Report from the Appalachian State University Global Climate Change Committee to the North Carolina General Assembly

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Introduction

Climate change is induced by different radiative forcings, or perturbations, to the balance of solar radiation in the Earth-atmosphere system. Radiative forcings result from both natural (e.g., fluctuations in solar intensity and volcanic emissions) and anthropogenic (human-induced) causes. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) concluded that it is *extremely likely* (95% confidence level) that humans have had a warming influence on the climate[1]. The direct cause of long-term climate change is increasing atmospheric concentrations of greenhouse gases such as carbon dioxide, methane, nitrous oxide, and water vapor, as well as black carbon (soot) particles. These gases absorb and re-emit long-wave (terrestrial) radiation, trapping heat that would otherwise return to space[1]. A portion of this radiation is directed back toward Earth's surface, a process similar to that which allows heat to be retained in a greenhouse. Significant increases in carbon dioxide, methane, and nitrous oxide concentrations (relative to pre-industrial times) are largely attributed to human industrial and agricultural activities[2,3], while recent increases in the most ubiquitous greenhouse gas, water vapor, are consistent with increasing temperatures (i.e., warmer air can "hold" more water vapor). A consensus has been reached among scientists regarding the certainty of links between human activities, increased greenhouse gas concentrations, and warming of Earth's atmosphere and oceans[1,4,5,6]. While uncertainty exists regarding the magnitude of warming and its related effects on natural and human systems in coming decades[1], there also is consensus among leading scientific organizations throughout the world that even for conservative projections, unchecked climate change will have serious economic and societal impacts by 2050[1,4,5,7].

While anthropogenic factors such as greenhouse gas emissions, land use and land cover changes, pollution, and aerosols are playing an important role in climate change processes, perturbations in the general circulation of the atmosphere and oceans also may be playing a central role in the observed changes in climate[8,9,10,11]. In particular, the North Atlantic Oscillation (NAO) has trended positive in recent decades, thereby favoring warmer winter conditions over eastern North America and Europe[11]. Likewise, the Pacific Decadal Oscillation (PDO) shifted abruptly in 1977 – known as the "Pacific Climate Shift," and this has significantly influenced northern hemisphere and global climate patterns[8].

Much of the uncertainty in the estimate of anthropogenic climate forcing results from a lack of understanding of the radiative forcing due to aerosol direct and indirect effects (Fig. 1). The aerosol direct effect is due to the scattering and absorption of shortwave and longwave radiation within the atmosphere. This perturbation creates a disruption in the radiative balance of the Earth-atmosphere system, and consequently a climate forcing. Most aerosols, particularly in the U.S., predominantly scatter solar radiation, creating a negative radiative forcing or net cooling effect comparable in magnitude to the warming caused by anthropogenic greenhouse gases (see Fig. 1)[12].

