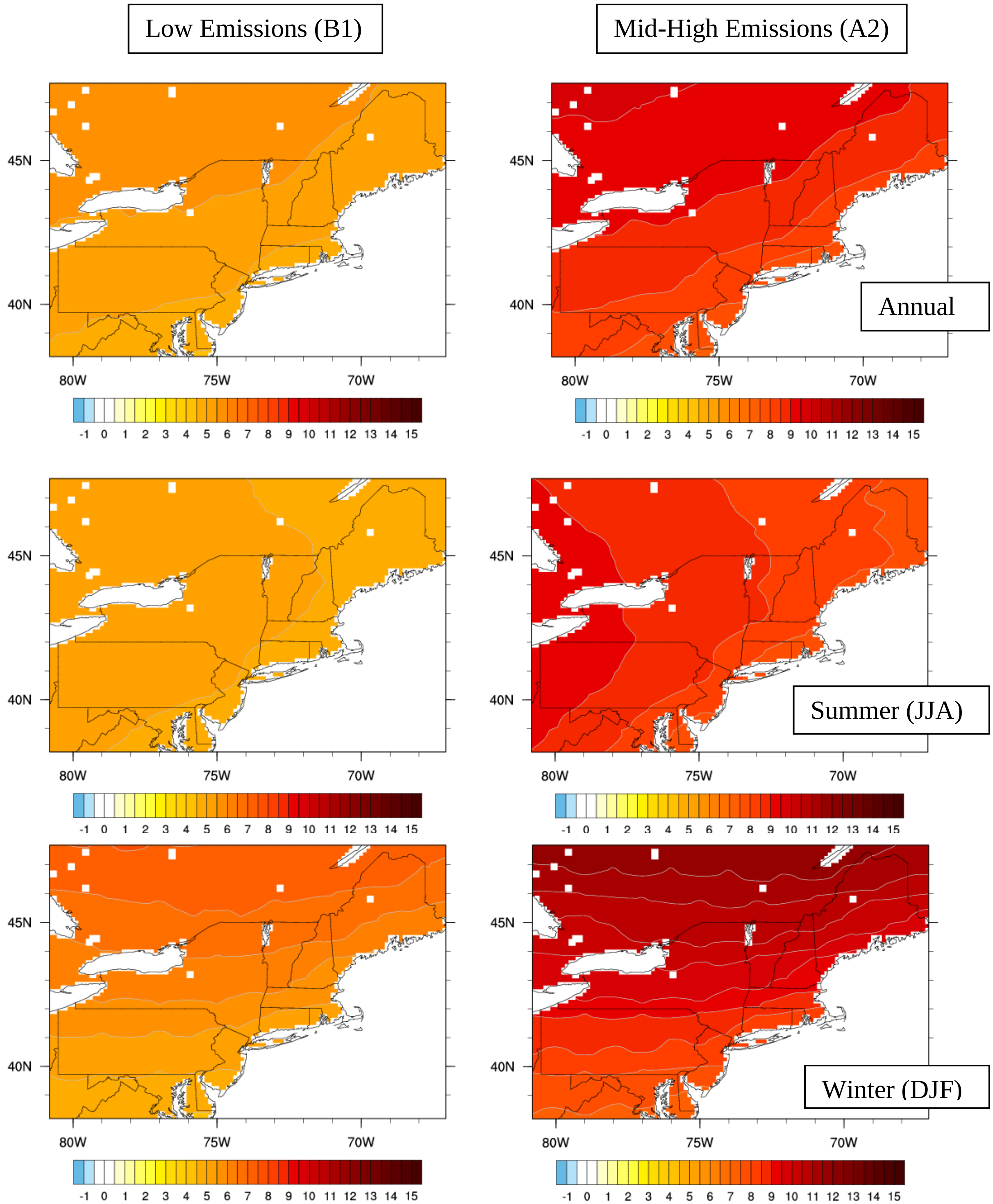

Figure 3. Projected mean temperature change (^{o}F) by 2080-2099 relative to 1971-2000. From NECIA, 2006.

