EARLY ONLINE RELEASE

This is a preliminary PDF of the author-produced manuscript that has been peer-reviewed and accepted for publication. Since it is being posted so soon after acceptance, it has not yet been copyedited, formatted, or processed by AMS Publications. This preliminary version of the manuscript may be downloaded, distributed, and cited, but please be aware that there will be visual differences and possibly some content differences between this version and the final published version.

Seasonal climate trends, the North Atlantic Oscillation and salamander abundance in the southern Appalachian Mountain region

Robert J. Warren II and Mark A. Bradford

School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511,

USA

Corresponding author:
Robert J. Warren II
Tel: +1 8285061253
Fax: +1 8285862351
Email: hexastylis@gmail.com

Figures: 3
Tables: 1

1

Abstract

The North Atlantic Oscillation (NAO) is a large-scale climate teleconnection that coincides with worldwide changes in weather. Its impacts have been documented at large-scales, particularly in Europe, but not as much at regional scales. Furthermore, despite documented impacts on ecological dynamics in Europe, the NAO's influence on North American biota has been somewhat overlooked. This paper examines long-term temperature and precipitation trends in the southern Appalachian Mountain region – a region well known for its biotic diversity, particularly in salamander species – and examines the connections between these trends and NAO cycles. In order to connect the NAO phase shifts with southern Appalachian ecology, trends in stream salamander abundance are also examined as a function of the NAO index. The results reported here indicate no substantial long-term warming or precipitation trends in the southern Appalachians, and a strong relationship between cool season (November-April) temperature and precipitation and the NAO. More importantly, trends in stream salamander abundance are best explained by variation in the NAO as salamanders are most plentiful during the warmer, wetter phases.

1. Introduction

Increased radiative heating at the Earth's surface is driving the mean global temperature upward nearing a rate unseen in 10,000 years (IPCC 2007). The warming trend both explains current large-scale ecological patterns and may foreshadow what is to come (Root et al. 2003; Walther et al. 2002). However, there exists an enormous discrepancy between mean warming trends at global and regional scales (Hurrell 1995; IPCC 2007;

Parry et al. 2007; Smith et al. 2007). Contributing to this variance are teleconnections: fluctuations in atmospheric circulation patterns that impact multiple regions concurrently (proximate and distant). The El Niño/Southern Oscillation (ENSO) is a well known teleconnection that incurs worldwide synchronized impacts. These linkages dictate that warming in one region corresponds with cooling in another (Hurrell and Dickson 2004).

The North Atlantic oscillation (NAO) is a recurrent teleconnection influencing weather throughout Western Europe and eastern North America, and as far as eastern Asia (Durkee et al. 2008; Hurrell 1995; Hurrell and Dickson 2004). The NAO, which is particularly robust in the Northern Hemisphere winter, is named for the distribution of atmospheric pressure between the Arctic (polar low) and mid-Atlantic (subtropic high) regions. The NAO oscillates between positive and negative phases (corresponding with relative pressure differentials) and variation in the strength of these lows and highs influences oceanic wind strength and direction, heat and moisture transport, and storm paths and intensities (Durkee et al. 2008; Hurrell and Dickson 2004). These phases vary greatly within- and across- seasons, yet often persist over multiple consecutive years. Since the 1970s, the NAO has tended toward the positive phase resulting in warmer, wetter winters in northern Europe and eastern North America and colder, drier conditions in southern Europe and North Africa (Durkee et al. 2008; Hurrell 2008; Hurrell and Dickson 2004). While these impacts are well-described for European ecology (Stenseth et al. 2002), the NAO influence on North American ecology is relatively unknown.

Teleconnections set up an intriguing conundrum for those interested in explaining and forecasting ecological responses to historical and future climate variation. In looking to explain biological trends, researchers may focus on climate signal trends, but failure to

connect ecological and weather patterns may reflect the comprehensive effect of teleconnections (Stenseth et al. 2002) rather than a lack of biological climate response. Variation in the NAO corresponds with variation in the population dynamics of many terrestrial and marine species (*see* Stenseth et al. 2002 and references therein). The southern Appalachian Mountain region contains a high degree of salamander diversity and biomass, most notably lungless (Plethodontid) salamanders (Petranka 1998). What most distinguishes plethodontid salamanders from other salamander families, and amphibians as a whole, is their complete dependence upon cutaneous respiration (absorption of oxygen via moist skin) (Feder and Burggren 1985; Whitford and Hutchinson 1967). Plethodontid salamanders are often the dominant vertebrates in the mesic forests of the eastern U.S. (Hairston 1987; Jaeger 1979; Petranka and Murray 2001), with abundance and biomass that equals or surpasses that of small mammals and birds (Burton and Likens 1975). They are sensitive to desiccation caused by low moisture and/or high temperature (Bernardo and Spotila 2006; Bernardo et al. 2007; Feder and Londos 1984; Jaeger 1980; Spotila and Berman 1976; Tilley and Bernardo 1993).