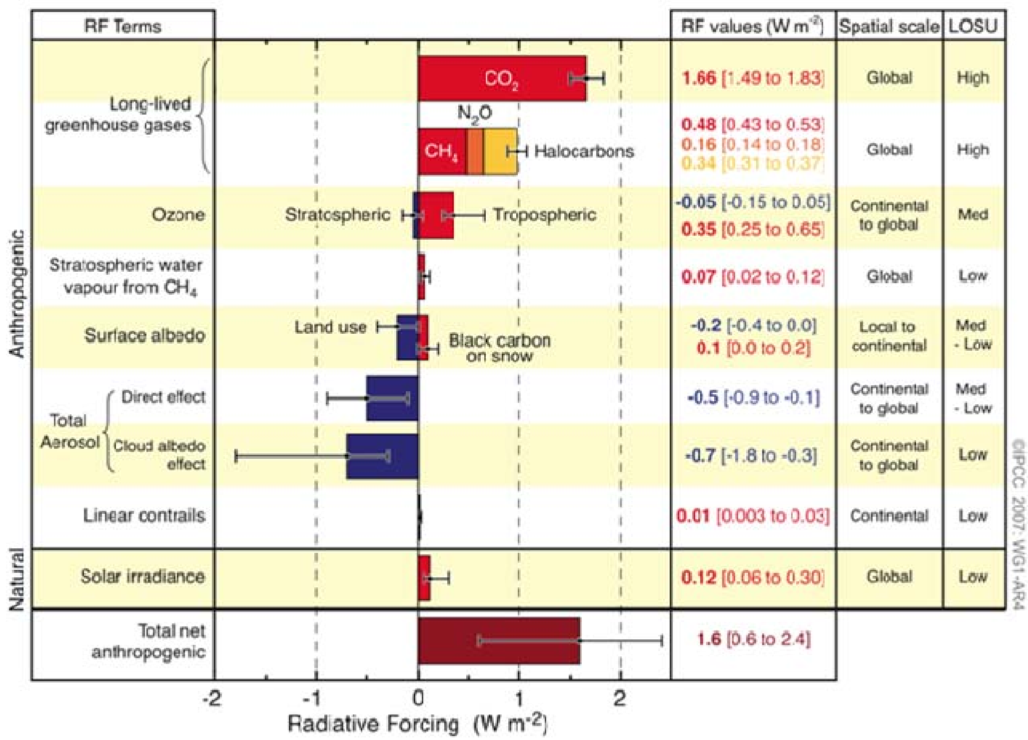

Figure 1. Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic greenhouse gases, aerosols, and other mechanisms, together with the typical spatial scale of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Source: IPCC 2007.

The aerosol indirect effect occurs as a result of the modification of cloud microphysical (and hence, radiative) properties, amounts, and lifetimes by aerosols. There are three types of aerosol indirect effects, summarized in Fig. 2. The first indirect effect occurs when aerosols, which act as effective cloud condensation nuclei, increase the number of and decrease the size of cloud droplets[13]. This occurs because the same number of water vapor molecules must be shared by more aerosol condensation nuclei. This effect modifies solar radiation through an increase in cloud albedo (reflectivity), producing a net cooling effect. The second indirect effect is an increase in the lifetime of clouds, due to a suppression of their precipitation potential[14] as the cloud droplet size decreases from the first indirect effect (smaller, lighter droplets remain suspended in the atmosphere for longer times). This also leads to a net cooling and a disruption of the hydrological cycle. Thus, there is a tremendous need for long-term monitoring of aerosol chemical composition and optical properties at the surface and in the vertical profile, in addition to simultaneous measurements of water vapor. The southeastern U.S. offers a unique location to investigate aerosol chemical and optical properties and the resultant radiative forcing, as the Southeast is subject to some of the highest particle concentrations in the country[15], and the highest concentration of organic aerosols[16,17] due to high concentrations of both anthropogenic and biogenic precursor organic species[18].

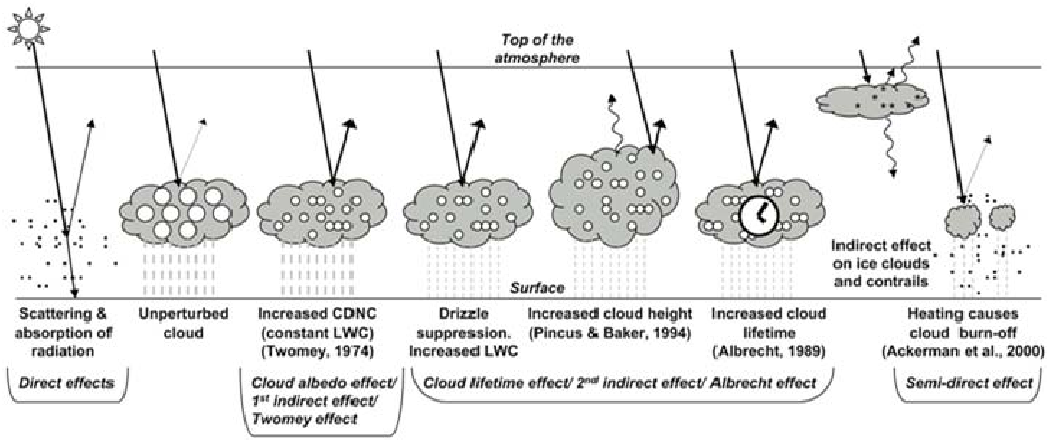

Figure 2. **Schematic diagram of the aerosol direct and indirect effects**. The small black dots represent aerosol particles; the larger open circles cloud droplets; the straight dark lines incident and reflected solar radiation; the wavy lines emitted terrestrial radiation; and the vertical grey dashes rainfall. The cloud droplet number concentration (CDNC) is lower in unperturbed clouds, which contain larger cloud drops, as only natural aerosols are available as cloud condensation nuclei (CCN). Perturbed clouds contain a greater number of smaller cloud drops, as both natural and anthropogenic aerosols are available as CCN. The LWC is the liquid water content. Source: modified from Haywood and Boucher, 2000.