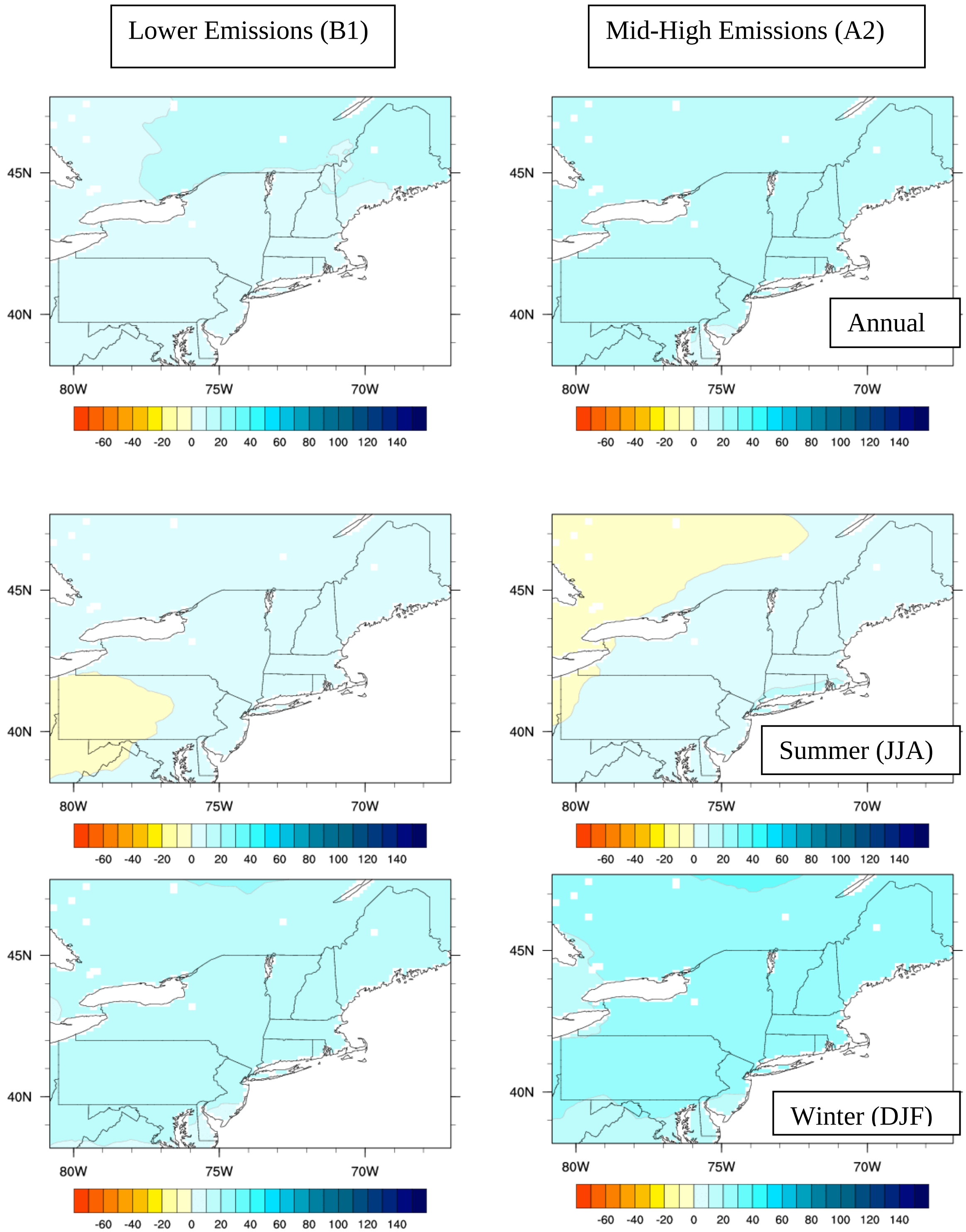

Figure 4. Projected mean precipitation % change relative to 1971-2000 by 2080-2099. From NECIA, 2006.

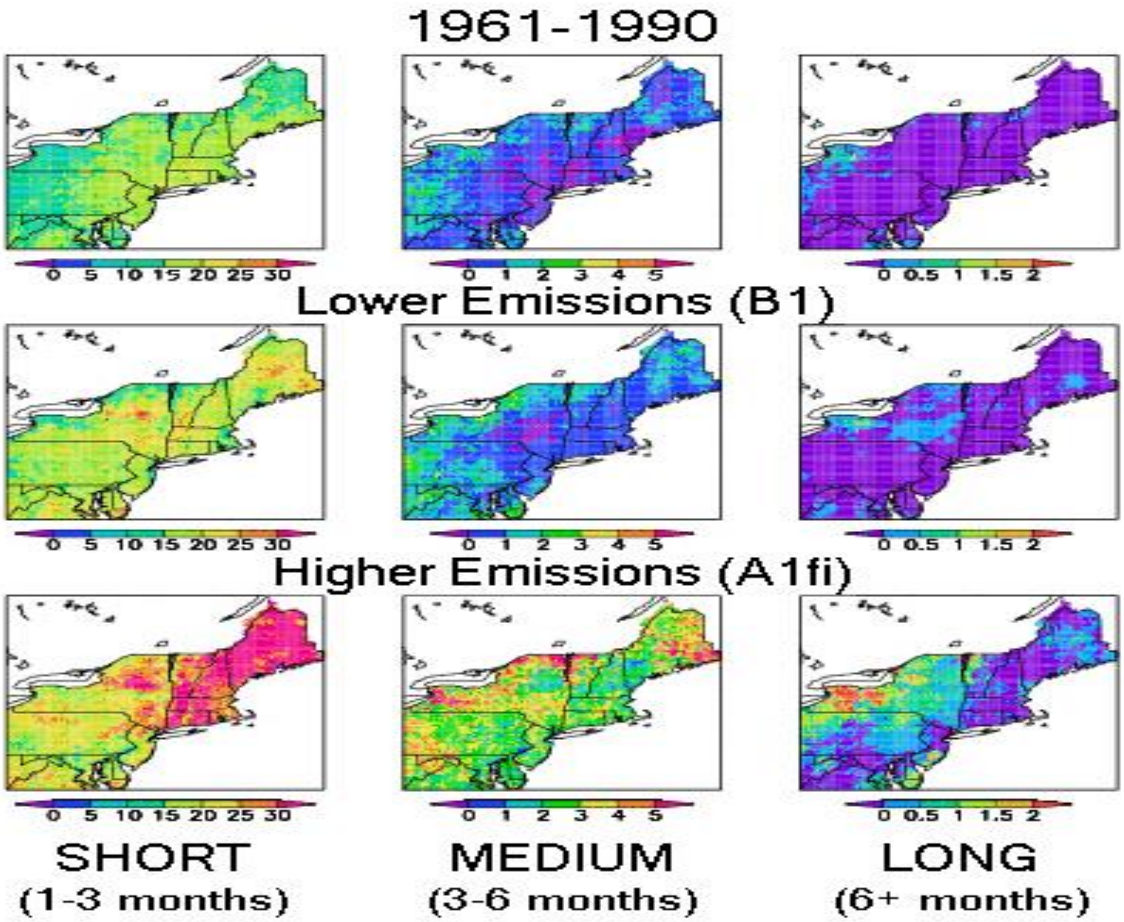

Figure 5. Frequencies of short-, medium-, and long-term droughts during 1961-1990 and projected for the 30 year period 2070-2099. Values are the average of the HadCM3 and PCM models. From NECIA, 2006.