This study examines seasonal variation in temperature and precipitation from 1931 to 2004 in the southern Appalachian region of North Carolina (Southern Blue Ridge Physiographic area). The objectives in this paper are to investigate the long term trends in regional temperature and precipitation and assess the correspondence between southern Appalachian climate trends and the NAO index. The study also examines whether a link exists between variation in the NAO index and local stream salamander abundance.

2. Methods

4

The southern Appalachian region is the site of a National Science Foundation Long-Term Ecological Research (LTER 2009) site (i.e. Coweeta Hydrological Laboratory) and receives the highest precipitation levels in the eastern U.S. It is characterized by high endemic diversity and functions as a water source for widespread human development in the surrounding lowlands. Understanding climate patterns and drivers is therefore important both for preserving diversity, and water quantity and quality in the region.

a. Climate data

Annual mean monthly temperatures and precipitation totals for the years 1931-2004 were gathered from monthly readings at 11 weather stations located within a 21,000 km^2 area in the southern Appalachian Mountains of North Carolina (Table 1). The climate data for these stations are compiled by the National Climatic Data Center (managed by the National Oceanic and Atmospheric Administration (NCDC 2010)), and were accessed via the Coweeta Long Term Ecological Research (LTER) Program internet site (LTER 2009). Whereas there are more than 11 weather stations within the target area, only those selected had complete temperature and precipitation data for the years 1931-2004. Climate trends were analyzed using temperature and precipitation anomalies from the mean of the base period, 1951-1980. The use of anomalies rather than means corrects for spatial variance between weather stations as well as confounding from variations in weather station methodology, vegetation and urbanization (Hansen et al. 1999). To ensure that individual stations did not follow different long term trends than others within the target region, we analyzed the coefficient of variation between stations as a function of time (1931-2004) and found no trends in temperature or precipitation variance.

Annual climate measures were divided into two seasons – the Northern Hemisphere "cool season" (November-April) and "warm season" (May-October) – which reduces the impact of weather noise inherent in three-month periods, the impact of seasonal autocorrelation between climate variables, and allows the investigation of the influence of large-scale climate drivers, such as the North Atlantic Oscillation (sensu Hansen et al. 1999). The NAO index is a dimensionless measure of strength of the North Atlantic Oscillation. It is calculated from the difference between the normalized sea level pressure over Gibraltar and the normalized sea level pressure over southwest Iceland. Monthly NAO index values for the years 1931-2004 were downloaded from http://www.cru.uea.ac.uk/cru/data/nao/.

The salamander abundance data (1976-2007) were collected near Ball Creek (elevation 686 m) at the U.S. Forest Service's Coweeta Hydrologic Laboratory (35º00'N, 83º30'W) and downloaded from http://www.unc.edu/~rhwiley/salamandertrends. Four species of *Desmognathus* salamanders (*D. quadramaculatus*, *D. monticola*, *D. ocoee*, *D. aeneus*) were collected and identified twice per year beginning in 1976. Abundance was estimated as the number of salamanders surveyed per person in 1.5 hours of searching from the creek and upslope. See Hairston and Wiley (1993) for more information on methods. Annual (or seasonal averages) surveys are reasonable estimates of relative abundance if standardized protocols are used (Smith and Petranka 2000; Welsh and Droege 2001). Whereas these *Desmognathus* sp. are stream salamanders, making hydroperiod the intuitive direct climate-driven effect (Camp et al. 2007), stream salamanders forage terrestrially (Hairston 1987), the extent governed by temperature and

moisture (Camp and Lee 1996; Feder and Londos 1984; Moore and Sievert 2001; Petranka and Smith 2005; Petranka et al. 1994).