Observations relevant to North Carolina and the southern Appalachian Mountains

At this point, it is not possible to fully separate the relative contributions of anthropogenic forcing versus natural variability to the observed climate changes, both globally and regionally. Further, it is difficult to predict likely impacts and effects of future climate changes with any degree of certainty. Numerical forecast models greatly oversimplify physical atmospheric processes over three-dimensional space and time, particularly with respect to clouds[19]. In the following series of bullets, we summarize some of the known patterns, processes, and impacts of global climate change in the state of North Carolina and the southern Appalachian Mountains.

- ***During the time period of reliable instrumental records, there are no trends in annual temperature or precipitation for the entire state of North Carolina.***

Using statewide averages for North Carolina, we created time series of temperature and precipitation for the period 1895-2007 (Fig. 3, 4). The long-term mean annual temperature for the state is 59.1° F. The warmest year on record was 1990 (61.5° F), and the coldest was 1917 (56.9° F). While no significant long-term linear trends exist (the linear trend line is flat and follows the value of the long-term mean), the last decade has experienced generally above average temperature, with 8 of the last 10 years exceeding the long-term mean. The 6th-order polynomial reveals an oscillating long-term pattern, on the order of 70 years, with temperatures peaking in the mid 1930s and early 2000s.

For precipitation, the long-term average for North Carolina is 49.5 inches annually, and the extremes occurred in the 2000s, with 2007 being the driest year on record (36.3”), and 2003 being the wettest (64.7”). Similar to temperature, the linear trend line is virtually flat, indicating there has been no change toward a wetter or drier climate in the long term. Unlike temperature, the oscillations of precipitation are considerably less, as the 6th-order polynomial suggests only minor fluctuations away from the long-term mean.

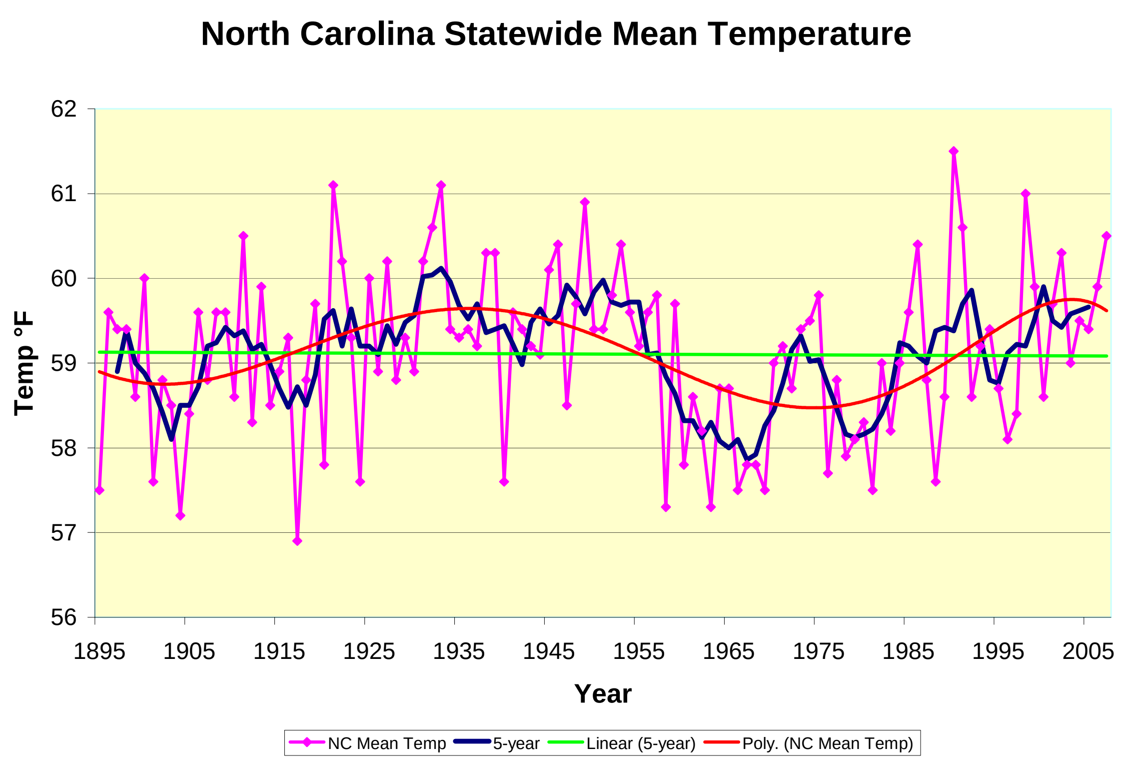

Figure 3. Statewide average annual temperature for North Carolina (purple line), linear trend (green line), 5-year low pass filter (blue line), and 6th-order polynomial (red line). Data source: http://www.sercc.com/climateinfo/monthly_seasonal.html.