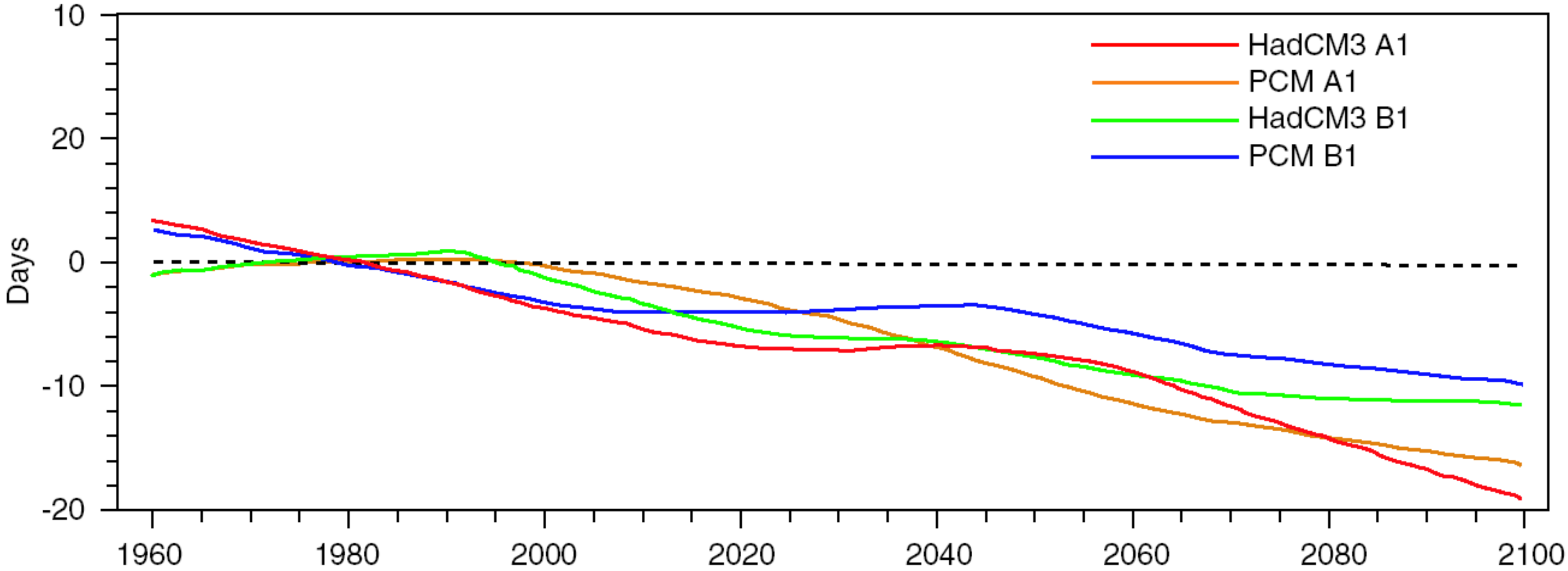

Figure 6. Projected advance in peak spring flow. From NECIA, 2006.