b. Data analysis

Time series of seasonal (warm and cool) southern Appalachian temperature and precipitation were analyzed to determine long-term (74 year) trends. The data were modeled using Box-Jenkins autoregressive moving average models (ARMA) (Box et al. 1994) using the R software package (R 2005) to account for the autocorrelation between observations inherent in time series analysis,. The autoregressive portion resembles a linear regression of the current time series value against one or more previous values; the moving average is essentially a filtering function that compares the current value against random error in previous values (Shumway and Stoffer 2006). Generalized Least Squares (GLS) regressions with maximum likelihood were used to analyze the models. The GLS model assumes that errors are correlated and may have unequal variances without assuming linearity in the data. The model order (degree of autocorrelation) was selected based on the autocorrelation (ACF) and partial autocorrelation (PACF) functions (Shumway and Stoffer 2006). Akaike Information Criterion (AIC) was used to select models where indications were ambiguous. First and second order polynomials were included in the time series models to account for non-linear, long-term trends. Southern Appalachian temperature, precipitation and salamander abundance trends as a function of NAO also were modeled using ARMA models.

3. Results

Climate patterns, drivers and ecological response

Statistically significant, long-term trends in southern Appalachian cool and warm season temperature anomalies were observed (Fig. 1a,b). Compared to the mean of the base period (1951-1980), cool season temperatures decreased considerably between 1931 and the 1960s (*coeff.* = -2.45, *SE* = 1.2, *t* = -2.1, *p* < 0.05) and then increased slightly between the 1960s and 2004 (*coeff.* = 0.006, *SE* = 0.003, *t* = 2.1, *p* < 0.05). A similar pattern was observed during the warm season as temperatures decreased significantly between 1931 and the late 1950s (*coeff.* = -2.36, *SE* = 0.5, *t* = -4.8, *p* < 0.001) and then increased slightly between the 1960s and 2004 (*coeff.* = 0.0006, *SE* = 0.0003, *t* = 4.8, *p* < 0.001). The slope coefficients indicate that the cooling trends were far greater than the warming, and cool and warm season temperatures in the latter half of the 1931-2004 study period do not exceed those at the beginning. Interannual variation in cool season temperature anomalies appeared more pronounced than interannual variation in warm season anomalies, which was emphasized by the magnitude of the fluctuations in the 5-year running means (Fig. 1a,b). In contrast to temperature, there were no long-term trends in precipitation during the 1931-2004 period (Fig. 1c,d). There were no significant temporal trends in precipitation in either cool (*coeff.* = 1.27, *SE* = 2.5, *t* = 0.5, *p* > 0.05) or warm (*coeff.* = -0.1, *SE* = 2.1, *t* = -0.51, *p* > 0.05) seasons as compared to the mean of the base period (1951-1980),

Variation in southern Appalachian temperatures varied significantly with the NAO index during the cool season (*coeff.* = 0.58, *SE* = 0.1, *t* = 4.8, *p* < 0.001) (Fig. 2a), but not during the warm season (*coeff.* = -0.33, *SE* = 0.4, *t* = -0.8, *p* > 0.05) (Fig. 2b). As with temperature, southern Appalachian precipitation trends also varied significantly with

the NAO index during the cool season (*coeff.* = 0.72, *SE* = 0.3, *t* = 2.3, *p* <0.05) but not during the warm season (*coeff.* = -0.47, *SE* = 0.5, *t* = 0.9, *p* >.0.05.). The correspondence between southern Appalachian temperature and precipitation and shifts in the NAO index also appeared to impact salamander (*Desmognathus* sp.) abundance during the cool season (*coeff.* = 0.76, *SE* = 0.4, *t* = 1.9, *p* <0.05) but not during the warm season (*coeff.* = -0.1, *SE* = 0.5, *t* = -0.2, *p* >0.05) (Fig. 3).

4. Discussion

We find that long-term trends in southern Appalachian cool and warm season temperatures are biased toward cooler temperatures since 1931 with a slight leveling in recent decades (Fig. 1). In particular, there is no evidence for an overall warming trend (Figs. 1-2). Variation in the southern Appalachian cool season temperature from 1931 to 2004 is significantly related to the decadal oscillations of the NAO index (Fig. 2). During the cool season, when the atmospheric influence of the NAO is strongest, southern Appalachian temperatures rise and fall with atmospheric pressure discrepancies in the North Atlantic summarized as the NAO index. During the warm season, when the influence of the NAO is weak, southern Appalachian temperatures do not correspond with the NAO index. The full impact of this on ecological response is unknown, but only cool season NAO indices statistically correspond with stream salamander abundance (Fig. 3).