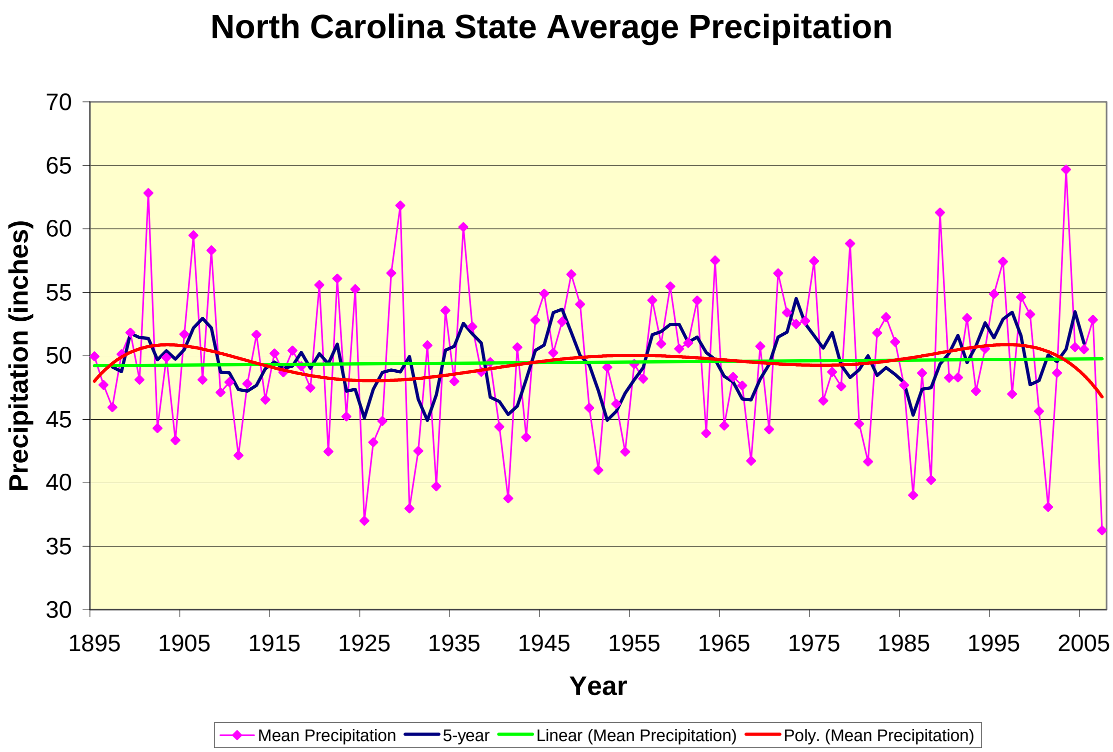

Figure 4. Statewide average total precipitation for North Carolina (purple line), linear trend (green line), 5-year low pass filter (blue line), and 6th-order polynomial (red line). Data source: http://www.sercc.com/climateinfo/monthly_seasonal.html.

- ***While the state of North Carolina as a whole has experienced no significant long-term trends in either temperature or precipitation, significant regional and local trends exist for certain climatic parameters.***

Changing Snowfall Patterns: Annual snowfall has decreased across the southern Appalachians during recent decades (Fig. 5), adversely affecting the NC Ski Industry, which contributes approximately $120 million to the NC state economy[20]. Despite this decrease in total annual snowfall, the percentage of annual snowfall associated with low-level northwest flow has increased[21], indicating that significant changes in winter atmospheric circulation may be occurring. Given the strong connection between northwest flow snowfall events in the NC Mountains and the Great Lakes[22], observed warming of the Great Lakes may be playing a role in the changing snowfall patterns. Warming of lake water temperatures has already been linked to increased lake-effect snowfall due to higher lake water temperatures and decreased ice cover[23], which could increase snowfall at the higher elevations in the NC Mountains during periods of favorable atmospheric circulation. Unfortunately, northwest flow snow events are difficult to forecast[24], thereby posing a significant challenge to the NC DOT, motorists, and the general public.

Drier Winters: Average precipitation (rain and melted snow) during the winter (December to January) has decreased slightly since 1950 across the southern Appalachians (Fig. 5), with a noticeable decrease during the last 10 years. This is likely a contributing factor to the continuing severe drought.