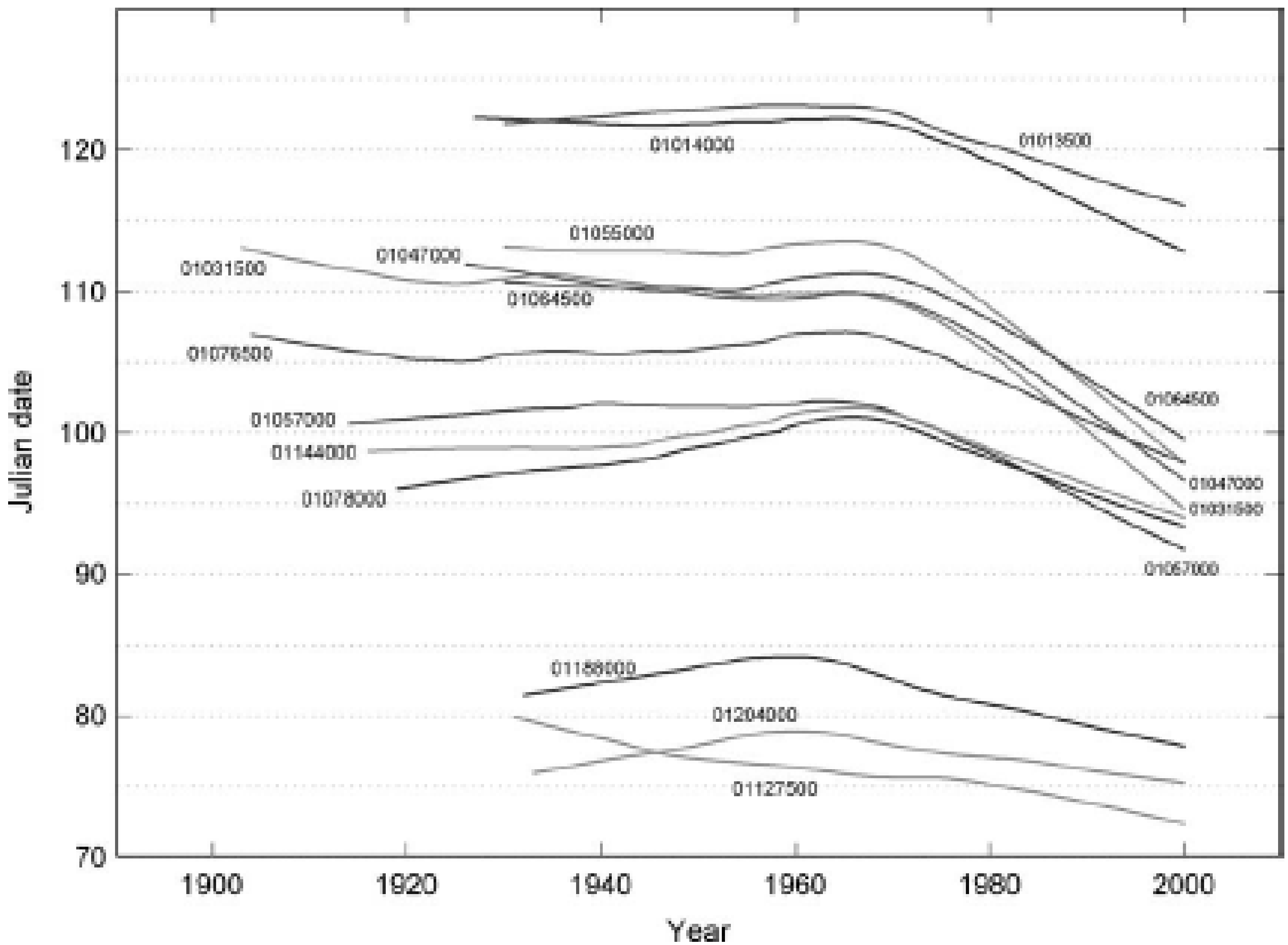

Figure 7. Observed earlier peak spring flow. From NECIA, 2006.

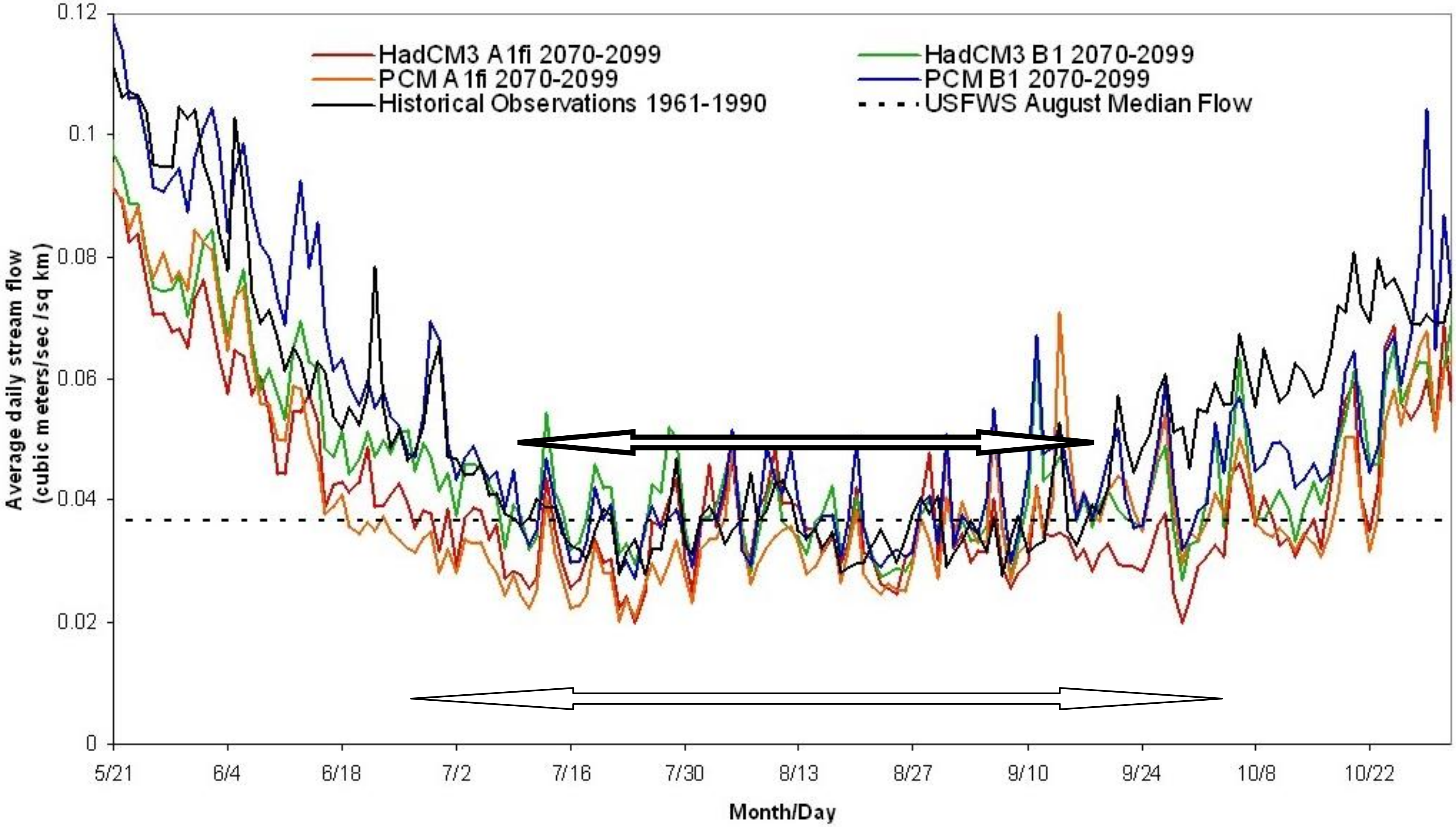

Figure 8. Increase in duration of summer low flow periods. From NECIA, 2006.