Despite pronounced interannual variability in cool and warm season precipitation anomalies, no long-term trends in southern Appalachian precipitation are apparent. Given that increased temperature speeds up the hydrologic cycle, and there is evidence of

increased precipitation in the United States that may be linked with global trends (Easterling et al. 2000), this may change in the next century. Cool season precipitation is statistically linked with the NAO index, suggesting that effective prediction of change in this teleconnection may facilitate robust projection of southern Appalachian cool season climate. Variation in the NAO appears to be driven by sea surface temperatures, particularly in tropical waters (Hurrell 2008). A definitive link with anthropogenic climate forcing has not been found, although NAO trends may reflect mean global temperatures (Goodkin et al. 2008). Indeed, as with the unprecedented spike in the rate of global warming, evidence suggests that atmospheric circulation drivers of climate variability (e.g., the NAO) are also beginning to reach intensities anomalous in the long term (Jones and Mann 2004). Positive NAO phases have dominated the oscillation since 1980 at a magnitude unprecedented in the observational and paleoclimatic record (see Hurrell and Dickson 2004), and this has been linked with warming tropical ocean waters (Hoerling et al. 2001). The uncertainty in whether there will be reinforcement or weakening of this oscillation trend means that ecologists need to consider multiple climate change scenarios to facilitate projection of possible ecological response in the southern Appalachians, as well as other regions around the world where climate is strongly influenced by teleconnections.

That stream salamander abundance in the southern Appalachians corresponds with variation in the NAO highlights the possibility that changes in the frequency and amplitude of the NAO have profound impacts on southern Appalachian biota, as it does on biota throughout the North Atlantic basin (Stenseth et al. 2002). Salamander abundance likely responds positively to positive NAO anomalies because warmer and

wetter cool seasons facilitate overwintering survival and/or increase spring foraging (Bernardo and Spotila 2006; Bernardo et al. 2007; Camp et al. 2007; Marshall and Camp 2006). Walls (2009) attempted to correlate statistically (without accounting for temporal autocorrelation) southern Appalachian terrestrial plethodontid salamander hybrid zone data with annual regional temperature trends, but only found a weak temperature correlate with the high elevation species and not its putative hybrid. In doing so, this may obscure actual seasonal trends driven by regional climate within the context of teleconnection oscillations. The term observed by Walls (2009), 1974-1990, coincides with a particularly biased phase of the NAO, and thus a species shift may actually reflect any or all of the multiple climate variables that shift in concert with the NAO (Huntley et al. 1995).

The IPCC (2007) state that ecological impacts research is hampered by uncertainties surrounding regional projections of climate change. The uncertainty concerning climate drivers has a substantial impact on climate projection. Indeed, a dizzying selection of climate prediction models outline scenarios for future climate (Parry et al. 2007), and selection of the climate projection is critical in assessing the potential impact on species (Beaumont et al. 2008). For the southeastern U.S. region, not enough of the global climate models predict congruent precipitation patterns to estimate reliably future patterns (IPCC 2007). The southern Appalachian region has yet to experience the recent, pronounced warming trend exhibited at the global scale, and predicted outcomes for this region vary greatly per model. Thus, models that project rapid warming and drying by the end of the century may better fit global than southern Appalachian trends.

Acknowledgments

References

Beaumont, L. J., L. Hughes, and A. J. Pitman, 2008: Why is the choice of future climate scenarios for species distribution modelling important? *Ecology Letters*, **11,** 1135-1146.

Bernardo, J. and J. R. Spotila, 2006: Physiological constraints on organismal response to global warming: mechanistic insights from clinally varying populations and implications for assessing endangerment. *Biology Letters*, **2,** 135-139.

Bernardo, J., R. J. Ossola, J. Spotila, and K. A. Crandall, 2007: Interspecies physiological variation as a tool for cross-species assessments of global warming-induced endangerment: validation of an intrinsic determinant of macroecological and phylogeographic structure. *Biology Letters*, **3,** 695-698.

Box, G. E. P., G. M. Jenkins, and G. C. Reinsel, 1994: *Time Series Analysis, Forecasting and Control.* Prentice Hall.

Burton, T. M. and G. E. Likens, 1975: Salamander populations and biomass in Hubbard Brook Experimental Forest, New Hampshire. *Copeia***,** 541-546.

Camp, C. D. and T. P. Lee, 1996: Intraspecific spacing and interaction within a population of *Desmognathus quadramaculatus*. *Copeia***,** 78-84.