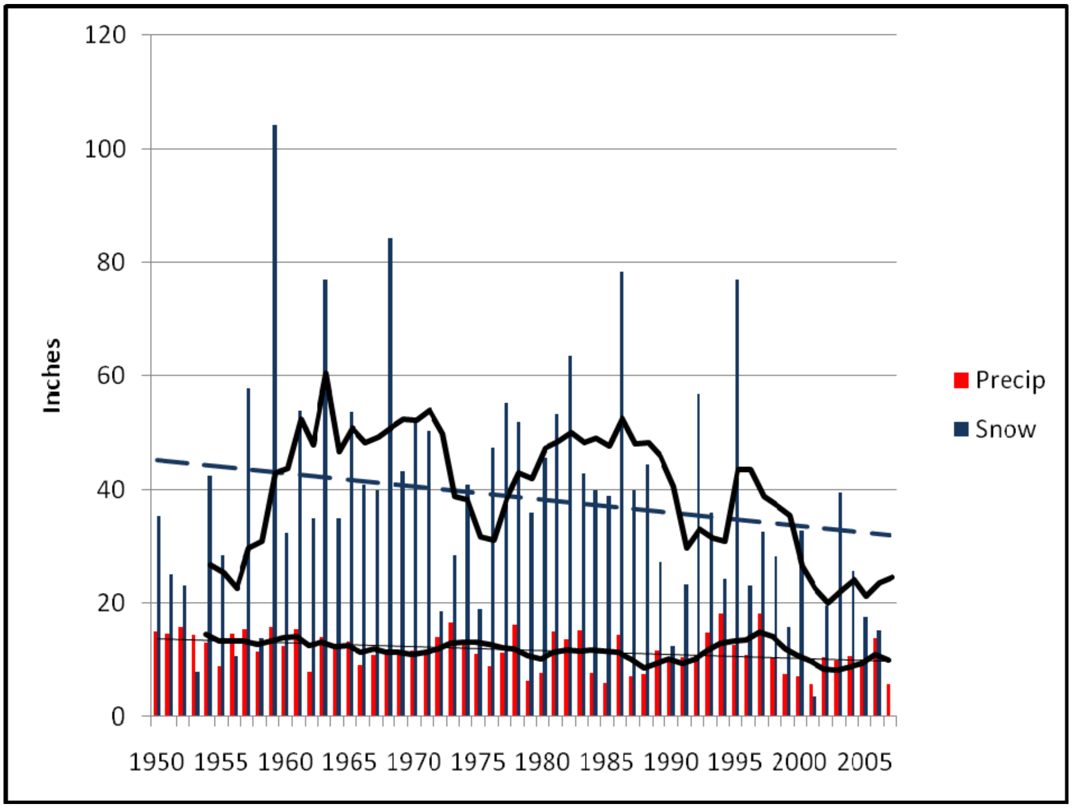

Figure 5. Trends in winter (December to January) precipitation (red bars with associated 5-year low pass filter), and annual snowfall (blue bars with 5-year low pass filter) for Boone, NC, 1950-2008. The dashed line is the linear trend for snowfall, the solid line the linear trend for precipitation. Data source: National Climatic Data Center.

Warmer Summers: The IPCC reports suggest that over the next century, global temperatures will rise anywhere from 1.5 ^{o}C to 6.5 ^{o}C, or possibly even more. In mountainous areas, these increases may be more evident at night than during the day: minimum nighttime temperatures may increase more than daytime maxima. Evidence from Grandfather Mountain suggests this trend has already occurred, and in dramatic fashion. Minimum summer temperatures (June to August) on Grandfather Mountain are trending significantly upward since the mid 1950s, and the increases are on the order of 1.5 to 2.0 °C in the last 50 years, a rate far exceeding that of global temperature trends (Fig. 6).