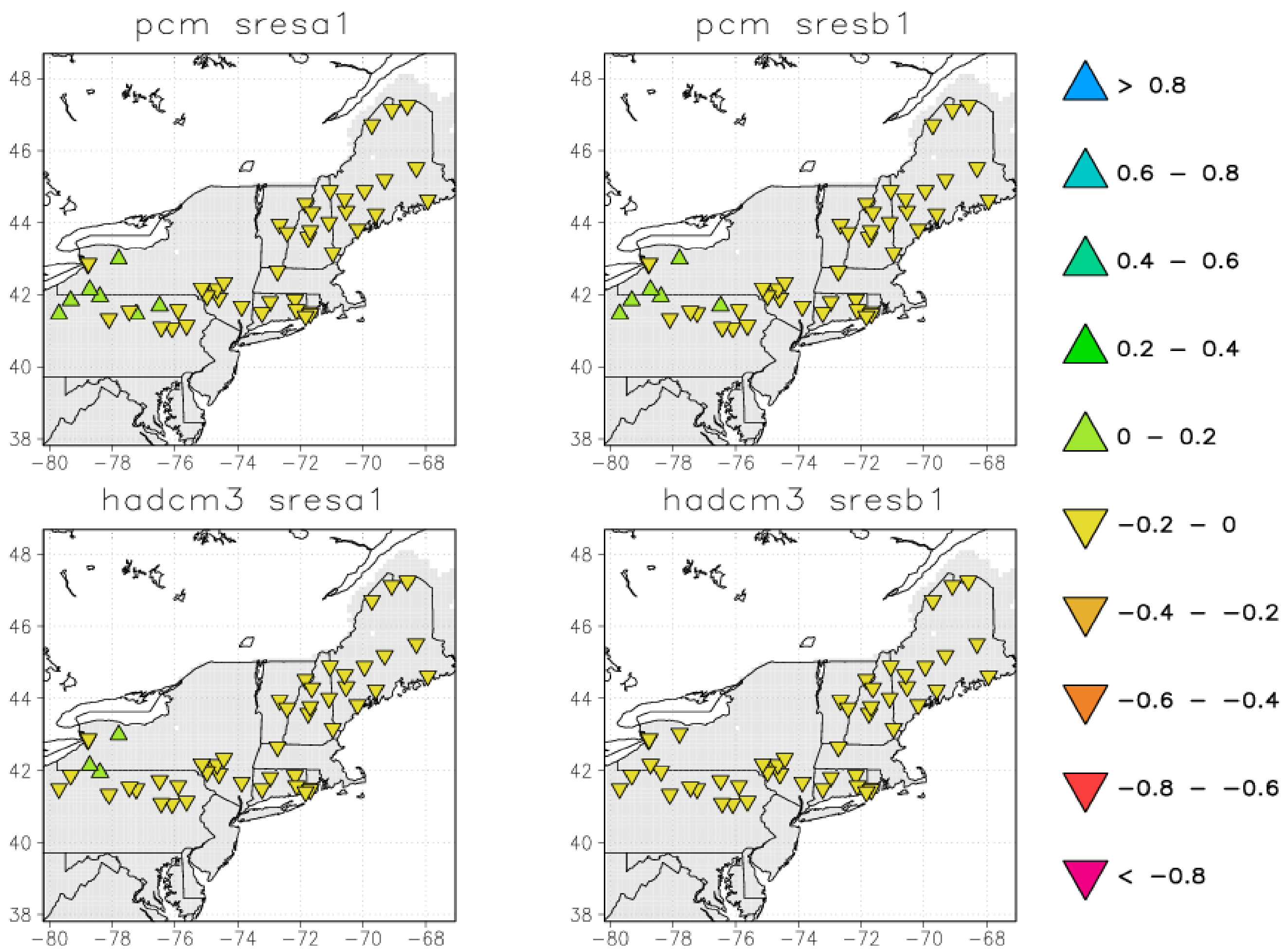

Figure 9. Projected change in the probability of low (10%) flows from the historic (1961-1990) to the future (2070-2099) periods for winter (DJF) for selected basins. Indicates a decreased probability of low flow events across much of the northern part of the NE under the A1FI scenario as compared with B1. From NECIA, 2006.