Camp, C. D., D. L. Huestis, and J. L. Marshall, 2007: Terrestrial versus aquatic phenotypes correlate with hydrological predictability of habitats in a

semiterrestrial salamander (Urodela, Plethodontidae). *Biological Journal of the Linnean Society*, **91,** 227-238.

Durkee, J. D., J. D. Frye, C. M. Fuhrmanny, M. C. Lacke, H. G. Jeong, and T. L. Mote, 2008: Effects of the North Atlantic Oscillation on precipitation-type frequency and distribution in the eastern United States. *Theoretical and Applied Climatology*, **94,** 51-65.

Easterling, D. R., G. A. Meehl, C. Parmesan, S. A. Changnon, T. R. Karl, and L. O. Mearns, 2000: Climate extremes: Observations, modeling, and impacts. *Science*, **289,** 2068-2074.

Feder, M. E. and P. L. Londos, 1984: Hydric constraints upon foraging in a terrestrial salamander, *Desmognathus-Ochrophaeus* (Amphibia, Plethodontidae). *Oecologia*, **64,** 413-418.

Feder, M. E. and W. W. Burggren, 1985: Cutaneous Gas-Exchange in Vertebrates - Design, Patterns, Control and Implications. *Biological Reviews of the Cambridge Philosophical Society*, **60,** 1-45.

Goodkin, N. F., K. A. Hughen, S. C. Doney, and W. B. Curry, 2008: Increased multidecadal variability of the North Atlantic Oscillation since 1781. *Nature Geoscience*, **1,** 844-848.

Hairston, N. G., 1987: *Community Ecology and Salamander Guilds*. Cambridge University Press.

Hairston, N. G. and R. H. Wiley, 1993: No decline in salamander (Amphibia: Caudata) populations: a twenty-year study in the Southern Appalachians. *Brimleyana*, **18,** 59-64.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato, 1999: GISS analysis of surface temperature change. *Journal of Geophysical Research*, **104,** 30997-31022.

Hoerling, M. P., J. W. Hurrell, and T. Y. Xu, 2001: Tropical origins for recent North Atlantic climate change. *Science*, **292,** 90-92.

Huntley, B., P. M. Berry, W. Cramer, and A. P. McDonald, 1995: Modelling present and potential future ranges of some European higher plants using climate response surfaces. *Journal of Biogeography*, **22,** 967-1001.

Hurrell, J. W., 1995: Decadal Trends in the North-Atlantic Oscillation - Regional Temperatures and Precipitation. *Science*, **269,** 676-679.

——, 2008: Decadel climate prediction: challenges and opportunities. *Journal of Physics: Conference Series*, **125,** 12-18.

Hurrell, J. W. and R. R. Dickson, 2004: Climate variability over the North Atlantic. *Marine Ecosystems and Climate Variation: The North Atlantic : a Comparative Perspective*, N. C. Stenseth, G. Ottersen, J. W. Hurrell, and A. Belgrano, Eds., Oxford University Press.

IPCC, 2007: *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change, 104 pp.

Jaeger, R. G., 1979: Seasonal spatial distributions of the terrestrial salamander Plethodon-Cinereus. *Herpetologica*, **35,** 90-93.

——, 1980: Microhabitats of a terrestrial forest salamander. *Copeia*, 265-268.

Jones, P. D. and M. E. Mann, 2004: Climate over past millennia. *Reviews of Geophysics*, **42**.

LTER, C., 2009: Monthly Climate Data Across the Southern Appalachians (NOAA/NCDC) Coweeta Hydrologic Laboratory, Otto, NC, USA.

Marshall, J. L. and C. D. Camp, 2006: Evironmental correlates of species and genetic richness in lungless salamanders (family Plethodontidae). . *Acta Oecologia*, **29,** 33-44.

Moore, M. M. and L. M. Sievert, 2001: Temperature-mediated characteristics of the dusky salamander (*Desmognathus fuscus*) of southern Appalachia *Journal of Thermal Biology*, **26,** 547-554.

NCDC: National Climatic Data Center. [Available online from www.ncdc.noaa.gov.]

Parry, M. L., O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, Eds., 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution*

of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Petranka, J., 1998: *Salamanders of the United States and Canada*. Smithosonian Institute Press.

Petranka, J. W. and S. S. Murray, 2001: Effectiveness of removal sampling for determining salamander density and biomass: A case study in an Appalachian streamside community. *Journal of Herpetology*, **35,** 36-44.