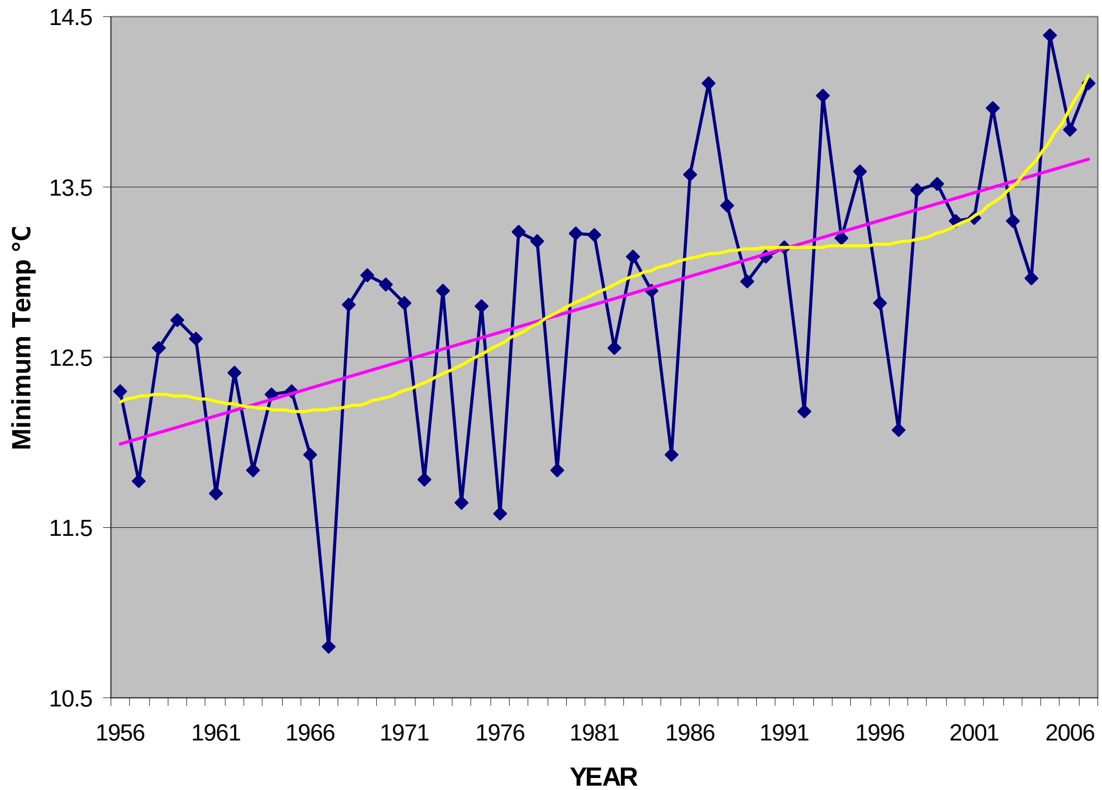

Figure 6. Trends in summer (June to August) minimum temperatures on Grandfather Mountain, North Carolina. The purple line is the linear trend (significantly upward), and the yellow line is a 6th-order polynomial. Data source: National Climatic Data Center.

- ***Rising temperatures will result in species-specific migrations upslope, resulting in a re-structuring of present-day plant communities into ones that have not been present in recent historical time.***

Tree species in the North Carolina Mountains have very specific temperature tolerances, which determine, in part, their elevational distribution. One of the most endangered ecosystems is the high elevation spruce-fir forest, which is distributed among the highest peaks in the Southern Appalachians[25]. Temperature increases could result in the extirpation of these species from these areas. Recent elevational shifts in species dominance have already been documented in New England[26], which has experienced measureable increases in temperature in the past half century.

Gleason's Individualistic Hypothesis[27] states that species in forests tend to segregate along environmental gradients according to their individual physiological tolerances. This means that as temperatures rise, species will sort themselves along the elevational gradient according to their own tolerances, resulting in new forest communities from those currently present. Such sorting took place nearly 16,000 years ago when the glaciers receded northward, and unique communities arose as species migrated at different rates[28,29]. This may happen again as species migrate not only upwards in response to increases in temperature, but northward also[30,31]. In the long-term, these processes may pose a threat to the southern Appalachian mountain region's thriving Christmas tree industry.

- ***Alterations in precipitation amounts and patterns also will result in the re-structuring of plant communities.***

How global change will affect precipitation in North Carolina is one of the great uncertainties remaining in model predictions. While no observed change exists for the state as a whole (Fig. 4), significant local changes are already evident (Fig. 5). Depending on which Global Circulation Model (GCM) is chosen (Canadian or Hadley) to predict future changes, precipitation may either rise by approximately 10% during the summer, or decrease by 20% even though both models predict increases in yearly totals[32]. Furthermore, it is not clear whether rising temperatures will affect the seasonal distribution of rainfall. In some scenarios, rainfall may occur more sporadically, but in more intense storms. In others, the distribution of rainfall may not be affected at all. However, rising temperatures, particularly at high elevations at night, may be altering ecosystem processes within spruce-fir forests in multiple, synergistic ways[33,34,35].

If precipitation amounts decrease, species more tolerant to reduced rainfall may increase in prominence while those that are more sensitive may decrease. Should rainfall events become more widely scattered in time, this too could favor the more drought tolerant species. Such changes also would increase the probability of forest fires, which in turn would cause changes in species composition (more fire tolerant species would be selected for) and increase greenhouse gas emissions from the combustion of both wood and forest floor carbon. More intense storms may result in increased run-off and less water storage in forest soils, decreased availability for plants during the times between storms, and greater erosion.