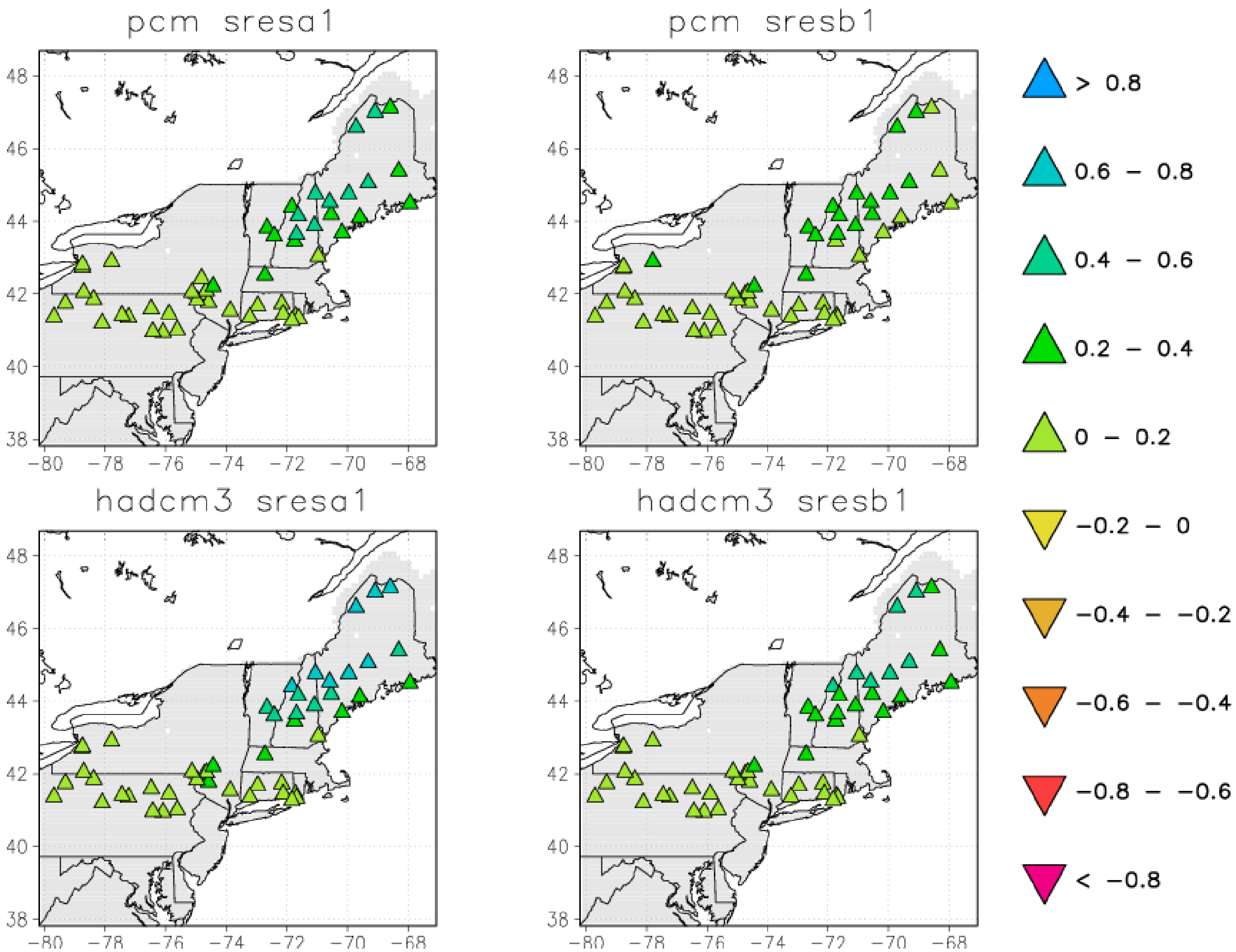

Figure 10**.** Projected change in the probability of high (90%) flows from the historic (1961-1990) to the future (2070-2099) periods for winter (DJF) for selected basins. Simulations indicate an increased probability of high flow events across much of the northern part of the NE under the A1FI scenario as compared with B1. From NECIA, 2006.

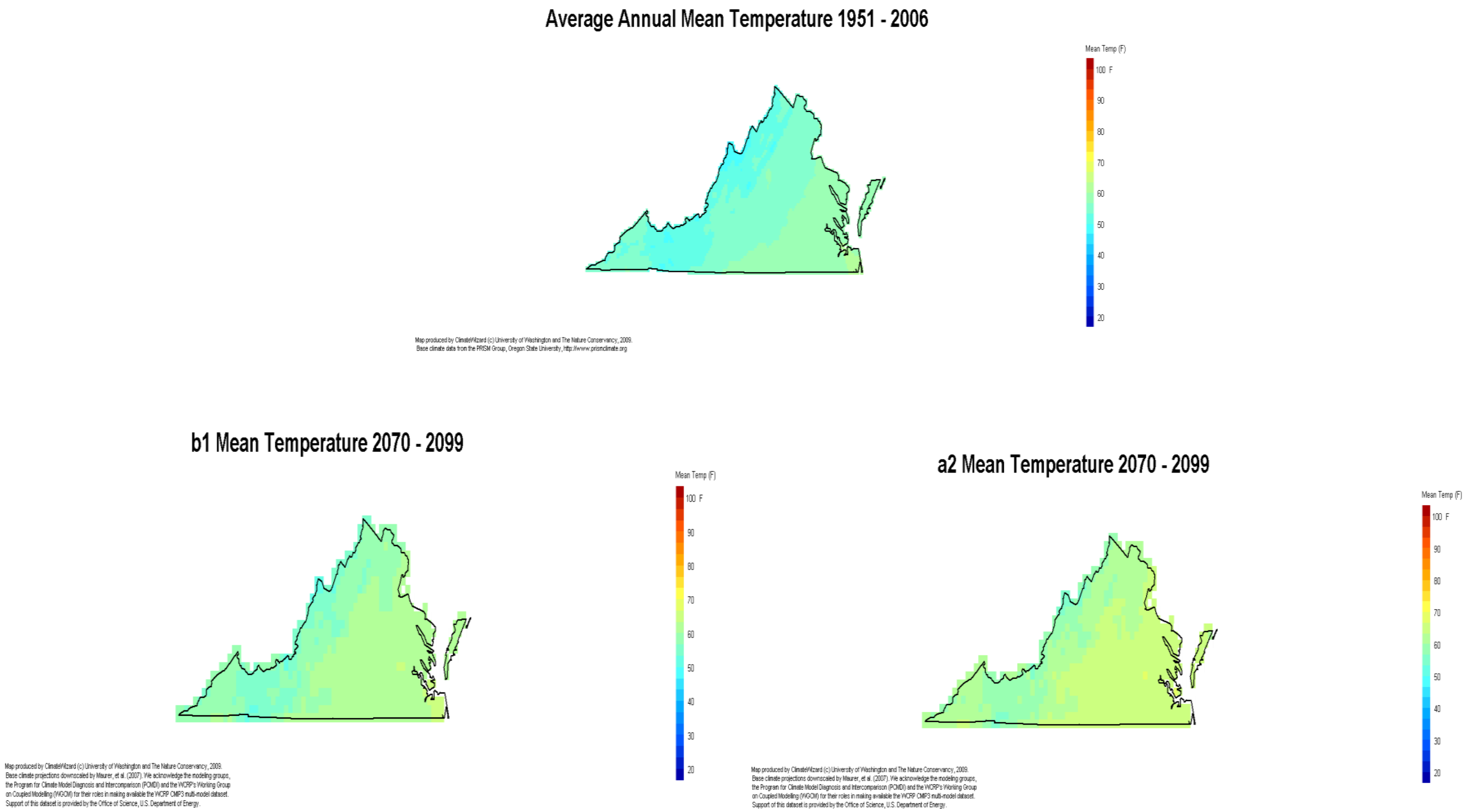

Figure 11. Current and projected annual mean temperatures in Virginia under the B1 and A2 emissions scenarios. Data are means of 16 GCM predictions (analyses from ClimateWizard).