Petranka, J. W. and C. K. Smith, 2005: A functional analysis of streamside habitat use by southern Appalachian salamanders: Implications for riparian forest management. *Forest Ecology and Management* **210,** 443-454.

Petranka, J. W., M. P. Brannon, M. E. Hopey, and C. K. Smith, 1994: Effects of Timber Harvesting on Low Elevation Populations of Southern Appalachian Salamanders. *Forest Ecology and Management*, **67,** 135-147.

R, 2005. R Foundation for Statistical Computing.

Root, T. L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig, and J. A. Pounds, 2003: Fingerprints of global warming on wild animals and plants. *Nature*, **421,** 57-60.

Shumway, R. H. and D. S. Stoffer, 2006: *Time Series Analysis and its Applications: With R Examples*. Springer Science.

Smith, C. K. and J. W. Petranka, 2000: Monitoring terrestrial salamanders: Repeatability and validity of area-constrained cover object searches. *Journal of Herpetology*, **34,** 547-557.

Smith, D. M., S. Cusack, A. W. Colman, C. K. Folland, G. R. Harris, and J. M. Murphy, 2007: Improved surface temperature prediction for the coming decade from a global climate model. *Science*, **317**.

Spotila, J. R. and E. N. Berman, 1976: Determination of skin resistance and role of skin in controlling water-loss in amphibians and reptiles. *Comparative Biochemistry and Physiology a-Physiology*, **55,** 407-411.

Stenseth, N. C., A. Mysterud, G. Ottersen, J. W. Hurrell, K. S. Chan, and M. Lima, 2002: Ecological effects of climate fluctuations. *Science*, **297,** 1292-1296.

Tilley, S. G. and J. Bernardo, 1993: Life-history evolution in Plethodontid salamanders. *Herpetologica*, **49,** 154-163.

Walls, S. C., 2009: The role of climate in the dynamics of a hybrid zone in Appalachian salamanders. *Global Change Biology*, **15,** 1903-1910.

Walther, G. R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J. M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein, 2002: Ecological responses to recent climate change. *Nature*, **416,** 389-395.

Welsh, H. H. and S. Droege, 2001: A case for using plethodontid salamanders for

monitoring biodiversity and ecosystem integrity of North American forests.

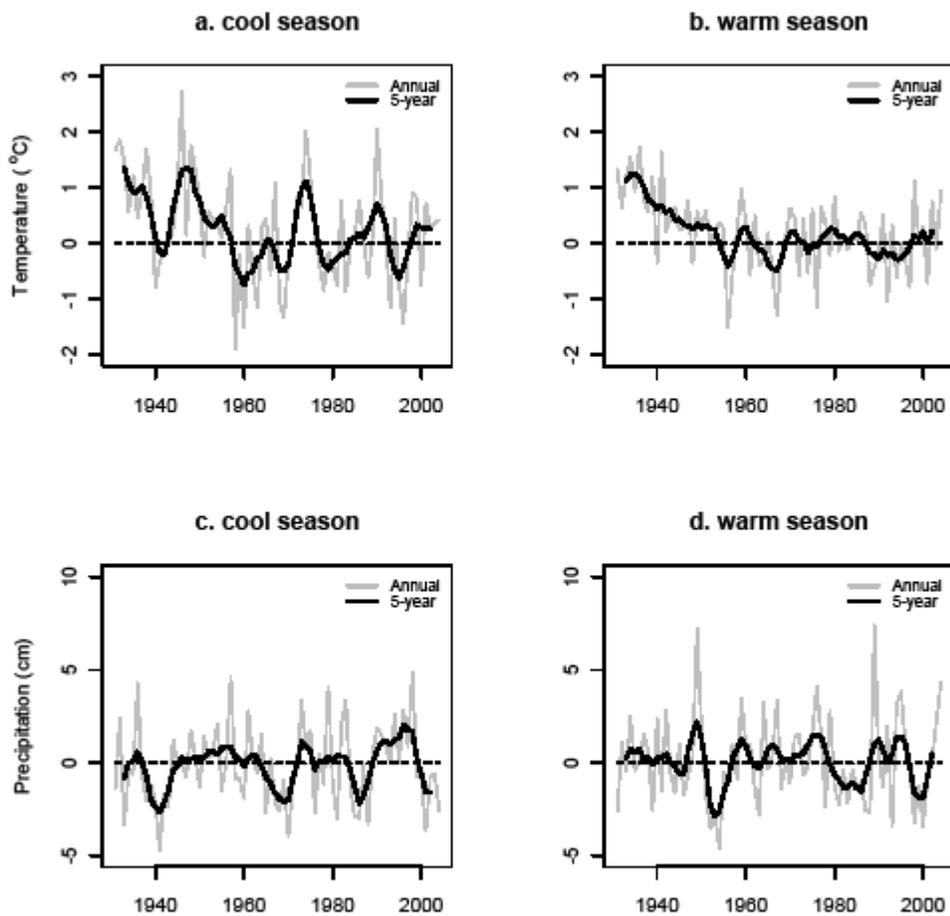*Conservation Biology*, **15,** 558-569.