- ***Rising carbon dioxide levels may cause temporary increases in productivity that will eventually be negated by depletion of soil nutrient reserves, particularly nitrogen.***

Elevated carbon dioxide may result in increased productivity for some tree species, a result mainly of higher photosynthesis rates. However, in at least two major studies, these increases were shown to be only temporary[36,37]. This was because the increased production resulted in higher uptake of nutrients to support that growth, and the soil nutrient supply was eventually depleted, whereupon productivity dropped back to pre-elevated levels. Once equilibrium is achieved between elevated carbon dioxide and soil nutrient levels, and the higher rates of carbon assimilation disappear, most of the carbon is then simply cycled through the system, only to re-appear in the atmosphere as the by-product of root and soil respiration[37]. In other words, the carbon is pumped *through* the system, but is not stored *in* the system. The long-term implications of faster carbon cycling within forest ecosystems is not well enough understood for us to be able to make predictions about the eventual consequences for productivity and species composition.

- ***Global environmental change factors will interact in complex and unpredictable ways to influence plant community structure and function.***

Global change involves a suite of factors that all change simultaneously. Rising temperatures are associated with higher carbon dioxide levels, with altered precipitation amounts and patterns, and also with other factors such as the pollutants ozone, sulfur dioxide, and mercury. In addition, human activities such as urbanization and logging may result in the fragmenting of forests into smaller units. When forests are fragmented, this causes an increase in the ratio of the perimeter to the area of the forest, and it is along the edges of forests where various weedy and alien species can persist. This is also prime habitat for deer. Edge effects, such as increased light and altered precipitation and temperature, can penetrate far into the forest understory, with adverse affects on forest regeneration[38]. If deer are superabundant, their browsing can have even further severe consequences on forest regeneration[39].

Rising pollution levels may offset any increases in productivity that result from the elevated carbon dioxide. For example, background ozone is expected to continue to increase for the foreseeable future, and studies show that this pollutant, which is extremely toxic to plants, can significantly reduce the capacity of forests to sequester carbon from the atmosphere[40]. If nitrogen deposition continues to increase and double by the year 2050, as predicted[41], that may alleviate some of the limitations on carbon assimilation. However, too much nitrogen can lead to nitrogen saturation of forest ecosystems[42], as supply exceeds demand. When forests become nitrogen saturated, they begin to leak nitrates into streams and rivers, thereby causing deterioration of the water supply. Since much of the water supply for the state originates in the mountains, this may place a greater strain on water treatment facilities downstream in order to cope with this problem. All of these interacting factors may result in changes in forest structure and function, and the end result is that climate change may create new and unique forests that function in ways we currently cannot predict, with consequences for human systems that may be significant.

- ***In the next twenty-five years, climate change in the southeastern U.S. is expected to result in increased water shortages because of drought, and these will be exacerbated further by large increases in population during this period.***

It has already been shown that natural climate variability in the Pacific Ocean has an impact on fluctuations of water supplies in North Carolina[43]; human-caused climate change may affect these fluctuations further. While some scientific evidence suggests that warming of the oceans may be related to an increase in hurricane activity in the Atlantic Ocean[44], this is an area of climate change research that is currently hotly contested[45,46]. Clearly, any increase in Atlantic hurricane activity has potentially far-reaching consequences for North Carolinians and our economy.

- ***Forests of the southeastern U.S. are important tools in the removal of carbon dioxide from the atmosphere.***

Preserving and expanding existing forest areas in North Carolina will maintain this important sink for atmospheric carbon dioxide[47,48]. Also, practicing no-till or reduced-till agriculture will help to prevent carbon stored in soils from being released to the atmosphere, and it will reduce the combustion of fossil fuels due to fewer hours of equipment operation[49].

- ***Incomplete knowledge of atmospheric aerosol effects on solar radiation and climate is a limiting factor in the ability of models to predict the future effects of climate change***

Atmospheric aerosols produced by natural sources (dust, organic carbon from biogenic sources, sea salts) and anthropogenic sources (industrial pollution, fossil fuel and biomass fuel burning) create perturbations to Earth's radiative balance that are comparable in magnitude to those of greenhouse gases[12] in many regions of the world. These perturbations, or forcings, can occur directly via absorption and scattering of solar radiation (direct forcing) by the particles and also indirectly through aerosol effects on cloud cover, cloud brightness, precipitation, and severe weather (as discussed earlier in this report). The effects of aerosols are primarily cooling and are consistent with an observed cooling trend in the Southeastern U.S. between 1949 and 1994[50]. Aerosol forcing influences are not yet well quantified, and uncertainties associated with changes in Earth's radiation budget due to anthropogenic aerosols (radiative forcing) are considered to be the greatest contribution to uncertainty in radiative forcing of climate change over the industrial period[1]. The most important improvement of understanding of aerosols and their role in global change is that the aerosol effect extends far beyond radiative forcing in the Earth's energy budget. Aerosols absorb sunlight and create differential heating within the atmosphere that affects atmospheric circulations and weather at many scales. Clouds and precipitation, in turn, affect aerosol properties and abundance.