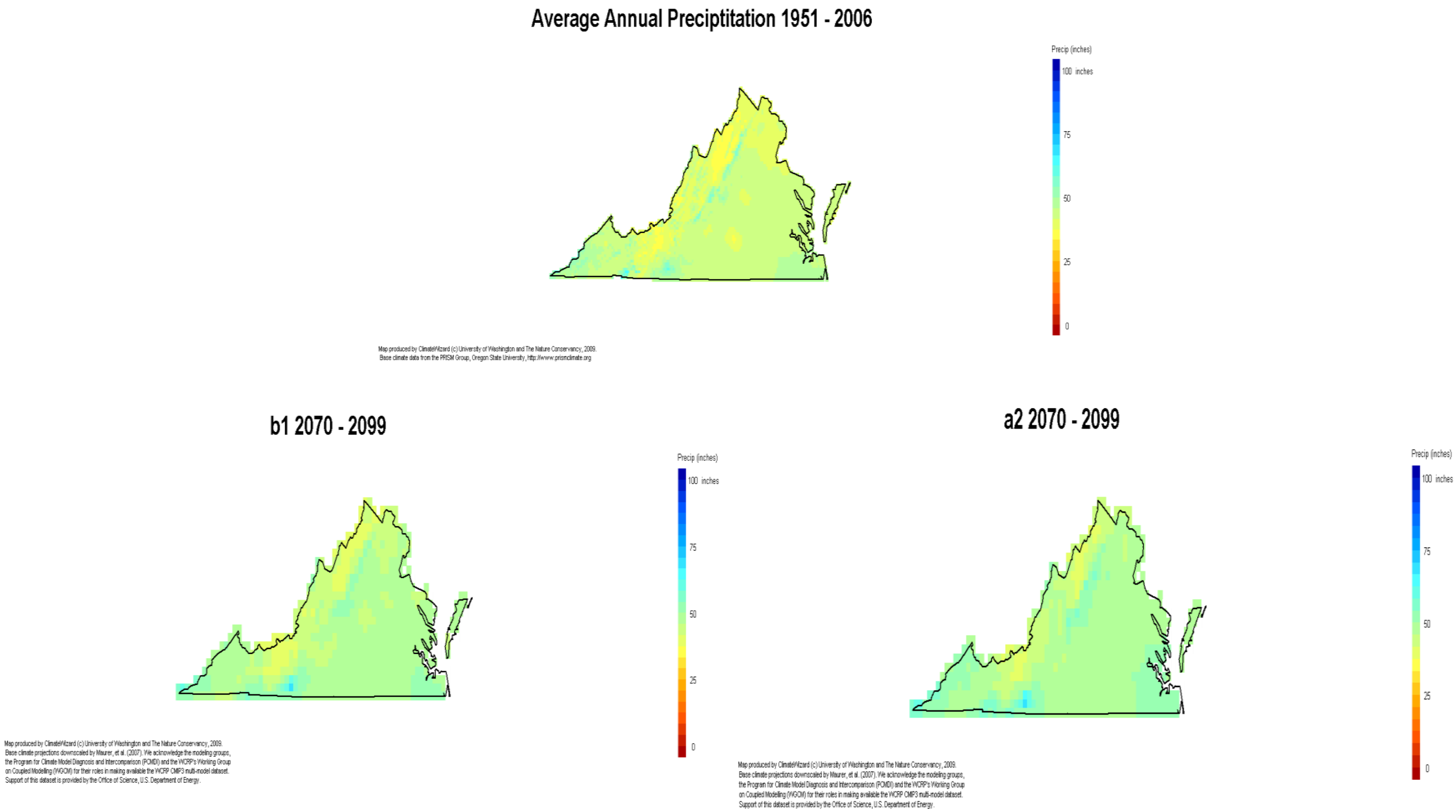

Figure 12. Current and projected annual mean precipitation in Virginia under the B1 and A2 emissions scenarios. Data are means of 16 GCM predictions. Analyses from ClimateWizard.