Whitford, W. G. and V. H. Hutchinson, 1967: Body size and metabolic rate in

salamanders. *Physiological Zoology*, **40,** 127-&.
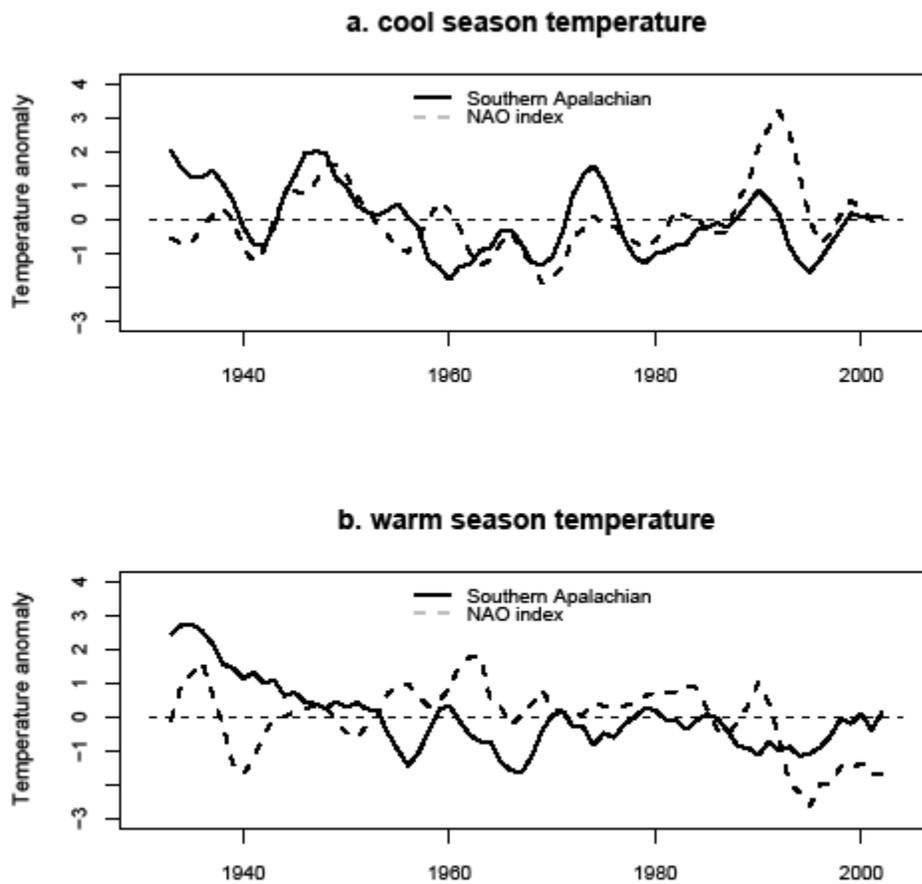
Figure captions

Fig. 1. Southern Appalachian region temperature and precipitation trends by cool (November-April) and warm (May-October) seasons. The trends are represented by annual-means (gray line) and center-weighted 5-year means (black line) of southern Appalachian mean temperature and precipitation anomalies (1931-2004). The climate anomalies are the difference between the yearly means and the mean for the base period 1951-1980.