- ***An increasing number of globally-distributed ground-based monitoring stations is necessary to complement satellite measurements and to better understand climate change on regional scales***

Because the distribution of pollution and natural aerosol sources and aerosol properties are highly inhomogeneous and aerosols only remain in the atmosphere for several days, modeling their effects on climate is difficult. For this reason, the inclusion of regional aerosol studies is suggested to more easily quantify the climatic impact of[51] and to complement satellite-based measurements. However, aerosol monitoring sites (e.g., NOAA-GMD, NASA AERONET) are virtually non-existent in the southeastern U.S, which is home to the largest levels of organic and sulfate-based aerosols in the country[15]. Changing U.S. and North Carolina emissions policies could result in an increase in organic aerosols relative to industrially produced sulfate-based aerosols[51]. Current models are not adequately equipped to accurately simulate the effects of this predicted change in aerosol mass fraction on the southeastern U.S. regional solar radiation budget and ultimately, on regional climate and weather. Comprehensive, continuous measurements of aerosol properties and vertical distributions from an increased number of regional sites are needed.

Summary and considerations for policy makers

The combustion of *any* fossil fuel adds carbon dioxide to the atmosphere, and atmospheric carbon dioxide levels have increased dramatically since the late 1800s and show no signs of abating. In essence, humans are conducting an experiment with Earth's atmosphere that has no control group. As atmospheric composition changes, there will continue to be cause and effect relationships. While the current state of Global Circulation Models gives us a scientifically grounded idea of what the impacts may be, the final results of this experiment are unknown. Adding to this uncertainty is the lack of understanding of aerosols impacts on the regional climate and the affects that future emissions changes will have on aerosol chemical composition. Realistic strategies for preventing further global warming and the associated climate change must have as their ultimate goal the reduction of greenhouse gas concentrations. According to the Law of Conservation of Mass, the only means of achieving this goal are reducing emissions of greenhouse gases to the atmosphere and/or removing additional greenhouse gases from the atmosphere. To minimize its contribution to human-caused climate change, North Carolina should implement policies that promote both short-term and long-term reductions in emissions of greenhouse gases and preserve natural sinks for atmospheric carbon dioxide (i.e., forests and agricultural soils). While North Carolina alone can not make a huge impact in the atmospheric concentration of greenhouse gases and their ultimate effects, we can choose to be proactive in addressing one of the most important issues in modern science. For example, the up front expenses associated with solar electricity are steep, but the impact of solar power in terms of reduced carbon dioxide emissions is immediate and persistent because this existing technology has no greenhouse gas emissions other than those associated with production. Conversely, development of technologies to capture and sequester carbon dioxide from fossil-fuel burning power plants is also expensive, and there will be no immediate effect of this investment on emissions since these technologies are years from implementation and their success is uncertain.

In light of the research summarized here, we, the members of Appalachian State University's Global Climate Change Committee, believe:

1. that North Carolina should actively seek to better educate our citizens and students regarding climate change and environmental stewardship.

2. there is a clear need for coordinated long-term monitoring of the atmosphere from multiple locations within the state to help aid the refinement of regional climate models that are, in part, driven by instrumental measurements of meteorological conditions.

3. that the skills of scientists, researchers, and educators employed by the State of North Carolina are best used in a coordinated manner to better understand the impacts of climate change on our state's environment and economy.

4. that funding for projects dealing with aspects of climate change that directly impact North Carolinians should be a high priority for our state legislature and state-sponsored funding agencies.

5. that the study of climate change is inherently interdisciplinary, and that state agencies and academic institutions should work together to embrace diversity as one of the best avenues to insure that the interests of North Carolinians are being served by efforts to better understand this rapidly evolving area of science.

6. that rising levels of greenhouse gases and aerosols are causing significant changes to Earth's climate, and these changes will potentially impact North Carolina's environment and economy

7. that "uncertainty" with respect to climate change does not imply that effects are potentially nonexistent (i.e., temperatures may or may not rise); rather, it implies a range of magnitudes in the effects.

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