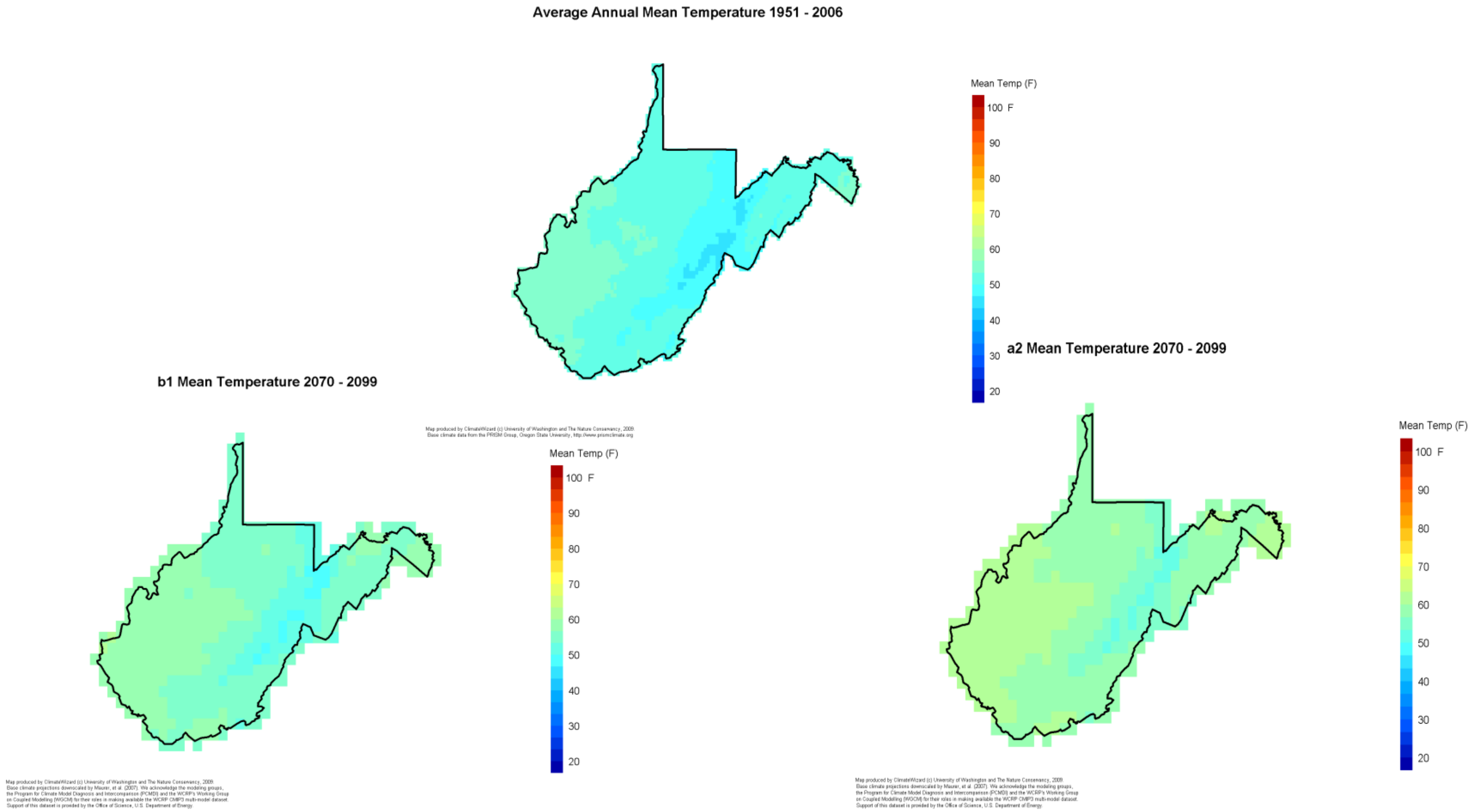

Figure 13. Current and projected annual mean temperatures in West Virginia under the B1 and A2 emissions scenarios. Data are means of 16 GCM predictions. Analyses from Climate Wizard.

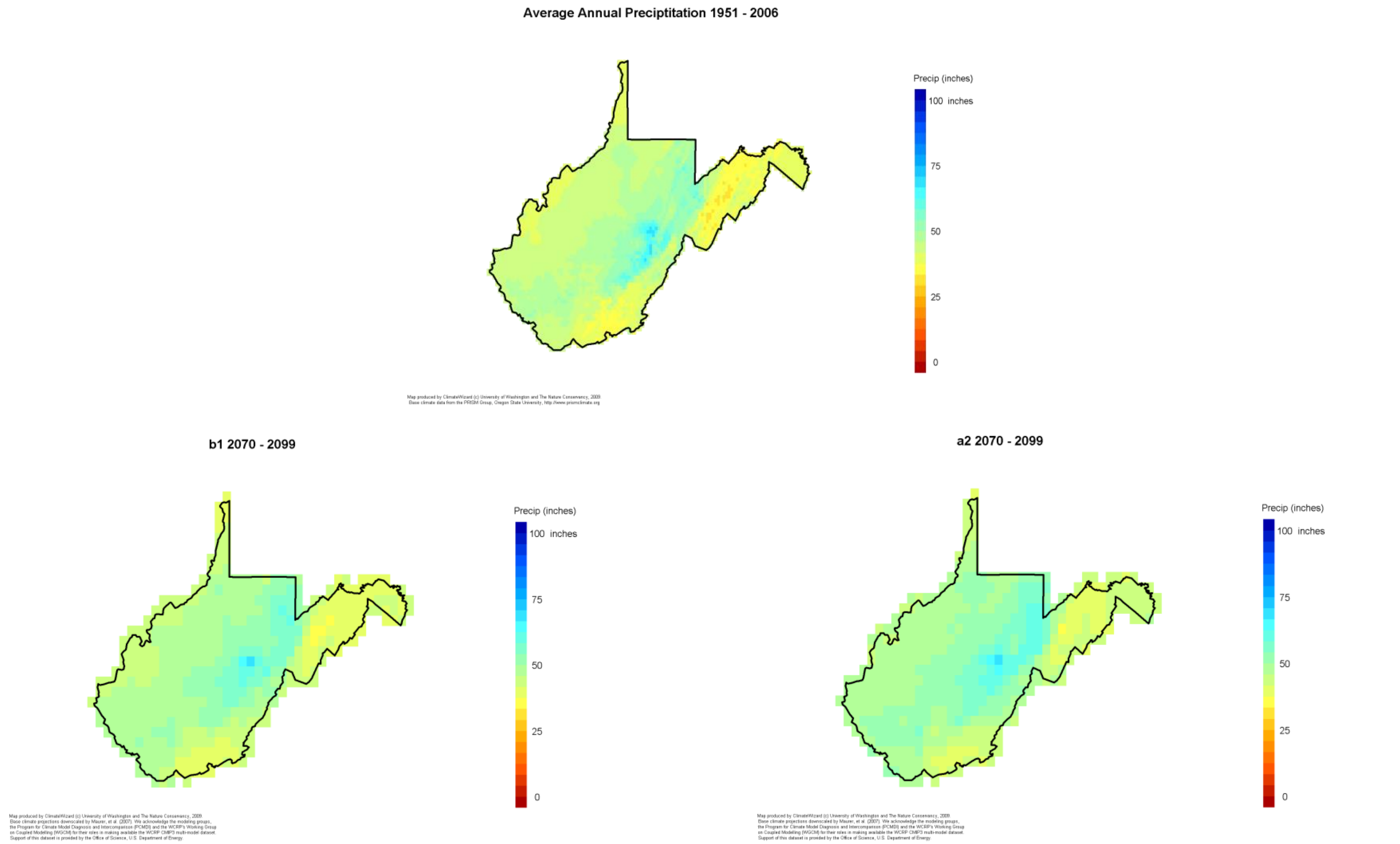

Figure 14. Current and projected annual mean precipitation in West Virginia under the B1 and A2 emissions scenarios. Data are means of 16 GCM predictions. Analyses from ClimateWizard.

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