Fig. 2. Standardized anomalies for southern Appalachian (solid black line) and North Atlantic Oscillation index (gray dashed line) for the years 1931-2004 by cool (November-April) and warm (May-October) seasons. The climate anomalies are the difference between the 5-year weighted means and the weighted mean for the base period 1951-1980. The anomalies were standardized to a normal distribution with mean = 0 and standard deviation = 1 in order to illustrate disparate trends at the same scale.
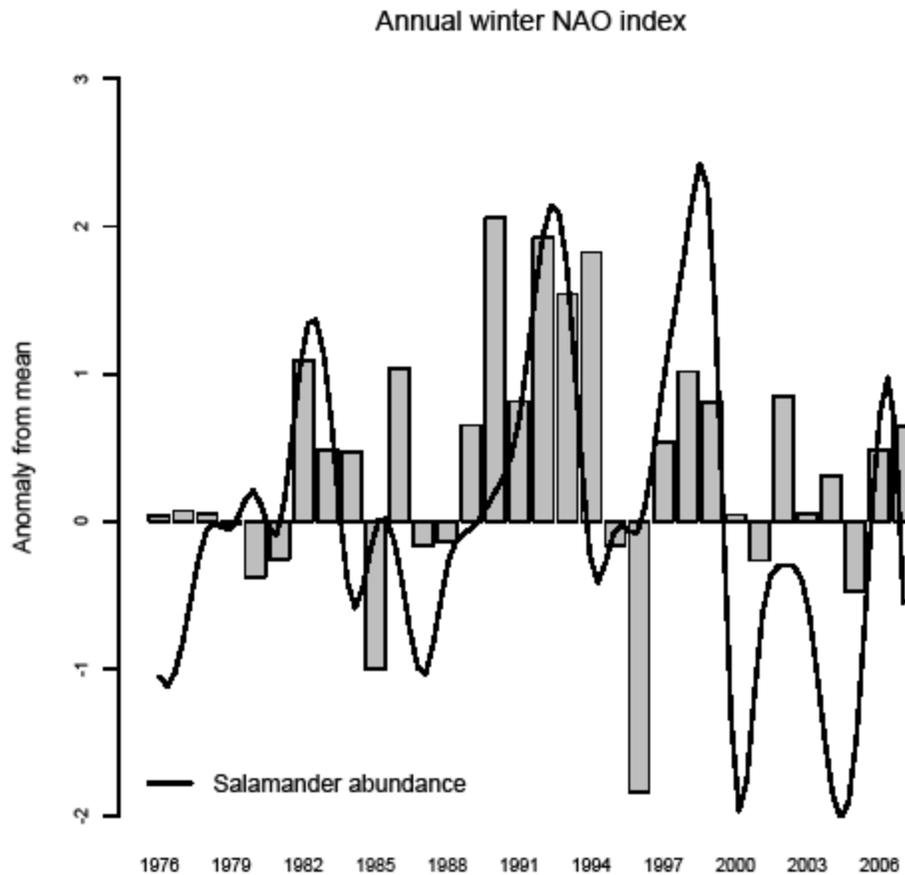
Fig. 3. North Atlantic Oscillation (NAO) index phase anomalies (barplots) overlain by anomalies in southern Appalachian Plethodontid abundance (line). The NAO index and salamander abundance anomalies are the difference between the yearly means and overall means. Positive NAO index anomalies are associated with warmer, wetter winters in the eastern United States.

Fig. 1. Southern Appalachian region temperature and precipitation trends by cool (November-April) and warm (May-October) seasons. The trends are represented by annual-means (gray line) and center-weighted 5-year means (black line) of southern Appalachian mean temperature and precipitation anomalies (1931-2004). The climate anomalies are the difference between the yearly means and the mean for the base period 1951-1980.

a. cool season temperature

b. warm season temperature

Fig. 2. Standardized anomalies for southern Appalachian (solid black line) and North Atlantic Oscillation index (gray dashed line) for the years 1931-2004 by cool (November-April) and warm (May-October) seasons. The climate anomalies are the difference between the 5-year weighted means and the weighted mean for the base period 1951-1980. The anomalies were standardized to a normal distribution with mean = 0 and standard deviation = 1 in order to illustrate disparate trends at the same scale.

Fig. 3. North Atlantic Oscillation (NAO) index phase anomalies (barplots) overlain by anomalies in southern Appalachian Plethodontid abundance (line). The NAO index and salamander abundance anomalies are the difference between the yearly means and overall means. Positive NAO index anomalies are associated with warmer, wetter winters in the eastern United States.

Table 1 - Southern Appalachian weather stations (North Carolina, US) used for regional trend analysis.

Station	County	Elev. (m)
Andrews	Cherokee	533
Banner Elk	Avery	1142
Boone	Watauga	988
Brevard	Transylvania	674
Cullowhee	Jackson	668
Hendersonville	Henderson	658
Highlands	Macon	1016
Hot Springs	Madison	426
Marshall	Madison	610
Swannanoa	Buncombe	1317
Waynesville	Haywood	810